Effects of abiotic factors and indigenous bee attractant on plant pollinators interaction in onion.

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Entomology

By

Pandit Trupti Rajesh

Registration Number: 12214266

Supervised By

Dr. Sunil Kumar Dwivedi (21186)

Department of Entomology

(Associate Professor)

Lovely Professional University

Co-Supervised by

Dr. Karuppaiah. V

Department of Entomology

Senior Scientist

ICAR-DOGR



LOVELY PROFESSIONAL UNIVERSITY, PUNJAB

2026

DECLARATION

I, **Pandit Trupti Rajesh**, bearing **Registration No. 12214266**, hereby declare that the research work embodied in the Ph.D. thesis titled **"Effects of abiotic factors and indigenous bee attractant on plant pollinators interaction in onion."** submitted to Lovely Professional University is the original and bonafide work carried out by me under the supervision of **Dr. Sunil Kumar Dwivedi**, Associate Professor, Department of Entomology/School of agriculture, Lovely Professional University and my co-guide Dr. Karuppaiah. V, Senior Scientist and Entomology Scientist at ICAR-DOGR

I further declare that:

a) The work presented in this thesis is a genuine contribution to the field of research and is a result of investigations carried out by me during the period of my doctoral study.

b) The research work has been conducted in accordance with the academic and ethical standards prescribed by the university.

c) Due acknowledgements and references have been duly given wherever the work of others has been cited or used.

d) The thesis has not been submitted either partly or fully to any other university or institution for the award of any degree or diploma.

I understand that any violation of the above declarations may lead to the cancellation of my degree by the university at any stage.

TPPandit

Name: Pandit Trupti Rajesh

Reg.no.12214266

CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled **"Effects of abiotic factors and indigenous bee attractant on plant pollinators interaction in onion"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in Department of **Entomology** in the **School of Agriculture** is a research work carried out by **Pandit Trupti Rajesh** (Reg No: **12214266**), is bonafide record of her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

Major advisor
Dr. Sunil Kumar Dwivedi
School of Agriculture
Lovely Professional University
Punjab, India

Co-advisor
Dr. Karuppaiah V.
ICAR- Directorate of Onion and Garlic Research
Rajgurunagar, Pune, MH, India

CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled **"Effects of abiotic factors and indigenous bee attractant on plant pollinators interaction in onion"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in Department of **Entomology** in the School of Agriculture, LPU, Phagwara is a research work carried out by **Pandit Trupti Rajesh** (Reg No: **12214266**), is bonafide record of her original work carried out under my supervision and has been approved by the research advisory committee after viva-voce in collaboration with external examiner.

Major advisor 08/09/2026
Dr. Sunil Kumar Dwivedi
School of Agriculture
Lovely Professional University
Punjab, India

Co-advisor
Dr. Karuppaiah V.
ICAR- Directorate of Onion and Garlic Research
Rajgurunagar, Pune, MH

HOD
Dr. Ankush M. Raut
School of Agriculture
Lovely Professional University
Punjab, India

External Examiner
Dr. Harish Kumar Sharma

10/09/26
Dean
Dr. Pardeep Kumar Chhuneja
School of Agriculture
Lovely Professional University
Punjab, India

Acknowledgement

Reflecting on the journey travelled and reminiscing about the days of dedication and perseverance brings a sense of satisfaction. While formal language may lack the ability to fully convey the depth of emotions, it remains the primary means of expressing gratitude in formal acknowledgments.

It is an immense pleasure and honor for me to have the opportunity to work under the guidance of Dr. S. A. Dwivedi, Associate professor, Department of Entomology, Lovely Professional University, Punjab, India. I wish to express my deepest gratitude for his unwavering dedication to science, systematic and inspiring mentorship, constructive feedback, continuous support, His teachings, devoted commitment to the profession, scientific perspective, punctuality, sincerity, and ethical values have served as a source of inspiration for shaping my career. I am sincerely thankful for his encouragement and guidance throughout my time in college.

I am delighted to extend my heartfelt gratitude to the esteemed members of the advisory committee: Dr. V. Mahajan, Director, ICAR- Directorate of Onion and Garlic Research, Rajgurunagar, Pune, Dr. V. Karuppaiah, Senior scientist, Department of Entomology ICAR-Directorate of Onion and Garlic Research, Rajgurunagar, Pune, MH. I wish to express my deepest gratitude for his patient listening, friendly demeanor and invaluable suggestions that aided in the completion of various tasks. I am sincerely thankful for his encouragement and guidance throughout my time in ICAR-DOGR, Pune. Dr. P. Soumya, Scientist, Department of Entomology ICAR- Directorate of Onion and Garlic Research, Rajgurunagar, Pune, MH. Dr. Wakhare, ICAR-Directorate of Onion and Garlic Research, Rajgurunagar, Pune, MH. Their prompt guidance, unwavering inspiration, moral support and invaluable assistance were instrumental during the investigation period.

I extend my gratitude to Hon. Vice-Chancellor Dr. Jaspal Singh Sandhu, LPU, Punjab, for fostering a conducive educational environment, offering research facilities and providing timely financial support throughout the investigation period. Additionally, I appreciate Dr. Ramesh Sadavarti, Ex-Dean, School of Agriculture and Allied sciences, LPU, Punjab, as well as Dr. Pradeep Kumar Chhuneja, Professor & Dean, HOS, School of Agriculture and Allied sciences, LPU, Punjab he is experts in Apiculture his guidance and support are most valuable also Dr. Shailesh Kumar Singh Associate Dean & Dr. Chandra Mohan Mehta Associate Dean for their provision of necessary facilities during my studies here.

I wish to express my sincere gratitude to Dr. Ankush Raut, Head, Department of Entomology, Lovely Professional University, Punjab, India. Dr. Satish Gharde, Assistant Professor, Department of Entomology, Dr. Krishnakumari Assistant Professor, Department of Entomology, Dr. Ajang Longkumar Assistant Professor, Department of Entomology, Dr. Devina Serum Assistant Professor, Department of Entomology, Dr. Pritha Ghosh Assistant Professor, Department of Entomology, Dr.Sandip Chaudhary Assistant Professor, Department of Entomology, Dr. Shimpy Sarkar Assistant Professor, Department of Entomology Their valuable suggestions, remarkable guidance, and friendly cooperation were invaluable throughout both the academic and research endeavours.

Also, I wish to thank Mr. Dhananjay Shirsat, JRF, Department of Entomology, ICAR-DOGR, Mr. Chandrasen Pote, JRF, Department of Entomology, ICAR-DOGR, Ms. Komal Gade, Young Professional, Department of Soil science, ICAR-DOGR , Ms. Payal Mahadule, JRF, Department of Soil science ICAR-DOGR friendly cooperation were invaluable throughout and research endeavours help in field and lab techniques.

Navigating financial constraints proved to be the most daunting aspect of my Ph.D. research journey, a challenge that many fellow students also faced, resulting in incomplete programs. I extend my gratitude to ICAR-DOGR, Pune and Mahatma Jyotiba Phule Research & Training Institute (MAHAJYOTI), Government of Maharashtra awarding me the merit fellowship during my II Ph. D for financial assistance. Additionally, I am deeply appreciative of the steadfast support provided by LPU, Punjab for their invaluable assistance has been truly appreciated.

I wish to convey my deepest gratitude to my best friends, Mr. Amol Rajkumar Pawar and Mr. Mayur Bhatu Patil, whose unwavering support was indispensable in reaching this significant milestone in my life. My heartfelt gratitude also goes to my husband for life Mr. Ravindra Janardhan Bhagwat for selfless love, unwavering emotional and constant presence.

As a family away from home and brothers for life, I am deeply grateful for the emotional, physical, and financial support extended to me by my dear papa & mummy as their dreams come true. No words are enough to express the great sacrifice, devotion, constant encouragement and inspiration of my beloved, respected and adorable mother Smt. Sharda Rajesh Pandit and enthusiastic father Shri. Rajesh Ramdas Pandit, Grandmother Nirmala Pandit and memory of My dadu Late shri. Ramdas Kaduba Pandit, I would also like to thank My Inlaws Shri. Janardhan Radhakisan Bhagwat

and Smt. Asha Janardhan Bhagwat without their moral support, affection and guidance, I would not have successful in this difficult endeavour of Ph. D. studies.

Special thanks to my brother Mr. Sanket Rajesh Pandit for encouragement. My family members Savita Mavshi, Mama, Khushi, Amol anna, Nilu bhaiyya, Sandu bhaiyya, Shivanya, Riyansh & Vrunda for constant Love.

I am deeply thankful to Lovely Professional University, Punjab, India, for granting me the opportunity to pursue my Ph. D. studies at this esteemed national institution to allow me to do research work under MOU with ICAR-Directorate of Onion and Garlic Research, Rajgurunagar, Pune. Numerous individuals have played a role in the progress of my research. While some may not have been explicitly mentioned, their contributions are cherished and remembered.

Place: LPU, Punjab

Date:

(Pandit Trupti Rajesh**)**

TABLE OF CONTENTS

	Chapter / Title	Page No.
	ABSTRACT	1-2
	INTRODUCTION	3-7
	REVIEW OF LITERATURE	8-52
2.1	To investigate the impact of abiotic variations on the onion pollinators on different dates of planting.	8-24
2.1.1	Species diversity of flower visitors associated with onion flowers	8-12
2.1.2	Foraging activity of honeybees and influence of date of sowing on yield of onion.	12-20
2.1.3	Correlation of weather parameters with foraging behaviour of honeybee species.	20-23
2.2	To study the role of varietal traits of onion on abundance, foraging behavior of insect pollinators (*Apis mellifera*).	23-52
2.2.1	Influence of Apis mellifera on Abundance, Foraging Behavior among Onion (*Allium cepa* L.) Varieties.	23-31
2.2.2	Physi chemical and Biochemical Composition of Onion (*Allium cepa* L.) Pollen and Nectar.	31-42
2.3	To Formulate and evaluate some indigenous bee attractants for enhancing the Pollinator's activity.	40-52
2.3.1	Onion	40-44
2.3.2	Other Crops	44-49
2.3.3	Pomegranate juice, Coconut water, Dates extract how they rich with Biochemical and physiochemical properties.	49-52
	MATERIAL AND METHODS	53-75
3.1	Geographical Location	53
3.2	Climate	53
3.3	Materials	55-57
3.3.1	Honeybee colonies and mosquito mesh	55
3.3.2	Bee attractants	55

3.3.3	Laboratory materials	55-56
3.3.3.1	Laboratory instruments	55
3.3.3.2	Glassware and tubes	55
3.3.3.3	Cleaning and sterilization of glassware	56
3.3.3.4	Chemical reagent	56
3.3.3.5	Other materials	56
3.4	Methods	56-
3.4.1	To investigate the impact of abiotic variations on the onion pollinators on different dates of planting.	56
3.4.1.1	Raising of the crop	56
3.4.1.2	Method of recording species diversity of pollinators	57
3.4.1.3	Percent forage visit	61
3.4.1.4	Impact of abiotic variations on the onion pollinators on different date of planting.	58 - 60
3.4.1.4.1	Abundance of floral visitors	58
3.4.1.4.2	Umbel visitation rate	59
3.4.1.4.3	Statistical analysis	59- 60
3.4.2	To study the role of varietal traits on abundance, foraging behaviors of insect Pollinators (*A. mellifera*).	60 - 62
3.4.2.1	Morphological parameters	61
3.4.2.1.1	Number of Umbels	62
3.4.2.1.2	Scape Length	62
3.4.2.1.3	Umbel Diameter	62
3.4.2.2	Influence of *Apis mellifera* on Abundance, Foraging Behavior among Onion (*Allium cepa* L.) Varieties.	62-
3.4.2.2.1	Foraging rate of *A. mellifera* on different onion varieties.	62
3.4.2.2.2	Foraging speed of *A. mellifera* on different onion varieties.	63
3.4.2.3	Methodology for Collection of Pollen and Nectar samples	63- 64
3.4.2.3.1	Collection of Floral Nectar	63

3.4.2.3.2	Collection of Pollen Grains	64
3.4.2.4	Physio chemical and Biochemical Composition of Onion (*Allium cepa* L.) varieties of Pollen and Nectar.	64- 70
3.4.2.4.1	pH	65
3.4.2.4.2	EC	65
3.4.2.4.3	Moisture	65
3.4.2.4.4	Total Antioxidant	65
3.4.2.4.5	Total Protein	66
3.4.2.4.6	Total Phenol	66
3.4.2.4.7	Total Flavonoid	67
3.4.2.4.8	Minerals	67
3.4.2.4.9	Total sugar	67-68
3.4.2.4.10	Glucose, Sucrose, and Fructose	68
3.4.2.4.11	Determination of Amino acids	68-70
3.4.3	To formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.	70- 75
3.4.3.1	Observations recorded	71
3.4.3.1.1	Honeybees' activity	72
3.4.3.1.2	Number of umbels/plants	72
3.4.3.1.3	Per cent flower set (%)	72
3.4.3.1.4	Seed weight/ umbel (g)	72
3.4.3.1.5	Seed yield (kg/ ha)	73
3.4.3.1.6	Test weight (weight of 1000 seeds in g)	73
3.4.3.1.7	Germination test (%)	73
3.4.3.1.8	ICBR	73
3.4.3.1.9	Benefit: Cost ratio	74
3.4.3.1.10	Statistical analysis	74- 75
	RESULT AND DISCUSSION	76- 263

4.1	To investigate the impact of abiotic variations on the onion pollinators on different dates of planting.	76-118
4.1.1	Diversity and abundance flower visitors of onion.	76-83
4.1.1.1	First year	76-77
4.1.1.2	Second year	77-81
4.1.2	Impact of abiotic variations on the onion pollinators on different dates of planting.	83-110
4.1.2.1	First year	84-99
4.1.2.1.1	Abundance of onion umbel visitors (Honeybees) on crop grown on different seven dates of planting 2023-24.	84-99
4.1.2.1.1.1	Activity of umbel visitors (Honeybees) of onion during 1st planting date 5 September 2023.	84-85
4.1.2.1.1.2	Activity of umbel visitors (Honeybees) of onion during 2nd planting date 20 September 2023.	86-87
4.1.2.1.1.3	Activity of umbel visitors (Honeybees) of onion during 3rd planting date 5 October 2023.	87-88
4.1.2.1.1.4	Activity of umbel visitors (Honeybees) of onion during 4th planting date 20 October 2023.	89-90
4.1.2.1.1.5	Activity of umbel visitors (Honeybees) of onion during 5th planting date 05 November 2023.	91-92
4.1.2.1.1.6	Activity of umbel visitors (Honeybees) of onion during 6th planting date 20 November 2023.	92-93
4.1.2.1.1.7	Activity of umbel visitors (Honeybees) of onion during 7th planting date 05 December 2023.	94-95
4.1.2.1.1.8	Correlation between weather parameters across standard metrological weeks (SMW) means abundance of honeybees (Rabi 2023-24).	95-99
4.1.2.2	Second year	99-118
4.1.2.2.1	Abundance of onion umbel visitors (Honeybees) on crop grown on different seven dates of planting 2024-25.	99-118

4.1.2.2.1.1	Activity of umbel visitors (Honeybees) of onion during 1st planting date 5 September 2024.	100
4.1.2.2.1.2	Activity of umbel visitors (Honeybees) of onion during 2nd planting date 20 September 2024.	101-102
4.1.2.2.1.3	Activity of umbel visitors (Honeybees) of onion during 3rd planting date 5 October 2024.	102-103
4.1.2.2.14	Activity of umbel visitors (Honeybees) of onion during 4th planting date 20 October 2024.	104-105
4.1.2.2.1.5	Activity of umbel visitors (Honeybees) of onion during 5th planting date 05 November 2024.	106-107
4.1.2.2.1.6	Activity of umbel visitors (Honeybees) of onion during 6th planting date 20 November 2024.	107-108
4.1.2.2.1.7	Activity of umbel visitors (Honeybees) of onion during 7th planting date 05 December 2024.	109-110
4.1.2.2.1.8	Correlation between weather parameters across standard metrological weeks (SMW) means abundance of honeybees (Rabi 2024-25).	110-118
4.2	To study the role of varietal traits of onion on abundance, foraging behavior of insect pollinators (*Apis mellifera*).	118
4.2.1	Morphological Characterization of Onion Varieties.	118-123
4.2.1.1	Number of umbels Rabi 2023-24.	118
4.2.1.2	Scape length Rabi 2023-24.	119
4.2.1.3	Umbel diameter Rabi 2023-24.	120
4.2.2.1	Number of umbels Rabi 2024-25.	120-121
4.2.2.2	Scape length Rabi 2024-25.	121
4.2.2.3	Umbel diameter Rabi 2024-25	122-123
4.2.2	Influence of *Apis mellifera* on Abundance, Foraging Behavior among Onion (*Allium cepa* L.) Varieties.	123-147
4.2.2.1	Foraging rate of *Apis mellifera* on different onion varieties.	123-135
4.2.2.1.1	First year (Rabi 2023-24).	123-127
4.2.2.1.2	Second year (Rabi 2024-25)	127-131

4.2.2.1.3	Pooled data Rabi 2023-24 & Rabi 2024-25	131-135
4.2.2.2	Foraging speed of *Apis mellifera* on different onion varieties.	135-147
4.2.2.2.1	First year (Rabi 2023-24).	135-139
4.2.2.2.2	Second year (Rabi 2024-25).	140-143
4.2.2.2.3	Pooled data Rabi 2023-24 & Rabi 2024-25.	143-147
4.2.3	Physicochemical and Biochemical composition of onion (*Allium cepa* L.) varieties of nectar and pollen.	148-198
4.2.3.1	Physicochemical and Biochemical composition of Different varieties of Onion umbel Pollen.	148-155
4.2.3.1.1	First year (Pollen).	148-150
4.2.3.1.2	Second year (Pollen)	150-153
4.2.3.1.3	Pooled data Rabi (Pollen) Rabi 2023-24 & Rabi 2024-25.	153-155
4.2.3.2	Physicochemical and Biochemical composition of onion (*Allium cepa* L.) varieties of Nectar.	156-1641
4.2.3.2.1	First year (Nectar Rabi 2023-24).	156-158
4.2.3.2.2	Second year (Nectar Rabi 2024-25).	158-161
4.2.3.2.3	Pooled data Rabi (Nectar) Rabi 2023-24 & Rabi 2024-25.	161-164
4.2.4	Amino acid Analysis.	164-179
4.2.4.1	Analysis of Amino acid by LCMS/MS.	164-176
4.2.4.2	Analysis of Amino acid by paper chromatography.	177-179
4.2.5	Correlation between Physicochemical and Biochemical composition of onion (*Allium cepa* L.) of Pollen, Nectar and *A. mellifera* forage rate.	180-186
4.2.5.1	First year (Rabi 2023-24).1	180-183
4.2.5.2	Second year (Rabi 2024-25).	183-186
4.3	To formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.	198-
4.3.1	Influence of bee attractants on *A. mellifera* visitation in onion crop.	199-208
4.3.1.1	First year (Rabi 2023-24)	199-202
4.3.1.2	Second year (Rabi 2024 - 25)	202-205
4.3.1.3	Pooled data (Rabi 2023-24 to Rabi 2024-25).	205-208

4.3.2	Influence of bee attractants on *A. dorsata* visitation in onion crop.	208-217
4.3.2.1	First year (Rabi 2023-24).	208-211
4.3.2.2	Second year (Rabi 2024-25)	212-214
4.3.2.3	Pooled data (Rabi 2023-24 to Rabi 2024-25).	215-217
4.3.3	Influence of bee attractants on *A. cerana* visitation in onion crop.	218-226
4.3.3.1	First year (Rabi 2023-24).	218-221
4.3.3.2	Second year (Rabi 2024-25).	221-223
4.3.3.3	Pooled data (Pooled data (Rabi 2023-24 to Rabi 2024-25).	224-226
4.3.4	Influence of bee attractants on *A. florea* visitation in onion crop.	227-235
4.3.4.1	First year (Rabi 2023-24).	227-229
4.3.4.2	Second year (Rabi 2024-25)	229-232
4.3.4.3	Pooled data (Pooled data (Rabi 2023-24 to Rabi 2024-25).	232-235
4.3.5	Influence of bee attractants on *T. iridipennis* visitation in onion crop.	235-245
4.3.5.1	First year (Rabi 2023-24).	235-238
4.3.5.2	Second year (Rabi 2024-25).	239-242
4.3.5.3	Pooled data (Pooled data (Rabi 2023-24 to Rabi 2024-25).	242-245
4.3.6	Influence of bee attractants on quantitative and qualitative parameters of onion.	245-263
4.3.6.1	First year (Rabi 2023-24).	245-249
4.3.6.1.1	No. of umbels /plant	246
4.3.6.1.2	No. of seeds per umbel	246
4.3.6.1.3	Onion seed setting increases over control (%).	246
4.3.6.1.4	1000 Seed weight (g)	247
4.3.6.1.5	Seed yield (g/ umbel)	247
4.3.6.1.6	Seed yield (kg/ha)	249
4.3.6.1.7	Germination percentage	249
4.3.6.1.8	Percent deformed seed	249
4.3.6.2	Second year (Rabi 2024-25)	250-254
4.3.6.2.1	No. of umbels /plant	250
4.3.6.2.2	No. of seeds per umbel	250
4.3.6.2.3	Onion seed setting increases over control (%).	250

4.3.6.2.4	1000 Seed weight (g)	251
4.3.6.2.5	Seed yield (g/ umbel)	251
4.3.6.2.6	Seed yield (kg/ha)	253
4.3.6.2.7	Germination percentage	253
4.3.6.2.8	Percent deformed seed	253-254
4.3.6.3	Pooled data (Rabi 2023-24 to Rabi 2024-25)	254
4.3.6.3.1	Number of umbels per plant	254
4.3.6.3.2	Number of umbelets per umbel	254
4.6.3.6.3	Number of seeds per umbel	254
4.6.3.6.4	Onion seed setting increases over control (%)	254
4.6.3.6.5	1000 Seed weight (g)	256
4.6.3.6.6	Seed yield (g/umbel)	256
4.6.3.6.7	Seed yield (kg/ha)	256
4.6.3.6.8	Germination percentage	256
4.6.3.6.9	Percent deformed seed	256
	Summary and conclusion	264-270
	SUMMARY	264-267
	CONCLUSION	267-269
	FUTURE LINE OF WORK	270
	References	271-288
	Appendix	289-298

LIST OF TABLES

Table No.	Particulars	Page No.
01	Details on source of experiment materials	58
02	Details of ICAR-DOGR onion varieties	64
03	Analysis of amino acid details of gradient program	72
04	Details of treatments	73
05	Diversity and abundance flower visitors of onion (ICAR-DOGR, Pune)	82
06	Activity of Honeybees visitors on onion umbel at peak period of day during 1st planting date (5 September 2023).	84
07	Activity of Honeybees visitors on onion umbel at peak period of day during 2nd planting date (20 September 2023).	86
08	Activity of Honeybees visitors on onion umbel at peak period of day during 3rd planting date (5 October 2023).	87
09	Activity of Honeybees visitors on onion umbel at peak period of day during 4th planting date (20 October 2023).	89
10	Activity of Honeybees visitors on onion umbel at peak period of day during 5th planting date (05 November 2023).	91
11	Activity of Honeybees visitors on onion umbel at peak period of day during 6th planting date (20 November 2023).	92
12	Activity of Honeybees visitors on onion umbel at peak period of day during 7th planting date (05 December 2023).	94
13	Relative abundance of honeybees (No. of bees /m2/ 5 min) on onion flowers under open field condition at different SMW (Rabi 2023-24).	96-97
14	Pearson correlation analysis between honeybee foraging activity (No. of bee Visitors/ m2/ 5 min) and weather parameters in onion at different SMW 2023-24.	98
15	Activity of Honeybees visitors on onion umbel at peak period of day during 1st planting date (5 September 2024).	100

16	Activity of Honeybees visitors on onion umbel at peak period of day during 2nd planting date (20 September 2024).	101
17	Activity of Honeybees visitors on onion umbel at peak period of day during 3rd planting date (5 October 2024).	102
18	Activity of Honeybees visitors on onion umbel at peak period of day during 4th planting date (20 October 2024).	104
19	Activity of Honeybees visitors on onion umbel at peak period of day during 5th planting date (05 November 2024).	106
20	Activity of Honeybees visitors on onion umbel at peak period of day during 6th planting date (20 November 2024).	107
21	Activity of Honeybees visitors on onion umbel at peak period of day during 7th planting date (05 December 2024).	109
22	Relative abundance of honeybees (No. of bees /m2/ 5 min) on onion flowers under open field condition at different SMW (Rabi 2024-25).	112-113
23	Pearson correlation analysis between honeybee foraging activity (No. of bee visitors/ m2/ 5 min) and weather parameters in onion at different SMW 2023-24.	114
24	Number of Umbels per Plant in Onion Varieties at Different Stages.	119
25.	Scape Lengths of Onion Genotypes at Four Growth Stages.	119
26	Umbel Diameter of Onion Genotypes at Sequential Growth Intervals	120
27	Number of Umbels per Plant in Onion Varieties at Different Stages.	121
28	Scape Lengths of Onion Genotypes at Four Growth Stages	121
29	Umbel Diameter of Onion Genotypes at Sequential Growth Intervals.	122
30	Foraging rate of Apis mellifera on different onion variety and time of observation 2023-24.	125
31	ANOVA and main effect mean for onion variety, time of observation, and their interaction on *A. mellifera* forage rate 2023-24.	126
32	Foraging rate of Apis mellifera on different onion variety and time of observation 2024-25.	129

33	ANOVA and main effect mean for onion variety, time of observation, and their interaction on A. mellifera forage rate 2024-25.	130
34	Foraging rate of Apis mellifera on different onion variety and time of observation Pooled data Rabi 2023-24 & Rabi 2024-25	133
35	ANOVA and main effect means for onion variety, time of observation, and their interaction on A. mellifera forage rate Pooled data Rabi 2023-24 & Rabi 2024-25.	134
36	Foraging speed of Apis mellifera on different onion variety and time of observation Rabi 2023-24.	137
37	ANOVA and main effect means for onion variety, time of observation, and their interaction on A. mellifera forage speed 2023-24.	138
38	Foraging speed of Apis mellifera on different onion variety and time of observation Rabi 2024-25.	141
39	ANOVA and main effect mean for onion variety, time of observation, and their interaction on A. mellifera forage speed 2024-25.	142
40	Foraging speed of Apis mellifera on different onion varieties and time of observation Pooled data Rabi 2023-24 & Rabi 2024-25.	144
41	ANOVA and main effect mean for onion variety, time of observation, and their interaction on A. mellifera forage speed Pooled data Rabi 2023-24 & Rabi 2024-25.	145
42	Physicochemical and Biochemical composition of Different varieties of Onion Umbel Pollen 2023-24.	149
43	Physicochemical and Biochemical composition of Different varieties of Onion Umbel Pollen 2024-25.	151
44	Physicochemical and Biochemical composition of Different varieties of Onion Umbel Pollen Pooled data Rabi 2023-24 & Rabi 2024-25.	154
45	Physicochemical and Biochemical composition of Different varieties of Onion Umbel Nectar Rabi 2023-24	157
46	Physicochemical and Biochemical composition of Different varieties of Onion Umbel Nectar Rabi 2024-25.	160

47	Physicochemical and Biochemical composition of Different varieties of Onion Umbel Nectar Pooled data Rabi 2023-24 & Rabi 2024-25.	163
48	Total amino acid, essential amino acid & non- essential amino acid of pollen.	165
49	Total amino acid, essential amino acid & non- essential amino acid of nectar.	165
50	Amino acids composition (mg/g) of pollen 2023-24.	170
51	Amino acids composition (mg/g) of pollen 2024-25.	170
52	Amino acids composition (mg/g) of pollen pooled data 2023-24 to 2024-25.	171
53	Amino acids composition (mg/g) of nectar 2023-24.	171
54	Amino acids composition (mg/g) of nectar 2024-25.	172
55	Amino acids composition (mg/g) of nectar pooled data 2023-24 to 2024-25.	172
56	Identification of amino acids in pollen and nectar extract of *Allium cepa* L.	177
57	Pearson correlation analysis between *A. mellifera* forage rate (No. of bee visitors mean of peak time/ m2/ 5 min) and physicochemical, biochemical, micronutrient properties of pollen of onion umbel (Upper diagonal) and nectar of onion umbel (Lower diagonal) 2023-24.	182
58	Pearson correlation analysis between *A. mellifera* forage rate (No. of bee visitors mean of peak time/ m2/ 5 min) and physicochemical, biochemical, micronutrient properties of pollen of onion umbel (Upper diagonal) and nectar of onion umbel (Lower diagonal) 2024-25.	185
59	Effect of bee attractant on activity of *Apis mellifera* in onion 2023-24.	201
60	Effect of bee attractants on activity of *Apis mellifera* in onion 2024-25.	204
61	Effect of bee attractant on activity of *Apis mellifera* in onion Pooled data (Rabi 2023-24 to Rabi 2024-25).	207
62	Effect of bee attractants on activity of *Apis dorsata* in onion (Rabi 2023-24).	211
63	Effect of bee attractants on activity of *Apis dorsata* in onion (Rabi 2024-25).	214
64	Effect of bee attractant on activity of *Apis dorsata* in onion (Rabi 2023- 24 to 2024-25).	217
65	Effect of bee attractant on activity of *Apis cerana* in onion (Rabi 2023- 24).	220
66	Effect of bee attractant on activity of *Apis cerana* in onion (Rabi 2024- 25).	223

67	Effect of bee attractant on activity of *Apis cerana* in onion (Rabi 2023-24 to Rabi 2024-25).	225
68	Effect of bee attractant on activity of *Apis florea* in onion (Rabi 2023-24).	228
69	Effect of bee attractant on activity of *Apis florea* in onion (Rabi 2024-25).	230
70	Effect of bee attractants on activity of *Apis florea* in onion (Rabi 2023-24 to Rabi 2024-25).	233
71	Effect of bee attractant on activity of *T. iridipennis* in onion (Rabi 2023-24).	237
72	Effect of bee attractants on activity of *T. iridipennis* in onion (Rabi 2024-25).	241
73	Effect of bee attractant on activity of *T. iridipennis* in onion (Rabi 2023-24 to Rabi 2024-25).	243
74	Effect of bee attractant on activity bees on seed and yield contributing characters of onion (Rabi 2023-24).	248
75	Effect of bee attractant on activity bees on seed and yield contributing characters of onion (Rabi 2024 - 25).	252
76	Effect of bee attractants on activity bees on seed and yield contributing characters of onion (Polled data Rabi2023-24, Rabi 2024 - 25).	255
77	Cost economics of different bee attractants with respect to seed yield of onion 2023-24.	258
78	Cost economics of different bee attractants with respect to seed yield of onion 2024-25.	259
79	Cost economics of different bee attractants with respect to seed yield of onion Pooled data Rabi 2023-24 to 2024-25.	260

LIST OF FIGURES

Figure No.	Particulars	Page No.
1	Weekly meteorological data of experimental sites of Onion during the period from 5th Sept 2023 to 5th May 2024- 5th Sept 2024 to 5th May 2025.	57
2	Layout of field experiment on impact of abiotic variations on the pollinators on different dates of planting.	60
3	Layout of field experiment on role of varietal traits on abundance behaviors of insect pollinators.	64
4	Layout of the experiment to formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.	73

LIST OF ABBREVIATIONS

%	:	Per cent
/	:	Per
@	:	At the rate of
>	:	More than
=	:	Is equal to
0C	:	Degree Celsius
±	:	Plus or minus
√x + 0.5	:	Square root transformation formula
P-value	:	Probability value for significance
F-value	:	F-statistic from ANOVA
CV	:	Co-efficient of variation
CD	:	Critical difference
DAS	:	Days after spray
DBS	:	Day before spray
et al.	:	Co-workers
Fig.	:	Figure
g	:	Gram
h	:	Hours
ha	:	Hectare
HPLC	:	High Performance Liquid Chromatography
LCMS	:	Liquid Chromatography–Mass Spectrometry
i.e.,	:	that is
ICBR	:	Incremental Cost Benefit Ratio
IPM	:	Integrated Pest Management
kg/ha	:	Kilograms per hectare
l	:	Litre
mL	:	Millilitre
mm	:	Millimeter
mg	:	Milligram
mha	:	Million hectares
MT	:	Metric tonnes
mMT	:	Million metric tonnes
m2	:	Square Meter
Min	:	Minutes
µl/l	:	Microliter per Liter
No.	:	Number

NS	:	Non-significant
Pvt. Ltd.	:	Private Limited
q/ ha	:	Quintals per hectare
r	:	Correlation Coefficient
RBD	:	Randomized Block Design
RF	:	Rainfall
RH	:	Relative humidity
Rs.	:	Rupees
S.E.	:	Standard Error
SMW	:	Standard Meteorological Week
S. Em (±)	:	Standard error of mean
Spp.	:	Species
Sr. No.	:	Serial Number
sec	:	Seconds
Temp.	:	Temperature
viz.,	:	Videlicet (Namely)
DMRT	:	Duncan's Multiple Range Test
sq. m	:	Square meters
A.		Apis
T.		Tetragonula

LIST OF APPENDIXES

Appendix I: Meteorological data recorded at different standard meteorological weeks during the period of experimentation (*Rabi* 2023-24 and *Rabi* 2024-25) at ICAR-DOGR, Rajgurunagar, Pune.

Appendix II: Cost of hives of different bee species used in the experimentation**.**

Appendix III: Cost of cultivation of onion for seed production per hectare as per the package of practice recommended by ICAR-DOGR, Rajgurunagar, Pune during *Rabi* 2023-24 and *Rabi* 2024-25.

Appendix VI. Cost of bee attractants used in the experimentation**.**

Appendix V. Calendar of Operation.

ABSTRACT

Onion (*Allium cepa* L.) is a highly cross-pollinated crop requiring efficient insect pollination for commercial seed production; however, seed yields are frequently constrained by abiotic stress, poor floral attractiveness, and inadequate pollinator visitation. This investigation was conducted to optimize onion seed production by assessing the impact of abiotic variables on pollinator dynamics, evaluating the influence of varietal traits on foraging behavior, and determining the efficacy of indigenous bee attractants. The study on pollinator diversity documented thirty distinct insect species visiting onion flowers, with Hymenoptera constituting the dominant order (78.42% of visits). *Apis mellifera* emerged as the predominant pollinator (42.14%), followed by *Tetragonula iridipennis* (18.59%), *Apis dorsata* (7.36%), and *Apis cerana* (3.82%). Investigations into seven staggered planting dates (September 5 to December 5) revealed that the November 5th sowing date was optimal, synchronizing peak bloom with favorable abiotic conditions (25-30°C, stable humidity) during the 7th Standard Meteorological Week. Correlation analysis indicated species-specific thermal sensitivities: *Apis cerana* showed significant negative correlations with maximum temperature and evaporation, whereas *Apis mellifera* exhibited superior thermal plasticity. To elucidate the role of varietal traits, seven onion cultivars (Bhima Super, Bhima Red, Bhima Raj, Bhima Dark Red, Bhima Shakti, Bhima Shubra, and Bhima Shweta) were evaluated under open field conditions with *Apis mellifera*. Significant genotypic variations were observed; Bhima Super and Bhima Shakti recorded the highest reproductive potential with maximum umbels per plant (9–10), largest umbel diameters (35.87– 37.2 cm), and longest scapes (>92 cm). These varieties also exhibited superior biochemical rewards, including higher nectar protein (31.23 mg/g), amino acids (45.81 mg/g), and balanced glucose-fructose ratios, resulting in significantly higher foraging rates (14.22 flowers visited bee/min) and longer handling times (6.70 s/umbel). In contrast, white varieties (Bhima Shubra, Bhima Shweta) displayed inferior floral attributes and lower biochemical rewards, correlating with reduced bee visitation. The evaluation of indigenous bee attractants (Pomegranate juice, Dates extract, and Coconut water at 10%, 15%, and 20%) demonstrated that foliar application of Pomegranate juice (20%) significantly enhanced pollinator activity. This treatment resulted in a 2- to 4-fold increase in *Apis mellifera* visitation (peak 71.3 bees/m²/5 min) compared to open pollination controls. Consequently, Pomegranate juice (20%) recorded the highest seed yield of 945.7 kg/ha—an 80.36

kg/ha increase over the control and a 249% increase over open pollination (270.7 kg/ha). This treatment also maximized seed quality parameters, including seeds per umbel (1313.4), germination percentage (99.5%), and minimal seed deformation (0.9%). Economic analysis confirmed the viability of this intervention, yielding the highest net returns (₹3,48,758/ha) with an incremental cost-benefit ratio (ICBR) of 5.80. This study establishes that optimizing planting dates to early November, utilizing colored varieties with superior biochemical rewards, and applying fruit-based bee attractants such as Pomegranate juice (20%) can synergistically enhance pollinator visitation and significantly improve onion seed yield and quality under changing climatic conditions.

Keyword: Nectar, Pollen, Biochemical, Seed, Yield

CHAPTER 1

INTRODUCTION

The onion (*Allium cepa* L.) originates from the Amaryllidaceae family. It is a well-known bulb vegetable that grows in Central Asia (Brewster, J. L. (2008). The ancient Egyptians believed that the onion's spherical stalk represented the universe. For more than five thousand years, it has been a big business in India. The volatile oil and allyl-propyl disulphide in the medication give it a strange fragrance, taste, and scent. Onion is a flexible food that can be used in a lot of various cuisines, salads, and even medicines. It helps with ulcers and boils by acting as a diuretic. People eat both the mature bulbs and the green leaves of the onion (Shaikh *et al.*, 2015). People are learning that onions are excellent for you and can be utilised in many different ways while cooking. This is why the demand for value-added onion products like onion flakes and dehydrated onions is expanding. Onions are a great source of nutrients like calcium (180 mg/100 g) and phosphorous (50 mg/100 g) (Thamburaj and Singh, 2014).

Onions are the second most grown vegetable in the world, after tomatoes. A survey found that onions account for 18.61% of all vegetables grown in the world. They are grown on 1.79 million hectares of land and yield 31.01 million metric tonnes (Anon., 2023c). After China, India is the second greatest producer (31.01 mMT) and area (1.79 mha) of onions. The US, the Netherlands, and India are the main places where onions are grown (Anon., 2023c). The state only grows 17.32 tonnes of onions per hectare, which is less than the world average of 19.4 tonnes per hectare (Anon., 2023c). India sold 2,525,258.35 MT of fresh onions in 2022–23 for Rs. 4,522.79 crores/561.38 million dollars (Anon., 2023b). The primary states in India that grow onions are Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh, Rajasthan, Tamil Nadu, and Haryana (Anon., 2023a). Maharashtra grows 13.30 million tonnes of onions, which is 42.73 percent of the entire production (Anon., 2023a).

The districts of Nashik, Pune, Ahmednagar, Jalgaon, Dhule, Solapur, and Satara in Maharashtra usually grow the crop. People grow it to utilise it themselves and to sell it to other countries. A major reason why onion production and productivity are low is that there aren't enough high-quality seeds. This also impacts the productivity of bulb onions. Because of this, making onion seeds is very important for India's vegetable seed business. The sector needs roughly

9400 tonnes of seeds every year to cover 11.73 lakh hectares (Anon., 2023a). The organised industry provides 40% of the seeds, while farmers provide the other 60%.

Farmers don't always observe isolation requirements (Anon., 2023a). You need to buy new onion seeds every year since they only last that long. You can make onion seeds in two ways: by planting bulbs or by planting seeds. The most frequent way to do this is bulb-to-seed, which is especially popular in temperate and subtropical climates. Onions are protandrous, which means that they regularly cross-pollinate with other plants. Blooming normally starts 64 to 67 days after the bulb is planted, and the most flowers appear between 88 and 91 days (Kavitha and Reddy, 2018). The flowers are white to blue and comprise six parts that make up the perianth and two whorls of filaments. Between 7:00 and 17:00 hours, the anthers open up (Devi *et al.,* 2015b). The pollen and stigma sensitivity is highest during anthesis (Devi *et al.*, 2015b). Insects are responsible for about 80–85% of cross-pollination, and the blooms are very appealing to insects looking for nectar and pollen (Free, 1993; Abhishek *et al.,* 2023). There have been 267 flower visitors on onion fields, including honey bees, syrphid flies, bumble bees, halictid bees, drone flies, butterflies, and other insects that are crucial for pollination (Devi *et al.,* 2015a; Sajjad *et al.,* 2008). The foraging rate, visitation frequency, and abundance of pollinating insects on onion flowers are governed by floral morphological characteristics such as flower number, shape, and size; corolla colour and depth; the availability of floral rewards; and prevailing meteorological conditions (Gilbert, 1980; Mevetty *et al.*, 1989).

Honey bees are the main pollinators of onions, making up about 60–95% of the pollinator population (Abhishek *et al.,* 2023; Paschapur *et al.*, 2022; Pushpalatha *et al.,* 2023; Hosamani *et al.,* 2019; Karuppaiah *et al.,* 2018; Abrol, 2010; Kumar *et al.,* 1985; Jadhav, 1981; Parker and Hatley, 1978; Singh and Dharamwal, 1970). Honeybees collect pollen by putting their heads in the midst of a flower's staminal column and spinning their abdomens around the anthers. This causes a lot of pollen to stick to their bodies. The bee's hairy filaments can pick up as many as 250,000 to 300,000 pollen grains while it is working on flowers (Devi *et al.,* 2015a). The nectar tubes of flowers that bees pollinate are usually less than two centimetres long. Nectar guides help pollinators find the nectar by pointing them to flowers that are white, blue, or yellow. Meléndez-Ramirez *et al.*, (2002) reported that bees fly best when the temperature is above 21°C (70°F), the humidity is below 75%, the wind speed is below 25 km/hr, and there are few or no clouds.

Honeybees are very good in pollinating onions, which is vital for making sure that seeds thrive. Managed stingless bee pollination increased onion seed yield by over 36% and improved germination rates, highlighting their significant role in enhancing seed productivity under varying seasonal conditions (Pandit *et al.,* 2025). They have a lot of unique qualities, such as being faithful to flowers, being thorough while dealing with floral organs, working long hours, having a large population, a social structure, means of communication, and changing shape. Honey bees are the only insects that have all of these qualities to the same degree (Sanderson and Wells, 2005; Suwannapong *et al.,* 2012). But the number of these pollinators in the fields has dropped in the last few decades because of how people use land and how habitats change (Winfree *et al.,* 2011). To fix this problem, you can either put farmed beehives in the fields or try to get wild pollinators to come there. You can relocate domesticated beehives to agricultural fields that need pollination, which is not possible with wild bees (Kevan *et al.,* 1990). Honeybees have a "consistent" and "fairly faithful" technique of dealing with plants. While gathering nectar and pollen, they make associations to certain areas of crops (Devi *et al.,* 2015b). The stigma of onion flowers is open for one to two days, giving these bugs more opportunity to pollinate them (Baswana, 1984). You need a lot of pollinating bugs around to get more seeds from your plants. This is due to the fact that more visits from different types of pollinators result in more seeds (Meena *et al.,* 2015; Chand *et al.,* 1994; Free, 1993; Sihag and Varghese, 1985).

The duration that plants can grow until they bloom is primarily based on when the seeds are planted, which is determined by how long the days are. It also tells the plant how tall it should be, how many branches it should have, when it should blossom, and how it should grow. The date of sowing has a huge effect on how the onion grows and reproduces, which in turn has a big effect on how much it produces. To get the most out of a variety's genetic potential, it's necessary to plant at the proper time. This makes sure that the plants have the ideal growing conditions, like temperature, light, humidity, and rainfall (Eberhart and Russell, 1966). Temperature, relative humidity, wind speed, and sunlight are all essential abiotic factors that have a big impact on how well insect pollinators function on onion flowers. The planting date affects how the crop is exposed to different climatic conditions during the flowering phase, which varies these factors. Because of this, the dates when seeds are planted can have a huge impact on how animals look for food and how many pollinators there are. To enhance pollination efficacy and optimise onion seed yield, it is crucial to examine the impacts of various abiotic factors (Silva *et al.,* 2004).

The different types of onions have a major impact on how insect pollinators are drawn to them and how they look for food, which is vital for making good seeds. Morphological factors that determine how simple it is for pollinators like honey bees, syrphid flies, and other beneficial insects to see and get to the flowers include the size of the umbel, the number of florets, the shape and colour of the flowers, and the position of the inflorescence. In general, umbels with more florets create more nectar and pollen, which makes pollination more effective and brings in more pollinators (Divija *et al.,* 2022; González *et al.,* 2023). Biochemical traits are crucial for attracting pollinators, in addition to physical traits. The proportion of sucrose, glucose, and fructose in nectar sugars has a direct effect on how attractive onion flowers are to insects hunting for food (Waller, 1970). Pollinators are more likely to visit plants that have more nectar or nectar that is better for them, which means they stay longer and come back more often. The amino acid composition of nectar, the presence of volatile organic compounds, and unique fragrance emissions may enhance the visitation rates and fidelity of bees and other pollinators (Abrol and Kapil, 1991). The length of stigma receptivity, the timing of pollen release and nectar availability, and the time of flower opening (anthesis) are all physiological aspects that might affect how well pollinators perform and how likely they are to cross-pollinate. Timing floral incentives to coincide with periods of peak local pollinator activity can substantially increase seed set (Waller, 1970). Nectar and pollen also have small amounts of potassium, calcium, and magnesium, which can draw in more pollinators and keep them healthy while they rear their young. This, in turn, makes it more probable that bees will come to onion fields and stay there (Patil *et al.,* 2010; Waller, 1970). Consequently, it is imperative to conduct a comprehensive evaluation of these integrated morphological, biochemical, physiological, and nutritional factors when assessing or developing onion varieties for seed production. This insight enables the creation of cultivars that are not only agronomically superior but also very appealing to pollinators, hence improving pollination efficiency, seed set, and yield across various agro-ecological contexts (Divija *et al.,* 2022; González *et al.,* 2023). Onions only produce fruit 17% of the time because there are no pollinators throughout the flowering season, they have shown, nonetheless, that the fruiting rate could go up by as much as 73% when there are a lot of pollinators, especially honey bees (Rao and Suryanarayana, 1989). This proof illustrates that pollinators are needed for good pollination and the growth of healthy onion seeds. Pollination services were provided by both wild and managed insect pollinators. Wild honeybees such as *Apis dorsata*, *Apis florea*, and *Apis cerana* contribute importantly to floral visitation and ecosystem conservation, although they are not practically used as managed pollinators. In contrast, domesticated pollinators such as *Apis mellifera* and *Tetragonula* iridipennis. can be actively managed for crop pollination to generate onion seeds. This approach

is environmentally friendly and cost-effective. Putting colonies of tamed Italian bees (*A. mellifera*) in the field is the best technique to control pollination in onions, though. Many seed growers use this since bees are easy to find, cultivate, and move (Free, 1993).

For honeybee pollination to work, the target crop has to be better than the plants around it. To improve pollination and keep the pollinators that are already there safe, it is important to use eco-friendly, cheap, and effective bee attractants to attract natural pollinators (Naik, 2019). Bee attractants are quite important in this instance. Food-based, pheromone-based, and plant-based attractants are the three basic types. Honey bees get gluconic acid, glucose, maltose, sucrose, lactose, protein, lipids, minerals, vitamins, and lactose from food-based and plant-based attractants. Although commercial bee attractants such as Bee-Q, Bee-scent Plus, Fruit Boost, Pollenaid-D, Bee-lure, Pollinus, and Api-fix are not readily available in India, naturally extracted attractants can be used to increase honeybee visitation in gardens in an eco-friendly and cost-effective manner. These locally prepared or commercially procured attractants may also be obtained online for research evaluation and comparative studies (BABAN, 2024; Naik, 2019). Pomegranate juice, coconut water, and date extract are some natural attractants that are strong in carbs, vitamins, and minerals, you can find them in varied amounts (Waller, 1973; Patil *et al.*, 2010). To help the bee population and promote the pollination of onion crops, it is vital to encourage and improve the use of these natural attractants.

Thus, considering the crucial role of varietal traits, indigenous attractants, and abiotic factors, the present investigation was undertaken with the following objectives:

1. To investigate the impact of abiotic variations on the onion pollinators on different dates of planting.
2. To study the role of varietal traits of onion on foraging behaviour of insect pollinators.
3. To formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.

CHAPTER II

REVIEW OF LITERATURE

2.1. To investigate the impact of abiotic variations on the onion pollinators on different date of planting.

2.1.1 Species diversity of flower visitors associated with onion flowers

Studying the diversity of pollinators associated with onion flowers is crucial for optimizing crop yields, ensuring food security and improving the quality of onion production. It helps maintain biodiversity, contributes to sustainable agriculture and aids in the conservation of beneficial pollinator species. Understanding the specific interactions between pollinators and onion plants can lead to better farming practices and the preservation of vital ecosystem services.

(Divija *et al.,* 2022) reported that the pollinator community of onion was composed of thirty hymenopteran, sixteen dipteran, eight lepidopteran, four hemipteran and one coleopteran species. However, hymenopteran and dipteran contributed for>75 per cent of the floral visitors. The major flower visitors included *A. cerana, A. mellifera, A. dorsata, A. florea, T. iridipennis, Ischiodon scutellaris* and *Eristalis obliquus*.

(Paschapur *et al.,* 2022) reported hymenoptera as the dominating order of flower visitors in onion field with 19 species *e.g., A. cerana, A. mellifera*, *A. dorsata, A. florea, Bombus haemorrhoidalis, Vespa tropica, Vespula vulgaris* and*rena hilaris, Megachile rotundata, Osmia inermis, Nomia incerta*., *Halictus sexcinctus, Ceratina smaragdula, T. iridipennis, Xylocopa latipes, Sceliphron curvatum, Megascolia azurea, Ceratina sutepensis* and *Lithurgus atratus*. In terms of dominance, lepidoptera (17 species), diptera (14 species) and coleoptera (5 species) were in the following order.

(Korichi *et al.*, 2021) reported that all the insect foragers of onion flowers were from apoidea superfamily belonging to apidae and halictidae families of hymenoptera. A total of seven species were reported but only four of them were observed during both the flowering periods: *A. mellifera, Lasioglossum malachurum, L. pauxillum* and *H. gemmeus*. *L. malachurum* and *L. pauxillum* were the most abundant upon flowers with average densities of 50.43 and 42.62 individuals in 2016 and 2017 observations respectively. Whereas, *H. gemmeus* (halictidae) visitation was comparatively low. In apidae family, *A. mellifera* was the most frequent visitor on onion flowers, with a density

of 37 to 44 individuals and the only one to be present on the flowers during the whole flowering period. The presence of *Bombus terrestris* and other species was just episodic during prospection years.

(Saleh *et al.*, 2021) found that the activity of pollinators in onion umbels was observed after opening of flowers and there was a fluctuation in visits of insect pollinators on different days. The community of pollinators was composed of two honeybee species (*A. mellifera* and *A. dorsata*), hornets, wasps, butterfly and syrphid fly. The most abundant pollinator was syrphid fly followed by *A. mellifera*.

(Tchindebe *et al.*, 2021) reported 32 insects distributed in seven orders as flower visitors of onion and highest number of insect pollinators harvested on the flowers was between 8.00 and 9.00 hrs. Hymenoptera was the dominating order and *A. mellifera* was the dominating species followed by *Lipotriches collaris* with 24.49 and 12.43 per cent of the total insect visits, respectively. Other species included *Amegilla calens, Xylocopa olivacea, Chalicodoma rufipes, Belonogaster juncea, X. inconstans, X. nigrita, L. azarensis, L. saegeri, Megachile bituberulata, V. vulgaris* and *L. atricrum*. Whereas the reported accidental species includes, *Danaus chrysippus, Eurema* spp., *Camponotus flavomarginatus, Episyrphus balteatus, Musca domestica.*

Studies conducted by Ahmad *et al.* (2020) revealed that the pollinator's community of onion was composed of two orders, hymenoptera and diptera. Among hymenopterans, *A. mellifera* was the most abundant pollinator (32.99 / m^2 /5 min) while among true flies, *S. bengalensis* was abundant (7.49 / m^2 /5 min). The foraging activity of bees (*A. mellifera* and *A. cerana*) was prevalent during 11.00 to 13.00 hrs with mean of 32.99 and 32.00 visitors/ m^2/ 5 min. The *Eristalis* sp. spent maximum time 9.44 sec/ flower while *A. mellifera* spent 9.44 sec/ flower/ visit during different hrs of the day.

Hosamani *et al.* (2019) documented total of 666.17 pollinators visiting the onion plot at different times in a day. Among them, hymenopterans contributed 87.79 per cent (83.55 pollinators), followed by dipterans with 8.62 per cent (8.20 pollinators), lepidopterans with 1.91 per cent (1.82 pollinators) and others with 1.66 per cent (1.59 pollinators). Four species of honey bees (*A. dorsata*, *A. mellifera*, *A. cerana* and *A. florea*) belonging to apidae constituted the largest group of pollinators followed by twelve other families. For the dominant group, the onion crop served as a source of both pollen and nectar.

Onion flowers are rich source of nectar and thus attracted various insect visitors as reported by Kavitha and Reddy (2019). Since nectarines of the onion flower were located at shallow depth, short tongued bees were attracted more. The flower visitors included honey bees *viz*., *A. cerana*, *A. florea*, *A. dorsata* and *T. irridipennis* of apidae family whose activity was dependent on temperature.

Montes (2019) reported that umbels of onion were visited by the insects belonging to the orders hymenoptera, diptera and coleoptera. The species included *A. mellifera*, *Bombus* sp., syrphid fly, *M. domestica*, *Diabrotica speciosa*, coccinellid beetles, black wasp and mosquitoes. However, *A. mellifera*, syrphids and *M. domestica* stood out as the most abundant and persistent insects considered as potential pollinators.

Karuppaiah *et al.* (2018) reported a total of eleven insect species *viz*., *A. florea*, *A. cerana*, *A. dorsata*, *A. mellifera*, *Tetragonula* sp., *Xylocopa* sp., *Vespa* sp., *Pieris rapae*, *D. chrysippus*, *Eristalis* sp. and *M. domestica* visiting onion flowers. Of these, 98 per cent of forage visits were of hymenopterans, with most of these happening during 13:30-14:30 hrs. The index of alpha diversity including Shannon- Weiner, Berger- Parker and Margalef Richness was 1.805, 0.288 and 1.846, respectively. The computed Berger-Parker Index of abundance revealed that *A. dorsata* was the dominant species.

Mazeed and Marey (2018) reported that onion flowers were visited by 21 species of insects belonging to 14 families and 7 orders. Among different orders, diptera was most abundant (30 %) followed by hymenoptera (21 %), lepidoptera and coleoptera (14 %), hemiptera (7 %), neuroptera and thysanoptera. Among all the insect visitors, *A. mellifera*, *M. domestica*, *Lucilia illustris* and *Syrphus* spp. were the most abundant visitors and were detected during the last week of March till the last week of April.

Hymenopterans were found to be the most abundant (50 %) flower visitors of onion flowers followed by lepidoptera (Biradar *et al.*, 2017). Three *Apis* species *viz*. *A. dorsata*, *A. cerana* and *A. mellifera* were top workers on onion umbels as pollen and nectar gatherers. Hover fly, *Coccinella* sp., *Pieris* spp., thin waisted wasps, yellow banded wasp, big black wasp, black ants, *M. domestica*, monarch butterfly, *Nezara* spp. and spiders were the other pollinators that visited onion umbels.

Kamal and Akand (2017) reported that honeybee, syrphid fly and horse fly were the major insect pollinators of onion while blow fly, house fly, bumble bee, paper wasp, yellow jacket, butter fly etc. were the minor pollinators. The best insect pollinator of onion crop was horse fly. Honeybee was the second best and syrphid fly was the third best insect pollinator.

Padamshali (2017) enumerated that 28 species of insects belonging to 24 genera in 21 families under 7 orders visited onion umbels. The flower visitors included *A. mellifera, A. dorsata, A. cerana, A. florea, Megachile* sp., *X. violacea, V. cincta, Formica* sp., *E. balteatus, Sphaerophoria scripta, M. domestica, C. bezziana, Sarcophaga* sp., *Athalia lugens proxima, D. chrysippus, D. genutia, Pieris* sp, *A. passalis, Cheilomenes* sp, *Helicoverpa armigera, Spodoptera litura, Plutella xylostella, Mylabris pustulata, Mausoleopsis amabilis, Leptochorisa oratoria, Thrips tabaci, Sympetrum flaveolum* and *Enallagma cyathigerum*. However, *A. dorsata* was most predominant species representing 28.79 per cent of insect visitors followed by *A. mellifera* with 23.48 per cent of total insect fauna. Other major insect visitors were syrphids *E. balteatus, Sphaerophorea sp.* and other dipterans.

Rana *et al.* (2017) reported a total 19 insects belonging to 17 genera under 8 families and 3 orders *viz*. diptera, hymenoptera and lepidoptera pollinating the onion bloom. The bee group included *A. cerana, A. mellifera, A. dorsata, Bombus* sp., *Ceratina* sp. *Xylocopa* sp. The syrphid group included *E. balteatus, Eupeodes frequens, E. tenax, Melanostoma univittatum, M. serarius* and other pollinators group included *Andrena* sp., *Halictus* sp., *Lassioglossum* sp., *Musca* sp., *Orthellia* sp., *P. brassicae, Polistes* sp. and *Scolia quadripustulata.*

Abrol (2016) studied the foraging strategies of honeybees, *A. dorsata* F. and *A. florea* F. in relation to availability of energy rewards. The result revealed that as a result of high nectar content a large number of flower visitors were attracted towards the flowers. However, dwarf honey bee *A. florea* and rock bee, *A. dorsata* were the most common visitor, comprising more than 94 per cent of the total flower visitors.Hymenopterans were the dominant pollinators of onion flowers followed by dipterans and lepidopterans as reported by Thakur and Kumarnag (2016). *A. mellifera,A. dorsata, A. cerana, A. florea, Megachile* sp., *X. violacea, Vespa cincta, E. balteatus, Sphaerophoria scripta, M. domestica, Chrysomya bezziana, Sarcophaga* sp. and *Amata passalis* were the different species of flower visitors which were recorded during the study.

Badade *et al.* (2017) reported nineteen species of pollinators on onion flowers out of which

ten belonged to hymenoptera, four from lepidoptera, four from diptera and one from coleoptera order. Among all the floral visitors, *A. florea* was the dominant species constituting 62 per cent of total pollinators followed by *A. dorsata* and *Trigona* sp. (28 and 4.5 %, respectively).

Orford *et al.* (2015) reported 71 families of dipteran insects regularly visiting flowers of mango, onion and cocoa. Gadhiya and Pastagia, (2015) observed that the stingless bee *T. laeviceps* visit the onion umbels during flowering.

Bezabih and Gebretsadikan (2014) reported that a total of eight flower visitors belonging to 4 different orders *viz*., hymenoptera, diptera, lepidoptera and coleoptera visited the onion umbels. The species included *A. mellifera, Dasyproctus bipunctatus, Maliponula spp.,* halictid bee, *Philoliche rostrata, D. chrysippus, Mausoleopsis amabilis and Decapotoma lunta.*

According to Devi *et al.* (2014), hymenopterans were the most dominant flower visitors of onion flowers (60 %) followed by lepidoptera (20 %), diptera (12 %) and coleoptera (8 %). All the four *Apis* species *viz*., *A. dorsata, A. cerana*, *A. mellifera* and *A. florea* were recorded as top pollinators on onion umbels as pollen and nectar gatherers. Among all the insect visitors, *A. dorsata* and *A. mellifera* were the most frequent visitors.

Kumari (2014) recorded 19 insects belonging to 17 genera under 8 families and 3 orders as a pollinators of onion. The pollinators list included *A. cerana, A. mellifera, A. dorsata, Bombus* sp.*, Ceratina* sp.*, Xylocopa* sp. *andrena* sp.*, Halictus* sp.*, Lassioglossum* sp.*, Scolia quadripustulata, Polistes* sp.*, E. balteatus, Eupeodes frequens, E. tenax* L.*, Melanostoma univittatum, M. serarius, Musca* sp.*, Orthellia* sp. and *P. brassicae* L.

Tchindebe and Fohouo (2014) reported that a total twenty-two species of insects were visiting onion flowers. *A. mellifera adansonii* was the most frequent visitor with 40.62 per cent and 51.48 per cent of visits in 2010 and 2011, respectively. Whereas, *Amegilla* spp., *Xylocopa* spp, *Polyrachis* spp., *L. collaris, Macronomia vulpine*, *Chalicodoma* spp., *Megachile* spp., *Philanthus triangulum, Synagris cornuta, Coryna* sp, *Acraea acerata* and *Catopsilia florella* were the other flower visitors.

Adel *et al.* (2013) reported a variety of insects belonging to hymenoptera order visiting the onion umbels for pollination *viz. andrena* sp., *H. patellatus* Morawitz, *H. quadricinctus, X. valga, Amegilla* sp., *E. balteatus, E. corolla, E. aeneus* and *M. domestica*.

Pollinator community of onion was dominated by hymenoptera (66.30 %) followed by diptera (16.70 %) with *A. mellifera* as a dominant one. Insects belonging to thysanoptera, collembola, psocoptera, hemiptera and coleoptera were also present (Walker *et al.*, 2011).

Abrol (2010) reported a total of 20 species belonging to four different orders *viz*., hymenoptera, diptera, coleoptera and lepidoptera as a common onion flower visitors. The species diversity of flower visitors included *A. florea*, *A. dorsata*, *A. mellifera*, *A. cerana*, *X. fenestrate*, *Camponotus compressus*, *Halictus* sp., *Lasioglossum* sp., *P. hebreaus*, *E. balteatus*, *E. tenax*, *M. domestica*, *Sarcophaga* sp., *C. megacephala*, *M. corolla*, *Coccinella septumpunctata*, *Coccinella* sp., *P. brassicae*, *D. chrysippus* and *Genepterynx hemmi*. *A. florea* was the dominant flower visitor followed by *A. dorsata*, *A. mellifera* and *A. cerana* with 94.41, 0.50, 0.34 and 0.18 per cent proportion of species that visited onion flowers.

Howlett *et al.* (2009) reported that, of the total large arthropod individuals collected from onion flowers with traps, hymenoptera represented 73.3 and diptera 16.5 per cent share. These orders also contributed equal proportions of the total large arthropods during direct observations, with hymenoptera 76.1 and diptera 22.5 per cent share. Coleoptera, the only other order with less numbers of individuals, represented 9.3 per cent of the trapped individuals and 1.0 per cent of the observed individuals. Other large arthropod orders recorded were lepidoptera, neuroptera (traps only), trichoptera (traps only), hemiptera and araneae. However, each represented a very minor component of the overall assemblage.

Saeed *et al.* (2008) reported that the community of onion pollinators was composed of four bee species (*A. dorsata*, *A. florea*, *Xylocopa* sp. and *Nomia* sp.) and twelve true fly species (*E. balteatus*, *Eupeodes* sp., *Sphaerophoria scripta*, *Helophilus* sp., *E. aeneus*, *E. arvorum*, *E. quadristriatus*, *E. laetus*, *Calliphoridae* sp., *Sarcophaga* sp., *Stratiomyidae* sp. and *M. domestica*). The family syrphidae made up 74 per cent of the population of the order diptera.

Pollinators community of onion consisted of two species of honeybees *(A. dorsata* and *A. florea*) and eight species of flies *i.e*., *E. balteatus*, *E. corollae*, *S. scripta*, *Mesembrius bengalensis*, *E. aeneus*, *M. domestica*, calliphoridae sp. and *Sarcophaga* sp. The spectrum of pollinator abundance was composed 87 per cent of dipteran species and remaining 13 per cent of hymenopteran species (Sajjad *et al.*, 2008).

Studies conducted by Kalmath and Sattigi (2004) revealed that the onion ecosystem contained four different kinds of pollinators with hymenoptera as the most dominant order (90.15 %), followed by diptera (6.63 %), lepidoptera (1.70 %) and other insects (1.52 %). The pollinator fauna was most active between 10:00 and 12:00 p.m.

As reported by Chandel *et al.* (2004), hymenoptera was the most prominent group of pollinators on onion. *A. dorsata* was a more frequent pollinator of onion in mountainous Hindu Kush Himalayan areas of India. *A. florea* and syrphids (*E. balteatus, M. conferator* and *M. corollae*) were also visited the crop. However, *A. florea* worked consistently though in low numbers.

Al-sahaf (2002) reported a wide range of insect species pollinating onion florets during the period of blooming. The most common pollinators documented were honey bee (*A. mellifera*), blowfly (*C. vomitoria* L.), house fly (*M. domestica*) and oriental hornet (*V. orientalis*).

Priti (1998) reported that the most prominent group of pollinators of onion umbels belonged to the orders hymenoptera, diptera, lepidoptera and coleoptera. Bees and wasps, sarcophagid species, muscid flies, hover flies, *Chrysops dispar*, blowflies. *A. florea, A. dorsata* and *A. mellifera* were the most abundant of the eighteen species of the insect pollinators that visited onion bloom.

Studies undertaken by Free (1993) revealed that the blossoms of onion are highly attractive to both pollen and nectar collecting insects. Observations of the study depicted bees as predominant floral visitors on onion. The abundance of *A. florea* was high throughout the different hrs of the day on onion flowers. Schittenhelm *et al.* (1997) found that red mason bees (*Osmia rufa*), hover flies (*E. tenax*) and blow flies (*Calliphora* sp. and *Luciia* sp.) as the pollinators of onion, carrot and turnip, respectively. Whereas, Hwang *et al.* (1998) reported that among various pollinators, flies were the most frequent visitors of the onion crop.

Honey bees were the main pollinators in onion ecosystem as reported by Rao and Suryanarayana (1989). *A. cerana* was more efficient pollinator of onion and visited higher number of florets and umbels in a unit time than *A. florea* and *T. iridipennis*.

Kumar *et al.* (1985) reported that the pollinator fauna of onion included honey bees which constituted 66.1, 68.4 and 60.4 per cent of all insect visits during 9.00- 10.00, 11.00-12.00 and 14.00-15.00 hrs of the day respectively. The Indian honeybee (*A. cerana*) and rock bee (*A. dorsata*)

were the most frequent insect visitors. Other hymenopterans included *A. florea*, *Bombus* spp., *C. hieroglyphica, Megachile* spp., *Halictus* spp., *Nomia* spp., *Allodape* spp. and *Polistes* spp. The frequency of visits by *E. tenax*, other syrphids (*E. balteatus*, *Scaeva pyrastri*, *I. scutellaris* and *Melanostoma* spp.) and other diptera (*Musca* spp. and *Orthellia* spp.) did not differ significantly among species. The predominance of honey bees on onion flowers in the range of 60-95 per cent was also recorded by various researchers (Jadhav, 1981; Parker and Hatley, 1978; Singh and Dharamwal, 1970).

Jablonski *et al.* (1982) and Wójtowski *et al.* (1980) have shown that onion flowers are visited by honey bees, bumble bees, dipterans and butterflies. The dominance of bee and fly individuals indicated that these taxa were the important insect pollinators of native flora (Howlett *et al.*, 2005; Newstrom and Robertson 2005; Primack 1983; Godley 1979).

Bohart *et al.* (1970) reported 267 species of insect visitors on onion flowers, the most important of which were honey bees, small syrphid flies, halictid bees and drone flies. The most abundant insect involved in onion pollination was a syrphid fly (*Syritta pipiens*) followed by chloropid fly (*Thaumatomyia glabra*). *E. tenax* and *E. brousii* were next in abundance among the flies. Among hymenoptera, honey bees were the most abundant followed by a species of sweat bee, *H. farinosus* and sand wasp, *Bembix amoena*.

2.1.2 Foraging activity of honeybees and influence of date of sowing on yield of onion

The study addressed the challenge of successful onion seed production, which is limited by rising temperatures and early rains after winter. To find the best planting time for high-quality true seed, a field experiment was conducted at BARI, Bogra, from September 2010 to June 2011, using five sowing dates (1 Oct., 15 Oct., 30 Oct., 15 Nov., and 30 Nov.) in a randomized complete block design. Results showed that all measured growth, yield, and seed quality parameters varied significantly with planting dates, with 15 November giving the highest yield and best seed quality (Mollah *et al.*, 2015).

A field experiment using a randomized complete block design with three replications tested nine different planting dates (from September 1st to December 30th) to assess their effects on onion seed production in Jari, northeastern Ethiopia. Statistical analysis showed that all measured growth, yield, and seed quality traits were significantly affected by planting time. The earliest

planting date, September 1st, produced the highest seed yield (1032.7 kg/ha) and germination rate (94.3%), while the latest planting in December led to the lowest yield (29.7 kg/ha) and germination (15.3%). The data clearly demonstrated strong relationships between planting date and both yield and quality, suggesting that September 1st is the optimal planting date for maximizing onion seed yield and quality in this region (Tesfaye *et al.*, 2018).

Krishnaveni et al (1990) reported that weekly plantings of the onion cultivar 'Rampur Local' were evaluated from the second week of November to the fourth week of February. The findings indicated that plantings made during the second and third weeks of November resulted in the highest bulb and seed yields, as well as superior seed quality, with seed germination rates between 86.0% and 90.0%. In contrast, plantings carried out after the third week of January produced no seed yield. These results highlight the critical impact of planting time on both yield and seed quality in onions, demonstrating that timely sowing is essential for successful seed production, while delayed planting beyond late January can lead to total seed crop failure. This aligns with previous research emphasizing the importance of synchronizing planting schedules with favorable climatic conditions to optimize both productivity and seed viability in onion cultivation.

A study conducted by Muktadir, M. S. (2000) at Bangladesh Agricultural University (2018–2019) assessed how bulb size and variety influence onion seed production. Results showed that both factors significantly affected growth and yield. The variety Kalash Nagari,especially when grown from large bulbs, produced the highest seed yield and plant vigor, while Taherpuri and small bulbs gave the lowest results. This highlights the importance of selecting both suitable onion varieties and larger bulbs to maximize seed yield and quality.

Md Mosleh Ud-Deen’s research showed that onion mother bulb size and planting date significantly affect growth, bulb, and seed yield. Larger bulbs (20g) planted early (30 October) produced the highest yields, with bulb yield reaching 17.52 t/ha and seed yield 402.80 kg/ha. This is because larger bulbs have more stored nutrients, promoting better initial growth, while early planting aligns with favorable climatic conditions for development. Smaller bulbs and later planting dates resulted in reduced yields, confirming that using large mother bulbs and timely planting optimize onion production.

A field experiment conducted at Cairo University by El-Helady, M.A. during 2008/2009 and January) on seed production of onion cv. Giza 20. The study revealed that planting in mid-

November significantly enhanced seed yield components such as the number of scapes per plant, scape diameter, main scape length, umbel diameter, seed yield per plant and per feddan, weight of 1000 seeds, and seed germination percentage. Delaying planting to mid-January resulted in the lowest values for these traits, though the number of sprouts per plant was unaffected by planting date. These findings suggest that mid-November is the optimal planting window for achieving high-quality onion seed yield in the Giza region. Supporting research by Karam, S.S. and others reinforce the importance of timely planting to maximize reproductive growth and seed quality in onion cultivation, consistent with global studies emphasizing early planting within the ideal climatic period for best seed production.

Mehri *et al.*, 2015 conducted experiment at the Seed and Plant Improvement Institute, Karaj, Iran, during 2012-2013 evaluated the effects of planting dates on morphological traits and seed production in two onion cultivars, Texas Early Grano 502 and Ghermez Iranshahr. The study used four planting dates ranging from late September to early November and found that planting date significantly influenced key growth characteristics such as number of leaves per plant, plant height, number of flowering stalks, and seed yield components. Both cultivars showed distinct responses, with Texas Early Grano 502 planted on 22nd September producing the highest seed yield (2166.4 kg/ha), while Ghermez Iranshahr showed its highest yield (1005.8 kg/ha) when planted on 6th October. The interaction effect was significant for leaf number and total seed yield, indicating cultivar-specific optimal planting times. This study confirms that earlier planting favors better vegetative growth and seed production, consistent with findings from other onion research highlighting the critical role of planting date in maximizing yield and growth parameters in different cultivars under varying climatic conditions. Such findings provide valuable guidance for optimizing sowing schedules for onion seed production.

Ashagrie *et al.* (2014) reported that onion seed yield and quality are significantly influenced by the interaction of planting date and mother bulb size. Their field experiment at Sirinka Agricultural Research Centre tested three planting dates and three bulb size categories under irrigation. The highest seed yield (1155.73 kg/ha) and best germination index were achieved by planting large bulbs (4.1-5 cm) early on October 25, while small bulbs planted late (November 15) gave the lowest yield (75.15 kg/ha) and germination. Early planting improved germination percentage by 39%, and larger bulbs increased germination by 13.32%. Key yield parameters such

as umbel diameter and seed number per umbel showed strong positive correlations with seed yield. The study recommends early planting of large bulbs for optimal seed production and suggests further research on related factors like spacing, fertilization, and seed storage to enhance onion seed industry practices. This aligns with other research emphasizing the crucial role of planting date and bulb size in onion productivity under irrigation.

Krishnaveni stated that sets of the onion cultivar Rampur Local were planted at weekly intervals from the second week of November to the fourth week of February 1990. The highest bulb and seed yields, along with the best seed quality (86.0-90.0% germination), were obtained from planting during the second and third weeks of November. No seed yield was recorded for sets planted after the third week of January. This indicates that early to mid-November planting is optimal for Rampur Local onions to achieve maximum yield and seed quality. Plantings beyond late January result in no seed production, highlighting the critical importance of timely planting for successful onion cultivation in this cultivar.

Rizk FA (1993/94 and 1994/95) found that early planting of onion cv. Giza 20 during the first or second ten days of November resulted in greater seed stalk height and diameter, larger umbel diameter, and more flowers per umbel compared to planting in the last ten days of November. Delayed planting reduced seed yield, seed germination percentage, and 1000-seed weight. Foliar spraying with growth hormones GA3 and IAA increased seed yield and quality, while CCC (chlormequat) reduced them. This study highlights the importance of early planting and hormonal treatments to optimize onion seed production and quality in cv. Giza 20.

The doctoral dissertation by N. Roy (1994) at BAU, Mymensingh, investigated optimal seed production in onion (*Allium cepa* L.) cv. Taherpur by studying how growth conditions, planting times, and durations of cold (vernalization) treatment of bulbs affect seed yield and quality. Roy's work identified that factors such as proper timing of planting and adequate cold exposure to bulbs are crucial for enhancing flowering, reproductive development, and seed productivity. This research helped clarify that optimizing these parameters leads to better plant growth and higher seed yield, contributing valuable knowledge to onion seed production practices in regions with challenging climates.

G. P. Singh and R. K. Singh studied the effect of planting date and spacing on seed yield of onion cv. Patna Red. Their trials showed that planting bulbs at 30 × 10 cm spacing on 15 November

gave the highest seed yield, reaching 22.29 q/ha, while the lowest yield (8.45 q/ha) occurred with bulbs planted on 30 November at the widest spacing (30 × 40 cm). These results highlight that closer spacing and mid-November planting optimize seed yield for Patna Red onions, while delayed planting and wider spacing significantly reduce productivity.

Field experiments by El-Helady, M. A., & Karam, S. S. (2012) at the Faculty of Agriculture, Cairo University (2008/2009 and 2009/2010) assessed the impact of planting date on seed production of onion cv. Giza 20. Results showed that planting in mid-November significantly increased key yield and quality traits, including scapes number per plant, scape diameter, main scape length, umbel diameter, seed yield per plant and per feddan, 1000-seed weight, and seed germination percentage. In contrast, delaying planting to mid-January led to notably lower values for these parameters. The number of sprouts per plant was not affected by planting dates. The study concluded that mid-November is the optimal planting period for producing high quality and quantity onion seeds in Giza 20 under Giza region conditions.

A study at the Seed and Plant Improvement Institute, Karaj, Iran investigated by Mehri *et al.*, 2015 stated that planting dates and their effect on morphological traits and seed yield in onion cultivars Texas Early Grano 502 and Ghermez Iranshahr. The results showed that planting date significantly influenced plant growth and seed yield traits, with Texas Early Grano 502 sown on 22nd September yielding the highest (2166.4 kg/ha) and Ghermez Iranshahr planted on the same date yielding the lowest (407.9 kg/ha); Ghermez Iranshahr had its highest yield (1005.8 kg/ha) when planted on 6th October. Cultivar and planting date interactions also impacted total seed yield and leaf number, underscoring the importance of cultivar-specific optimal planting times for maximizing onion seed production.

Vianney, M.T.W *et al.* (2011) conducted a multi-year study (2006–2009) in northern Burkina Faso to understand how the seasons of bulb and seed production affect early bolting in onion plants. The researchers tested bulbs produced in normal and late seasons and monitored seed sensitivity and average time to bolt. Results showed that seeds produced in the normal season with bulbs from the same season had 75.3% bolting and took 133.6 days to bolt, while bulbs produced in the late season led to 93.3% bolting and 134.1 days to bolt. The study concluded that lower temperatures in bulb and seed production seasons increase bolting rates and suggested that producing bulbs during cooler periods can improve bolting resistance, aiding in selection for

breeding and better seed quality in onions.

Belayneh *et al.* (1986) observed reduction in yield when planting was delayed beyond early July because of the number of days required to reach maturity decreased with late planting. However, Nayak and Paikray (1991) reported that September sown crop gave maximum net return (Rs. 910/ha) and benefit-cost ratio (1.52) and delayed sowing caused progressive reduction in both the values due to decrease in seed and stalk yield. Sowing of unirrigated niger beyond October 1 was not remunerative. The seed and stalk yield were maximum in crop sown on September 1st as compared to the other dates of planting. Sowing on September 16th, October 1st and October 16th reduced seed yield by 20, 32 and 49 percent and stalk yield by 12, 25 and 43 per cent respectively.

Sowing *G. abyssinica* cv. Chhindwara-1on 20th July produced the highest seed yield(5.36q/ha) which was attributed mainly to the increased number of branches (9.6) and capitula (26.9) per plant, and a high 1000-seed weight (4.18 g). Both early and delayed sowings significantly reduced seed yield and net profit. (Thakur *et al.,* 2000).

Priya Kivadasannavar *et al.* (2007) reported that seed yield was significantly higher with July 15th sowing and seed yield was significantly reduced as the sowing was delayed beyond mid-July. The reproductive phase of early sown crop coincided with rains and resulted in lodging of crop eventually resulted in low yield due to poor seed setting (Sharma and Kewat, 1994). The crop duration was reduced by delayed sowing after mid-July and resulted in decreased seed yield due to inferior yield attributes viz, capitula per plant, seeds per capitulum and test weight.

Saleh *et al.* (2021) found that the activity of pollinators in onion umbels was observed after opening of flowers and there was a fluctuation in visits of insect pollinators on different days. The community of pollinators was composed of two honeybee species (*A. mellifera* and *A. dorsata*), hornets, wasps, butterfly and syrphid fly. The most abundant pollinator was syrphid fly followed by *A. mellifera*.

Ongoing climate change intensifies abiotic fluctuations like temperature extremes and altered precipitation patterns, threatening pollinator populations and their activity periods (Martén-Rodríguez *et al.,* 2025). These changes cause mismatches between pollinator availability and flowering times, further complicating the impact of planting dates on pollination success. Additionally, climate change-induced stress factors like habitat loss and pesticide use exacerbate

pollinator declines (Kline, O., & Joshi, N. K. 2024). Pollinator declines under changing abiotic conditions ultimately reduce crop yields and quality.

Rodo and Filho (2003) emphasized the importance of using high vigor seed lots to ensure adequate stand establishment under varying environmental conditions. Supporting this, Dawar et al. (2007) investigated the effects of three planting densities (40, 60, and 80 plants per m^2) on onion varieties Swat-1, Terich-02, and Gilassi local at the Horticultural Farm, NWFP Agricultural University, Peshawar. Their research revealed that a lower planting density of 40 plants per m^2 significantly increased the number of leaves per plant (14.80) and the weight of large bulbs (720.29 g). In contrast, higher planting density (80 plants per m^2) significantly increased leaf length (52.51 cm), weight of small bulbs (738.11 g), medium bulbs (958.50 g), single bulb weight (1774.00 g), and the total bulb yield (7072 kg ha^{-1}). The interaction between planting density and varieties was significant only for bulb yield, with the maximum yield of 7958 kg ha^{-1} produced by Terich-02 at the highest density.

Mahmud (2008) reported that bolting percentage increased with the size of the set; larger sets bolted earlier and yielded more seeds per umbel. Additionally, bolting percentage and seed yield were influenced by planting dates, with earlier December planting giving the highest seed yield of 5.1 g per plant across varieties.

Asaduzzaman et al. (2012) investigated bulb size (10±1g, 15±1 g, and 20±1 g) and plant spacing on onion seed quality in Bangladesh. They found the highest seed yield per plant (3.78 g) from bulbs of 20±1 g planted at 25 × 20 cm spacing, while maximum seed yield per plot (411.61 g) occurred with the same bulb size at closer spacing of 25 × 15 cm. This suggests that large bulb size combined with wider plant spacing is beneficial for quality seed production.

In Himachal Pradesh, Sharma and Jarial (2017) reported cultivar Agrifound Dark Red produced the highest average yield (229.03 q ha^{-1}), with the highest bulb yield (197.54 q ha^{-1}) from transplanting on 25th July. Thus, this cultivar is recommended for kharif production with transplanting around late July for maximum yields.

Similarly, Gosai et al. (2018) recorded tallest plants (60.97 cm) in Agrifound Light Red, while Bhima Shakti showed highest neck thickness (2.09 cm), bulb weight (82.99 g), marketable and total bulb yields (553.17 q ha^{-1} and 589.82 q ha^{-1} respectively), and shortest maturity (126.33

days) under North Gujarat conditions.

Ginoya et al. (2018), under Junagarh, Gujarat conditions, documented the highest seed yield per plant (8.05 g) and seed yield per hectare (288.78 kg) with the largest bulb size (75±5 g) and spacing of 45 × 30 cm in onion cultivar Gujarat Junagarh White Onion 3 (GJWO 3). Economic analysis showed that the combination of large bulb size and optimal spacing produced the highest gross and net returns, with the best benefit-cost ratio (3.39) achieved at this setting.

Demisie and Tolessa (2018) found that both variety and intra-row spacing significantly affected onion seed production traits, except leaf diameter which was only influenced by spacing. The variety Nafis with 13 cm intra-row spacing produced the highest leaf number per plant (13.9). Generally, wider intra-row spacing resulted in increased leaf number, leaf length, and plant height. However, closer spacing (7 cm) favored higher marketable and total bulb yields.

Mohamedali and Nourai (1988) reported whole bulb planting yielded more seed than splits in summer multiplier onions, with mid-October to mid-November as the best planting window. Under Kanpur conditions, Yadav et al. (2002) found bulbs sized 5.5 to 6.5 cm produced more umbels per plant and maximum seed yield (8.20 q ha^{-1}) when transplanted on 3rd November at 45 × 30 cm spacing in Kalyanpur Red Round variety. Optimal planting between 24th October and 13th November also gave good seed yield.

Planting dates and gibberellic acid (GA3) concentration significantly influenced onion growth and seed yield (Islam and Mondal, 2005). The tallest plants, highest leaves per plant, flower umbel number, seeded fruit per umbel, seed yield (1.14 g $plant^{-1}$), and seed yield per hectare (392.27 kg ha^{-1}) were recorded with planting on 30th October. GA3 at 75 ppm further enhanced these parameters with the best seed yield of 398.67 kg ha^{-1} in combination with the 30th October planting. Seed quality traits such as 1000-seed weight and germination were also highest in treatments with late October to November planting and GA3 application.

Shanmugasundaram (2007) stressed the importance of environmental conditions for onion seed production, advocating low humidity and mild cool temperatures in early growth stages followed by temperature rise in later stages. Ud-deen (2008) confirmed that large mother bulb size (20 g) and early planting (30th October) significantly improved growth, bulb and seed yields, flowering, and fruit set compared to later plantings.

Anisuzzaman et al. (2009) found that planting on 21st November produced the highest plant height, leaves per plant, earliest flowering, and maximum seed yield (460.8 kg ha^{-1}) in onion cv. Taherpuri. Verma et al. (2011) reported that early October planting gave maximum dry weight of shoots, flowering, seed yield per plant, and days to maturity, with November planting lagging but still better than later dates.

Under Ethiopian conditions, El-Helaly and Karam (2012) recorded the best seed yield-related parameters, including scape number and length, umbel diameter, seed yield per plant, 1000-seed weight, and seed germination with November planting. Delayed planting beyond November resulted in sharp declines.

Hamma (2013) showed that planting onion seedlings on 15th October combined with white polyethylene mulching significantly enhanced plant height, leaf number, flower and bulb number, and yield (4345 kg ha^{-1}) compared to later planting dates and other mulching types which had lower performance.

2.1.3 Correlation of weather parameters with foraging behaviour of honeybee species.

Activity of flower visitors on onion umbels was dependent on temperature as reported by Kavitha and Reddy (2019). As the time of the day progressed, temperature kept increasing and the number of pollinators decreased. Maximum pollinator activity was observed between 9.00 am and 12.00 pm coincided with temperature 28^{o}C to 32^{o}C.

Karuppaiah *et al.* (2018) reported that irrespective of bee species the visitation on onion umbels was more during noon hrs. Air temperature around the canopy was significantly positively correlated (r = 0.874) with bee activity whereas, relative humidity had a negative correlation (r = -0.737).

Maximum temperature, minimum temperature and relative humidity played a significant role in the foraging population of all four *Apis* species on onion umbels (Devi *et al.,* 2014). The number of *A. dorsata* foragers on onion umbels were significantly positively correlated with the maximum temperature (r= 0.619) of 26.6° to 40.5°C range and minimum temperature (r= 0.727) of 7.5° to 19.2°C range. A significant negative correlation was recorded between *A. dorsata* forager population and evening relative humidity (r = -0.702).

Temperature had a significant positive correlation (r= 0.8003) with the foraging behaviour of *A. florea* on onion umbels as reported by Abrol (2016). The overall significant positive association of temperature (r = 0.799) with bee visits was largely a reflection of positive inputs of light intensity and solar radiation. The simple correlation between bee visits and relative humidity was significantly high and negative (r= -0.653). The direct effect of light intensity was significantly positive (0.599). The total correlation between bee visits and solar radiation was high and positive (r = 0.389).

Among all climatic factors studied, maximum temperature (>30^0C) was the most crucial one which had negatively affected the activity of bees visiting onion umbels with correlation coefficients (r) of -0.72, -0.59 and -0.61 for outgoing bees, pollen and nectar collectors, respectively (Reddy *et al.,* 2015). The relative humidity showed positive impact on the frequency of worker bees moving out of hive (r = 0.69) and for those coming in with nectar (r = 0.68) but negatively affected the number of pollen collectors. Diurnal variations showed peak activity of bee foragers between 6.00 and 10.00 am. Rainfall hampered foraging activity while wind speed was found to have no significant effect on bee activity.

Caselles *et al.* (2019) reported that the bee activity on onion umbels varied throughout the flowering period as well as along the day. In those days when the weather conditions were not favorable for bees at noon, no insects were observed on the umbels and bees increased during the afternoon. The flowering percentage as well as the temperature positively influenced bee activity under open field conditions; on the other hand, RH (maximum and minimum), cloudiness and precipitation were the parameters that influenced the bees' activity negatively. The factor that had the greatest influence was the minimum RH. On days where the minimum percentage of RH was low (less than 20 %) or it was very high (above 55 %), bees did not fly.

Temperature and solar radiation had a significant positive correlation with foraging activity of *A. florea*, with r values 0.794 and 0.389, respectively (Abrol, 2010). Whereas relative humidity had a significant negative correlation with the foraging activity of *A. florea* (r= -0.542).

Pollination is crucial for the seed production of onion (*Allium cepa*), which is predominantly insect-pollinated. Honey bees, particularly Apis species, are the primary pollinators contributing to effective seed set in onion crops. Studies found that honey bees contributed up to 87% of pollination in onions, playing a critical role in productivity and yield quality. In onions, maximum

and minimum temperatures have significant positive correlations with populations of four species of Apis bees (*A. dorsata, A. cerana, A. mellifera, A. florea*), which were active between 7.5°C to 40.5°C (Singh *et al.*, 2015).

Abiotic factors such as temperature, humidity, wind speed, light intensity, and rainfall significantly affect insect pollinators' foraging behavior and population dynamics. For example, temperature influences the flight activity thresholds of bees, with optimal activity generally found between 20-30°C (Jiang *et al.*, 2016; Joshi and Joshi, 2010). Wind speed can negatively affect pollinator visitation by inhibiting flight, thus limiting pollination services (Rands & Whitney, 2010).

Evening relative humidity had a significant negative correlation with *A. dorsata* activity. Abiotic factors thus directly modulate pollinator abundance and foraging behavior, impacting onion seed productivity. Furthermore, light intensity and wind velocity are also significant abiotic determinants. Relative humidity also impacts the flight behavior, with bee activity declining in very high or low humidity. Light intensity is another factor that shapes foraging patterns by influencing the ability of pollinators to locate flowers Additionally, high rainfall inhibits pollinator visits by physically restricting flight and washing away floral scents (Farooqi *et al.*, 2021).

Temperature correlates positively with bee foraging up to a certain threshold; for example, Apis mellifera flies actively above 12-14°C, with optimal activity in the range of 20-25°C (Vicens & Bosch, 2000). Above 40°C, activity declines, but some bees can tolerate up to 46°C (Oskay 2023). Humidity shows a complex relationship, where high evening humidity negatively correlates with pollinator presence, possibly due to reduced nectar evaporation altering flower attractiveness (Paul *et al.*, 2022). Varying planting dates shift the flowering time, modulating the synchrony between onion anthesis and the peak activity of pollinators. Early or late planting can expose crops to suboptimal environmental conditions, reducing pollinator visits and seed yield (Kehrberger & Holzschuh, 2019). For example, early flowering plants may benefit from lower competition for pollinators but may face unfavorable weather conditions (Kehrberger & Holzschuh, 2019). This temporal misalignment can lead to reduced pollination efficiency and seed set, emphasizing the importance of selecting optimal planting windows to maximize pollination services.

Strategies such as intercropping onion with attractant plants like coriander or buckwheat have been shown to enhance pollinator visitation, contributing to higher seed quantity and quality

(Asritha *et al.,* 2025). Such modifications to agronomic practices can mitigate some negative abiotic impacts by enhancing local pollinator abundance and diversity.

Divija and Jayanthi (2022) reported that stingless bees differed from honey bees and flies in foraging preferences on onion flowers. Stingless bee (T.iridipennis) and little bee (*A. florea*) initiated the foraging activity 15–45 min before other floral visitors on onion flowers. All the floral visitors foraged for a mean of 10 hrs (08:00 to 18:00) per day. The flower visitation rate (number of flowers visited/ min) was highest in *A. dorsata* followed by *A. cerana*, *A. florea* and T. iridipennis. Whereas the visitation frequency (number of visits/ floret/ 10 min) was highest in *A. florea* followed by *A. dorsata*, *A. cerana* and *T. iridipennis*.

According to Kumar and Giri (2022), *A. mellifera* started visiting onion flowers early in the morning and ceased their activity later in the evening and remained active throughout the flowering period. The foraging rate of *A. mellifera* was minimum during afternoon (11.6 flowers/ min) and maximum during evening (24.3 flowers/ min) and its foraging speed was maximum in afternoon (12.1 sec) and minimum in evening (6.5 sec) however foraging rate and speed were inversely related.

2.2 To study the role of varietal traits of onion on abundance, foraging behavior of insect pollinators (*Apis mellifera)*.

2.2.1 Influence of *Apis mellifera* on Abundance, Foraging Behavior among Onion (*Allium cepa* L.) Varieties.

According to Neeraj kumar *et al.,* 2020 the experiments on "Foraging Behaviour of *Apis mellifera* L. on Onion, *Allium cepa* L. bloom" were carried out during the year 2019 at ELP Apiary, TCA, Dholi. Objectives of this investigation were to study the, foraging behaviour of Apis mellifera on onion. The result on foraging behaviour of Apis mellifera revealed that they started visiting onion flowers in early morning and ceased their activity later in the evening. It remained active throughout the flowering period. The foraging rate of Apis mellifera was minimum in afternoon (11.6 flowers/min) and maximum during evening (24.3 flowers/min) and its foraging speed was maximum in afternoon (12.1 sec) and minimum in evening (6.5 sec) and there was inverse relation between foraging rate and speed. The heaviest pollen load was carried by the Apis mellifera in afternoon which indicated that more pollens were collected by Apis mellifera during

afternoon from onion flowers. The result depicts that insect pollinators provide an important pollination service to the onion seed production. Among different insect pollinators, Apis mellifera was found most efficient pollinator of onion. Utilization of Apis mellifera bee colonies for seed production in onion will be highly remunerative as due to pollination, higher quantity of quality seed is produced.

Salmon (2022) reported that commercial honey bees often avoid onion blooms in South Africa's Klein Karoo region, causing seed yield losses up to 44%. While varying water irrigation levels during flowering did not significantly affect bee foraging, insect visitation strongly correlated with seed output, indicating that nectar/pollen chemistry and environmental factors drive cultivar attractiveness.

Ahmed, S. *et al.*, 2020 according to them an experiment was carried out at Horticulture Farm of Bangladesh Agricultural University, Mymensingh during the period from October 2018 to March 2019 to examine the effects of different bulb size viz., large size bulb (15±1 g), medium size bulb (10±1 g), small size bulb (7±1 g) on seed production of two onion varieties (Taherpuri and Kalash Nagari). Significant variation observed in both varieties for most of the parameters based on onion bulb size. The variety Kalash Nagari showed better performances compared to variety Taherpuri. After 60 days of planting, Kalash Nagari variety gave the highest plant height (55.07 cm), number of leaves (20.62), stalk length (100.78 cm), and total seed yield (630 kg ha^{-1}), while in Taherpuri plant height, leaf number, stalk length and total seed weight were 32.21 cm, 6.93, 61.47 cm and 270 kg ha^{-1}, respectively. Large sized bulb gave better performance compared to small sized bulb. The large sized bulb gave highest plant height (49.83 cm) and highest total seed yield (490 kg ha^{-1}). Medium size bulb gave the seed yield (460 kg ha^{-1}) and lowest in small size bulb (390 kg ha^{-1}). Seed yield was significantly affected by the combined effects of variety and bulb size. Kalash Nagari onion with large sized bulb gave the highest seed yield (660 kg ha^{-1}) and Taherpuri variety with small sized bulb gave the lowest seed yield (180 kg ha^{-1}).

Insects are responsible for pollinating over 75% of the world's flowering plants. Honeybees are well known for being important for many crops. Researchers Bezabih, G., & Gebretsadikan, K. (2014) at the Mekelle Agricultural Research Centre experimental farm looked into how managed honeybee pollination affected the yield and quality of onion seeds by excluding pollinators and doing surveys of pollinators on onion field plots.

In 2015-16, Padamshali, S., & Mandal, S. K. looked into how managed honeybee pollination affected the yield and quality of onion seeds in the Raninagar village of Chakdaha

block in West Bengal's Nadia district. They used three treatments: plants caged in nets without any pollinators (T1), plants caged in nets with only honey bees (Apis mellifera) as pollinators (T2), and plants open to all pollinators (T3). Pollination did not affect the amount of umbels generated per plant. Honey bee pollination and open pollination both increased the yield of onion seeds by 77.45% and 87.68%, respectively. Pollination also dramatically enhanced the number of pods per umbel, the number of seeds per umbel, the weight of a thousand seeds, and the rate of seed germination. Under net, open pollination worked better than honey bee pollination in all of these areas except seed germination, but not by a much.

This study examined by Carlson, E. 1974, the relationship between onion (*Allium cepa* L.) varieties, honeybee (Apis mellifera L.) visitation, and seed yield under field and isolated planting conditions in Davis and Dixon, California. Significant differences were observed among varieties in their attractiveness to honeybees, with Red Wetherfield and Yellow Sweet Spanish receiving higher bee visits than other varieties. Diurnal patterns showed maximum bee visitation between 11 am and 2 pm. Seed yield was generally higher in varieties with greater bee activity, though nectar acceptability also influenced outcomes. Yellow Sweet Spanish produced the highest seed yield, while Yellow Globe showed the lowest, correlating with poor bee visitation. Hybrid trials further demonstrated that varieties more attractive to honeybees produced significantly greater seed yields, confirming an inherent varietal effect on pollinator preference and seed productivity. Results highlight the importance of varietal selection and pollinator behavior in improving onion seed production efficiency.

Ali et al. (2015) evaluated the effect of bulb size (4g, 8g, and 12g) on 'Taherpuri' onion seed production in Gazipur, Bangladesh. Larger bulbs (12g) significantly increased plant height, leaf and umbel counts, seed yield per plant, and seed quality compared to smaller bulbs.

According to Soto *et al.,* 2013 Honey bees serve as the primary pollinators for onion crops intended for seed production; however, due to the low attractiveness of the flowers, pollination frequently proves insufficient. Insufficient pollination leads to reduced seed yields. The issue is exacerbated when male sterile lines (MSL) are employed in the production of hybrid onion seeds. This study assessed the influence of floral attributes and nectar composition on the preferences of honey bees for four MSLs and one open-pollinated onion cultivar. The analysis of sugars, trace elements, volatile organic compounds, and phenolic compounds elucidated the chemical composition of nectar. The analysed samples exhibited both qualitative and quantitative variations in the traits of flowers and nectar across the different lines. Field observations indicated significant

variation in the number of bee visits and seed yield across the analysed onion lines. This study reveals significant differences in the chemical composition of nectar and floral morphology between open-pollinated plants and managed seed lines, as well as variations within managed seed lines. Furthermore, these differences exhibited a correlation with the frequency of visits and seed yield. Consequently, it is feasible to indirectly identify the most promising productive MSL through straightforward assessments of chemical compounds or floral morphological traits.

Attractiveness to pollinators varies among onion varieties and especially among male-fertile (pollinator-friendly) and male-sterile lines used for hybrid seed production. Some hybrids exhibit higher nectar rewards or more conspicuous floral traits, leading to greater bee visitation and potentially higher seed yields when pollinators are present. However, not all hybrids are equally attractive, and responses can differ by location and pollination context. [web results referencing onion varieties, honeybee visitation, and seed yield]

According Goodwin, M. (2012) pollination moves pollen from floral anthers to stigma. This is vital to many crops' economic production. It is normally the least understood and optimised. Growers may leave it unmanaged and hope bees or other insects pollinate it. Adding beehives for pollination may not improve performance or measure levels. Pollination efficiency can boost agricultural production economics for several crops. This manual assists Australian and New Zealand growers, beekeepers, and pollination specialists maximise insect-pollinated commercial crop pollination. Honey bee biology, behaviour, and pollination are covered. Orchard management for honey bees and crop pollination issues are highlighted. Australian and New Zealand pollination methods differ substantially. Most New Zealand crops are pollinated by honey bees save white clover, which is appealing. Bumble bees are often used for artificial pollination in New Zealand. Like New Zealanders, many Australian farmers use maintained hives, although some use feral colonies.

The study revealed by Devi *et al.*, 2015 the pollination biology and floral traits of onions (*Allium cepa* L.), including nectar production and pollen availability, directly influence which pollinators visit and their frequency, showing that bee species—particularly Apis dorsata, A. cerana, and others—are the primary pollinators in most onion varieties. It discusses the floral biology of onions, including that flowers are enclosed in a sheath and contain many florets. Anthesis occurs in early morning, with anther dehiscence and pollen fertility peaking between 9:30-17:00 hours. The duration of anthesis is approximately 2-3 days. Onion cultivation is important worldwide but yields are lower in India compared to countries like the US, partly due to

differences in pollination. Managed pollination can help increase onion seed yields and quality.

Kavitha, S. J., & Reddy, P. R. (2018) stated that nectar production varies among onion varieties; varieties with higher nectar outputs attract more bee activity, making them more successfully cross-pollinated and yielding higher seed sets.

Khokhar (2014) highlighted that onion seed yield is influenced by pollinator attractiveness, mother bulb size, and vernalization conditions. Optimum floral induction requires storing mother bulbs at 5°C to 13°C for 90 to 120 days (or 154–185 days for bolting-resistant varieties) once plants complete Juvenility (4–14 leaves). High seed yields are best achieved using large mother bulbs combined with early planting and high post-planting temperatures (20°C–30°C) under long days.

Silva (2004) recorded that successful pollination of onion (*Allium cepa* L.) flowers greatly depends on adequate nectar production. In order to understand the nectar production dynamics of onion flowers, nectar was collected at regular intervals during a 24-hour period. Hourly nectar volumes were compared to a variety of environmental conditions, including amount of solar radiation, relative humidity, temperature, wind speed, and evapotranspiration. Production patterns showed mid- to late-morning peaks and late evening peaks in nectar volume. Nectar appeared to be reabsorbed by the flowers during the afternoon and overnight hours. Individual flowers produced the highest amount of nectar several days after initially opening. Nectar production was significantly and inversely related to relative humidity while the effects of temperature, evapotranspiration, wind speed and solar radiation on nectar production were not significant in this study.

Short-day onion varieties maintained as landraces and open-pollinated lines show greater genetic diversity, possibly resulting in more diverse floral cues and nectar yields that attract a wider pollinator spectrum (Lyngkhoi, *et al.,* 2021).

Currah, L. (1981). Stated that there is significant variation between onion varieties in terms of susceptibility to bolting, time to flowering, and umbel size, all of which influence pollinator visitation rates and subsequent seed development.

Hybrid onion varieties outperformed open-pollinated (OP) varieties in plant height and leaf number but not in traits directly affecting marketable production such as percentage of seedstalks, pink root incidence, percentage of marketable yield, bulb size, or marketable bulb yield. The comparative trial conducted over two fall planting seasons (1997 and 1998) in southern

New Mexico revealed that most OP varieties performed as well or better than most hybrid varieties in market-related traits (Mohamed, M. F., & Tawfik, A. A. 2025).

The study was conducted by Al-Juboori, *et al.,* 2020 in the vegetable field of the Department of Horticulture and Garden Engineering College of Agriculture and Forestry, University of Mosul during season 2018-2019 and in the soil mixture to show the effect of plant density and varieties on the adjectives Growth and yield in onions. The experiment was laid out in RCBD with 3 replications which included two factors: varieties, that were laying within the main plot of the experiment while the plant density was placed under sub plot . The results showed the superiority of the prolate white cultivars in the yield of the plant and the total yield. but No significant differences were found in the other traits. The plants under the high plant density gave high values in the traits of the plant yield and the total yield. While the interaction of the prolate white variety under high plant density gave the highest values in both plant yield and total yield values t/h.

Karuppaiah *et al.,* 2018 An experiment was carried out to examine the diversity and foraging behaviour of major insect pollinators in onion. Eleven insect species viz., *Apis florea*, *A. cerana*, *A. dorsata*, *A. mellifera*, *Tetragonula* sp., *Xylocopa* sp., *Vespa* sp., *Pieris rapae*, *Danais chrysippus*, *Eristalis* sp. and *Musca domestica* were observed pollinating. Of these 98% of forage visits were of hymenopterans, with most of these happening during 1330-1430 hrs. The Berger-Parker index of abundance computed revealed that *A. dorsata* was the dominant. The analysis of foraging behaviour revealed that maximum foraging was by *A. cerana* (3.17 umbels/min) followed by *A. dorsata* (3.0 umbels/min) and the least with *A. florea* (2.0 umbels/ min). Time spent/flower was the maximum with *Tetragonula* sp. (27.50 sec/umbel) followed by *A. florea* (18.83 sec/umbel) and *A. dorsata* (17.83 sec/umbel) and the least with *A. cerana*.

The assessment of onion genotypes during the kharif season of 2017 highlighted significant differences in plant growth and bulb yield traits, key for off-season production and premium market returns. The genotype COHBON18 had the greatest plant height (70.42 cm), COHBON01 had the most leaves (12.06), and Bhima Super had the longest leaves (60.92 cm) and greatest bulb yield per hectare (31.66 t/ha). Other notable performances included COHBON15 for leaf width and stem girth, COHBON34 for lowest premature bolting/split bulbs, COHBON11 for equatorial bulb diameter, and Bhima Super for superior polar diameter, bulb weight, and yield. Genotypes COHBON34 and COHBON27 also produced high yields and are

recommended for kharif season cultivation and as breeding material for further genetic improvement (Manjunath *et al.,* 2022).

According to Pérez *et al.,* 2018 Preserving old open-pollinated onion varieties offers a viable strategy to maintain genetic diversity while catering to renewed consumer and farmer interest due to distinct aroma and flavour profiles. A comparative study in South-West Germany assessed nine open-pollinated varieties against two commercial counterparts, revealing considerable diversity in yield and chemical properties. Notably, “Birnförmige” excelled in yield and held high concentrations of fructan and pyruvic acid, both associated with nutritional and medicinal value, while “Jaune des Cévennes” was characterized by low dry matter, low pyruvic acid, and a high bolting percentage. The findings also documented a negative correlation between mineral content (such as calcium and magnesium) and fructan in onion bulbs, underscoring the complex relationship of onion quality traits.

To assess the effects of Apis mellifera adansonii (Hymenoptera: Apoïdae) on *Allium cepa* fruit and seed, foraging and pollination activities were examined in Maroua from November 2010 to April 2011 and 2012. Bagged flowers to avoid visits, unfettered floral access by all visitors, and limited A. m. adansonii visits were treatments. Each treatment had 120 flowers observed. Al. cepa flowers were prospected four days a month from 07.00 to 18.00 h to record pollinator nectar and pollen gathering activity. We recorded the worker bee's seasonal rhythm, pollination efficiency, fruiting rate, number of seeds per fruit, and well-developed seed percentage. Honey bees foraged reportedly nectar virtually all day, peaking between 8 and 9 am. The foraging rate was 47.12 ± 7.19 flowers/minute. 22 bug species were found on Al. cepa blooms. A. m. adansonii was the most visited in 2010 and 2011 with 40.62% and 51.48% visits. Its foraging increased the fruiting rate by 62.5% in 2010 and 53.8% in 2011, the quantity of seeds per fruit by 86.44 and 89.77%, and the percentage of normal seeds by 63.26 and 59.78%. A. m. adansonii colonies can boost fruits, seeds, and honey (Tchindebe, G., & Tchuenguem, F. F. 2014).

2.2.2 Physio-chemical and Biochemical Composition of Onion (*Allium cepa* L.) Pollen and Nectar.

According to Soto *et al.,* 2018 Onion (*Allium cepa* L.) is one of the main vegetable crops. Pollinators are required for onion seed production, being honeybees the most used. Around the world, two types of onion varieties are grown: open pollinated (OP) and hybrids. Hybrids offer

numerous advantages to growers, but usually have lower seed yields than OP cultivars, which in many cases compromise the success of new hybrids. As pollination is critical for seed set, understanding the role of floral rewards and attractants to pollinator species is the key to improve crop seed yield. In this study, the correlation of nectar-analyzed compounds, floral traits, and seed yield under open field conditions in two experimental sites was determined. Nectar composition was described through the analysis of sugars, phenol, and alkaloid compounds. Length and width of the style and tepals of the flowers were measured to describe floral traits. Floral and nectar traits showed differences among the studied lines. For nectar traits, we found a significant influence of the environment where plants were cultivated. Nonetheless, flower traits were not influenced by the experimental sites.The OP and the male-sterile lines (MSLs) showed differences in nectar chemical composition and floral traits. In addition, there were differences between and within MSLs, some of which were correlated with seed yield, bringing the opportunity to select the most productive MSL, using simple determinations of morphological characters like the length of the style or tepals size.

(Kavitha & Reddy, 2019) stated that the experiment was conducted to study the relationship between the onion floral nectar characteristics and honey bee foraging activity. The role of nectar characteristics in influencing their attractiveness to honey bees was evaluated in three cultivars of onion. Onion varieties with more nectar, TSS and caloric rewards attracted large number of honey bees (Apis cerana, Apis florea, Apis dorsata and Tetragonula iridipennis). Arka Pragathi variety was found to produce significantly superior quantity and quality of nectar, that attracted a large number of honey bee foragers. All the onion varieties studied produced the floral nectar which is hexose dominant, rich in fructose and glucose sugars. The honey bee foraging populations showed a significant positive correlation with average nectar volume and TSS (except Apis dorsata for nectar volume), thus honey bee foragers were found to be guided to flowers mainly because of their nectar quantity and quality.

Nectar characteristics of six onion (*Allium cepa* L.) cultivars were examined to assess the potential for preferential foraging by honey bees (Apis mellifera L.). Mean nectar amounts for six cultivars ranged from 0.54 to 0.84 µl per floret per day. Onion cultivars differ in flowering potential, with cultivars varying from 176 to 359 flowers per umbel and 32 to 74 umbels per 30 onion plants. All cultivars examined contained highly concentrated nectar with total dissolved

solids ranging from 52 to 65%. Onion nectar was analyzed by gas chromatography to determine qualitative sugar differences among onion cultivars. All cultivars were hexose-dominant, having sucrose ranges from 4.0 to 14.4% and nearly equal amounts of fructose and glucose. There were significant differences in sugar content between the onion cultivars. Nectar composition and honey bee visitation among the six test cultivars were compared. It was determined that honey bees foraged preferentially on some of the onion cultivars (Hagler, *et al.,* 1990).

Soto et al. (2023) Nectar Composition: Bunching onion yields more seed and produces higher nectar sugar content than common onion, with total sugars averaging 56% fructose, 34% glucose, and 9% sucrose. Yield Link Fructose concentration strongly correlates with seed yield, explaining why bunching onions face fewer pollination bottlenecks than common onions.

Soto et al. (2021) Hive Placement Timing: Honeybee visitation peaks at 70% flowering, directly corresponding with peak fructose concentration in nectar. Recommendation To optimize pollination efficiency and address lower hybrid seed yields, beehives should be moved into onion fields at 40–50% bloom.

Nectar sugar content and solute concentration in the nectar of 3 Allium species were determined to assess their potential for honeybee foraging. The pattern of nectar secretion varied among the 3 onion species. In A cepa and A cepa fistulosum there was resorption of nectar sugars after 72 and 144 h of flower opening, whereas in A fistulosum even 144-h-old flowers contained 3.908 mg sugar/flower and there was no apparent resorption. The 3 onion species contained highly concentrated nectar and the solute contents were on average 68.96, 56.74 and 53.47% in A cepa, A fistulosum and A cepa fistulosum, respectively. The 24-h sugar value varied between 0.219 to 0.767 mg/flower, though significant amounts of sugar were produced after this period. Honeybees preferred the nectar of A cepa. Among honeybees, Apis dorsata dominated the blooms as compared to A mellifera and A cerana indica. The differential preference of A cepa by honeybees might be associated with the concentration of nectar solutes coupled with the amount of dry nectar sugars (Kumar, J., & Gupta, J. K. 1993).

According to Rodríguez-Peña *et al.,* 2021 when studying honey bee nutrition, it is important to pay attention not only to the quantity but also to the quality of pollen for floral visitors. The recommended way to determine the value of pollen is to determine both the protein concentration and the amino acid composition in the insect's hemolymph. In addition, the composition of pollen also includes lipids, sterols and biogenic elements such as carbon, nitrogen, etc. Very high protein concentration is observed in aloe pollen, averaging 51%. Plants with a high

protein content, at the level of 27% in Europe, are rapeseed and phacelia. In turn, a plant that is poor in protein (at the level of 11%) is buckwheat. The aforementioned plants are sown over very large areas. Vast acreages in Central and Eastern Europe are occupied by pollen- and nectar-providing invasive plants, such as goldenrod. Therefore, bees are forced to use one food source—a mono diet—which results in their malnutrition. In the absence of natural pollen, beekeepers use other foods for bees; including soy protein, powdered milk, egg yolks, fish meal, etc. However, the colony is the strongest when bees are fed with pollen, as opposed to artificial protein diets. More research is needed on the relationship between bee pollen composition and nutrition, as measured by protein concentration and amino acid composition in apian hemolymph, colony strength, honey yield and good overwintering.

Brassica napus L. pollen lipids and proteins are divided into two spatially distinct domains by the plasma membrane of the vegetative cell. The extracellular lipid and protein fractions can be separated from the internal cytoplasmic fractions by differential solvent and buffer extraction because the pollen grain wall and plasma membrane act as barriers to both lipid and protein extraction. Mature pollen is composed of 25.4% lipids and 26.0% protein (dry weight). The extracellular pollen-coat is estimated to contain 27.1% of the total lipids and between 9.6 and 19.6% of total protein depending upon the extraction method. We conclude that for assured determination of pollen grain lipid and protein content, the pollen should be fractured during extraction (Evans *et al.*, 1991).

Di Pasquale 2013 stated that honey bee populations depend on floral resources for pollen and other nutrients. However, agricultural intensification and terrain alteration affect foraging regions. Thus, bees face seasonal and spatial differences in floral resource abundance, type, and variety, which may compromise nutrition and threaten colonies. The positive effect of pollen availability on bee health is well known, but the impact of pollen diet quality and diversity is unknown. Thus, we examined the effects of pollen diet quality (monofloral pollens) and diversity (polyfloral pollen diet) on young nurse bees, which have a distinct nutritional physiology (e.g. hypopharyngeal gland development and vitellogenin level), and on their tolerance to the microsporidian parasite Nosema ceranae by measuring bee survival and the activity of enzymes involved in bee health and defence response. Pollen quality affects nurse bee physiology and parasite tolerance. Pollen diet diversity did not affect nurse bee or healthy bee survival. When parasitised, polyfloral blend-fed bees lasted longer than monofloral pollen-fed bees, save for the protein-richest. Survival was also favourably linked with healthy bee alkaline phosphatase activity and infected bee phenoloxydase activity. Our findings suggest that pollen quality and diversity can

affect bee physiology and may help us understand how agriculture and land-use intensification affect bee nutrition and health.

The mineral content of honeybee-collected pollen from 34 floral species was analysed for 10 elements. The mean concentrations (mg/kg) of major and minor elements were the following: potassium (K) 5530, phosphorus (P) 4600, sulfur (S) 2378, calcium (Ca) 1146, magnesium (Mg) 716, sodium (Na) 82, iron (Fe) 67, zinc (Zn) 58, manganese (Mn) 33 and copper (Cu) 12. Close correlations existed between Mn and Cu, P and S, K and S and K and Zn. Single species demonstrated similar element profiles. *Echium plantagineum* pollen had a high mean concentration of P (7411 mg/kg) and S (3133 mg/kg) when compared with the mean of the total; *Brassica napus* pollen had high concentration of Mg (1400 mg/kg) and Ca (1750 mg/kg) and low concentration of Fe (27 mg/kg); *Hypochoeris radicata* had low concentrations of 6 elements — Fe (4.5 mg/kg), Zn (20 mg/kg), Mg (240 mg/kg), S (1400 mg/kg), P (2066 mg/kg) and K (2433 mg/kg). *Asphodelus fistulosus* had the highest concentration of K at 38 000 mg/kg, the next highest value of 8200 mg/kg being for *Prunus dulcis* (Somerville, D. C., & Nicol, H. I. 2002).

According to Pernal and Currie (2001), honeybee (*Apis mellifera* L.) colonies respond to depleted pollen reserves by increasing the overall number of pollen foragers rather than accelerating their individual foraging pace or changing their floral preferences. Altering the quantity or protein quality of stored pollen did not affect the specific flower species selected, pollen particle size, or the weight of individual pollen loads. Instead, foraging experience played a primary role: inexperienced foragers gathered larger pollen loads and sampled a broader variety of floral resources compared to expert foragers. These findings indicate that honeybee colonies regulate their protein supply through colony-level feedback mechanisms driven by total store quantity rather than individual foragers assessing pollen nutritional quality.

Pollen pellets collected from honey bees foraging at 62 floral species were analysed for protein and amino acid content and their value for honey bee nutrition was determined. The crude protein levels of all pollen pellets analysed ranged from 9.2% for Hypochoeris radicata (flatweed)

to 37.4% for Echium plantagineum (Paterson's curse) with a mean of 25.9%. Pollen pellets from 15 species were identified as providing protein levels below those acknowledged to satisfy honey bee dietary requirements when they are the only source of pollen available to the honey bee colony. Pollens collected from species of the same genus demonstrated similar protein profiles. Isoleucine was deficient in 38% of the pollens with 69% of eucalypts and related species demonstrating a significant isoleucine deficiency (Somerville, D. C., & Nicol, H. I. 2006).

According to Layek *et al.*,2020 in southern West Bengal, India, Apis mellifera pollen loads were studied to determine their daily pollen collection, polleniferous flora, and pollen biomass. After that, bee species pollen host selection and foraging activities were determined. The average daily pollen harvest per honey bee colony ranged from 8.5 to 127.2 g. The monsoon had the lowest pollen movement across the colonies, followed by spring, winter, and summer. Pollen load weight varied from 3.22 mg to 11.73 mg and varied by season, but average values did not significantly differ. Arecaceae, Myrtaceae, Brassicaceae, Fabaceae, Pedaliaceae, and Apiaceae produced most biomass. Brassica nigra, Eucalyptus globulus, Borassus flabellifer, Sesamum indicum, Acacia auriculiformis, Coriandrum sativum, Cocos nucifera, Phoenix sylvestris, and Mikania scandens provided significant biomass. Since the bee species foraged on 26.32% (80 plant taxa) of the local angiosperm flora, wide polylecty was predicted. Pollen host selection by bee species is largely determined by the flower availability index (FAi) and pollen availability index (PAi) rather than an individual flower's pollen quality (morphological characteristics and crude protein content) and quantity. Bees' pollen-foraging activities varied by season and time. Activity increased between 9 and 10 am. Spring had the most activity, while monsoon had the least. The ratio of pollen foragers to total incoming foragers varied by season, time of day, and resource availability.

Pollen, the major protein source for honey bees, is mixed with regurgitated nectar or honey during collecting and stored as 'bee bread' before intake by young nurse workers. Pollen preservation is said to boost its nutritional content and digestion, but there is little evidence. Young worker bees were fed aloe, sunflower, and a mixed pollen with variable protein content. We tracked pollen and sugar consumption and survival after 14 days. We counted empty pollen grains in rectal contents at day 14 to measure ovarian activation and extraction efficiency. Pollen digestion is measured by extraction efficiency. Bees did not consume more fresh sunflower pollen than fresh aloe pollen to compensate for its lower protein content, contrary to our projections.

Additionally, they did not drink less sucrose solution when administered sugar-enriched stored pollen diets. Consuming stored sunflower pollen reduced protein-to-carbohydrate ratio. Survival and ovarian activity were increased on P:C-rich diets. We found that all pollen diets had great extraction efficiency (up to 99%) and that stored sunflower pollen was not easier to digest. Honey bees hardly benefit from pollen storage changes (Nicolson *et al.,* 2018).

According to Quinlan *et al.,* 2021 healthy bee diets require pollen-derived protein. Honey bee foraged-pollen protein concentration changes temporally and geographically, but its determinants are unknown. We examined honey bee pollen time and space in 12 Michigan apiaries over three summers (2015–2017). During the growing season, we monitored forage in uncultivated floristically-rich regions and conservation program property near these apiaries. These data and literature data on plant pollen protein content were used to assess if honey bees collected more pollen from abundant plant species or protein-rich plant species. Honey bee pollen protein declined from July to September every year, and levels varied between years, indicating that these insects acquire protein at different times. Pollen protein concentration was unrelated to broad-scale land use categories and geographically constant. We discovered that flowering habitats across land use categories can sustain honey bee foraging, which may complicate land use consequences. From late July to August, colonies collected more pollen from high-protein taxa, regardless of quantity, than from flowering plants in early July and early September. This shows pollen forager decision-making may shift throughout the season as colony demands and forage communities change. Understanding how plant abundance and protein content affect honey bee foraging could inform habitat restoration projects to improve honey bee nutrition.

Gosh *et al.,* 2020 stated that pollen provides protein and fats to numerous creatures, including honeybees. Pollen from three healthy experimental honey bee colonies was examined in June to understand their foraging behaviour and floral resource preferences. Pollen collections were related to the colony's requirement, shown by larval and adult bee numbers. Sequence of pollen collecting from different flowers was intriguing. All honey bee colonies obtained pollen from Trifolium repens first, then Erigeron annus, Coreopsis drummondii, and Oenothera biennis. Trifolium pollen had the highest total protein content (20.0 g/100 g DM), whereas others ranged from 8.9–11.4 g/100 g DM. The results showed that honey bees first choose pollens based on

protein content and resource availability of less nutritious floral sources. This knowledge can aid pollinator protection programs that manipulate blooming plant habitats for nectar and pollen.

According to Alshallash *et al.,* 2023 nutritional supplements aid protein synthesis, fitness recovery, and mental wellness. Pollen is a nutritious natural food. The therapeutic properties of bee-gathered pollen make it a popular dietary supplement worldwide. Pollen has different nutritional values depending on the flower species and area. Clover pollen had the most protein (31.4 g/100 g DM), while maize pollen had the least (21.3%). Eucalyptus pollen has the most lipids (9.49 g/100 g DM), while clover pollen had the least (7.46). Eucalyptus pollen had the highest total antioxidant activity (67.02%), followed by clover (58.25%) and maize (52.18%). Clover pollen had the highest phenolic content (1165 mg GAE/100 gm). Branch-chain amino acids made up 17.87, 18.44, and 16.53% of total amino acids in maize, eucalyptus, and clover at 29, 33.3, and 38.4 mg/g. Maize, eucalyptus, and clover pollen had 61.8, 73.0, and 83.5 mg/g EAAs. Only eucalyptus pollen met adult EAA minimums. Leucine, lysine, phenylalanine, and valine were present in at least 3–4 limiting quantities in the other two pollen types. Finally, pollen is a cheap source of nutrients that can be used as health supplements.

This study stated by Bayram *et al.,* 2021 identified 23 phenolic compounds and 42 free amino acids (FAAs) in bee pollen (BP) and bee bread (BB) samples from the same beehive using LC–MS/MS. Rutin was the most common phenolic compound in BP and BB samples. However, protocatechuic acid, 2,5-dihydroxybenzoic acid, and kaempferol molecules were considerably greater in BB samples than BP samples from the same hive, likely due to microbial activity and glycoside breakdown. Sample phenolic profiles vary by product kind and geography, according to the data. Proline was the most abundant FAA in all BP and BB samples, followed by l-asparagine and l-aspartic acid. High proline levels indicate sample freshness. PCA and cluster analysis showed that phlorizin could be a chemotaxonomic marker for Rosaceae (Malus or Prunus genus) pollen in BP1 sample. Amino acid profile exhibited a greater impact on BP and BB sample distinction due to reduced FAAs concentration in BB samples, likely induced by microbial activity We believe this is the first study to compare the phenolic compounds and free amino acids of bee pollen and bee bread samples from the same botanical families (Asteraceae, Fabaceae, Plantaginaceae, and Rosaceae).

When examining honey bee diet, pollen quantity and quality for floral visitors must be considered. Pollen value should be determined by measuring the insect's hemolymph protein and amino acid content. Pollen also contains lipids, sterols, and biogenic elements like carbon and nitrogen. At 51%, aloe pollen has substantial protein content. Rapeseed and phacelia have 27% protein in Europe. Buckwheat is a low-protein plant (11%). The above plants are sown widely. Invasive pollen- and nectar-producing plants like goldenrod cover large areas in Central and Eastern Europe. Unfortunately, bees must eat only one food source, which causes malnutrition. In the absence of natural pollen, beekeepers feed bees soy protein, powdered milk, egg yolks, fish meal, etc. The colony is strongest when bees are given pollen instead of artificial protein. Bee pollen content and nutrition, as indicated by protein concentration and amino acid composition in apian hemolymph, colony strength, honey yield, and overwintering, need further study (Bryś, M. S., & Strachecka, A. 2024).

According Vanderplanck *et al.,* 2014 bee larvae and imagos only eat flowers, but host-plant ranges vary. Unlike oligolectic species, polylectic bees like bumblebees collect pollen from multiple host plant groupings. We know little about how chemicals and chemical combinations affect bee growth and eating behaviour in polylectic species with interspecific variation in host-plant essential nutrients. We tested five pollen diets (Calluna vulgaris, Cistus sp., Cytisus scoparius, Salix caprea, and Sorbus aucuparia) to determine how chemical composition influences bumblebee colony formation and pollen/syrup Pollen contained polypeptides, amino acids, and sterols. Number and weight of larvae (total and mean weight), pollen weight, pollen efficacy (total larvae divided by pollen weight), and syrup collection were used to quantify microcolony nutrition. Pollen collection is steady, while syrup collection changes with pollen diet chemical variance. Micro-colonies fed S. aucuparia and C. scoparius pollen fed less nectar and produced larger larvae (better mates and winter survivors). Both species produce 24-methylenecholesterol and high polypeptide/total amino acid pollen. Thus, this pollen nutritional “theme” may improve B. terrestris micro-colony worker reproduction and queenright colony fitness. Since workers prefer high-quality pollen, flowers may have evolved to attract and boost the fidelity of generalist pollinators like bumblebees.

Pandit *et al.,* 2025 stated that honey bee (*Apis mellifera*) pollinate onion seeds. Pollinator foraging and seed production depend on pollen and nectar biochemistry. Few biochemical features

of short-day Indian onion cultivars that affect bee visitation and pollination are recognised. The biochemistry of pollen and nectar in short-day Indian onion varieties is examined to evaluate their role in bee pollination. We analyse nectar sugar, amino acid profiles, total phenols, antioxidants, and onion bee pollination. Field surveys measured flower visits, while LC-MS/MS and spectrophotometry examined nectar and pollen biochemistry. The onion cultivar 'Bhima Super' scored highest in bee-friendliness, with high protein (391.8 mg/g), flavonoids (855.3 mg/g), and antioxidant activity (3.6 µg/g) in its pollen. B. super nectar had 83.6 mg/g protein, 9.7 mg/g flavonoids, and 40.53 mg/g carbohydrates. This biochemical content was lowest in 'Bhima Shweta' onions. 'Bhima Super' has the highest bee foraging rate (14.151 visits/min) and speed (6.703 flowers/min) matching its biochemistry. The cultivar 'Bhima Shakti' has a strong correlation between nectar sugar (43.8%), antioxidants (r = 0.682), and bee activity, with its pollen containing iron (0.520 µg/g), zinc (0.75 µg/g), and manganese (0.37 µg These findings suggest strong links between pollen and nectar biochemistry and bee eating. The short-day India onion cultivar pollen and nectar study suggests new onion seed production managed pollination methods.

Pollinator nutritional ecology illuminates plant–pollinator relationships, coevolution, and pollinator population restoration. Pollen provides protein and fat nutrients for larval growth, adult health, and reproduction in bees. We previously found that pollen protein to lipid ratios (P:L) influence bumble bee foraging preferences among pollen host-plant species and colony health and fitness. However, we are just beginning to integrate plant and bee P:L ratio data. We present over 80 plant species' protein and lipid contents and P:L values using a standard laboratory methodology and evaluate three bee species' pollen P:L ratios. We address the overall evolutionary, phenotypic, behavioural, and ecological tendencies in these P:L ratios that may influence plant–pollinator interactions and propose future research issues to further pollination nutritional ecology. Researchers exploring the nutritional determinants of plant–pollinator interactions and stakeholders creating planting programs to benefit pollinators might use this dataset (Vaudo *et al.,* 2020).

Carter et al. (2006) showed in different crops that EC changes the taste of nectar, which in turn influences how well pollination works and how many seeds are set. The electrical conductivity of nectar indicates the concentration of dissolved ions and minerals, which can affect the preferences of pollinators. Research indicates that nectar with moderate electrical conductivity

(EC) values is often more appealing to pollinators such as honey bees, whereas very high EC levels may discourage visitation owing to bitterness or osmotic stress.

The pH of nectar generally ranges between 4.0 and 8.0, influencing the solubility and stability of sugars and secondary metabolites. Research indicates that pollinators prefer nectar with near-neutral pH, as extreme acidity or alkalinity can reduce nectar attractiveness and alter microbial growth, which affects floral scent and nectar quality. In onion, varietal differences in nectar pH have been linked to variations in bee visitation rates and pollination success (Divija *et al.,* 2022).

Moisture content in nectar and pollen determines the fluidity and availability of these floral rewards. Nectar with excessively low moisture can crystallize, reducing accessibility to pollinators, whereas high moisture aids in nectar dilution and ease of ingestion. Pollen moisture also affects viability and germination rates, critical for effective fertilization and seed production (Roulston & Cane, 2000).

According to Waller, 1972 overall, optimal EC, near-neutral pH, and appropriate moisture content in nectar and pollen contribute to increased pollinator visitation frequency, longer foraging times, and higher pollinator abundance, culminating in improved seed set and yield. Variability in these parameters among onion cultivars has been documented to influence pollinator assemblages and reproductive success.

2.3 To Formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.

Bee attractants are influencing the worker bees towards flowers for potential pollination. They are non-toxic and eco-friendly which can be used in organic production of crops. They enhance pollination in terms of both qualitative and quantitative parameters and are more useful in enhancing quality food; hence enormous value of bees in doubling the income of farmers.

2.3.1 Onion

Hosamani *et al.* (2020) reported that spraying of cacambe (10 %) on onion umbels effectively increased the seed yield of onion with 930.44 seeds/ umbel, 885.28 kg/ ha yield, 4.19 g test weight. It was followed by jaggery solution (10 %) which recorded 913.67 seeds/ umbel, 879.22 kg/ ha of yield and 4.10 g test weight. Bee-Q (1.25%) and open pollination without any spray were next in

their effectiveness.

More *et al.* (2020) reported that spraying of jaggery solution (10 %) on onion umbels was found significantly superior in attracting a greater number of bees (*A. mellifera*) on first, third and fifth days of first spray with 12.68, 15.18 and 13.75 bees/ m^2/ 5 min, respectively. Similar kind of results were obtained on second and third spray with 13.57, 15.89 and 13.57 bees/ m^2/ 5 min on first, third and fifth days of second spray, respectively; while 14.11, 16.25 and 14.82 bees/ m^2/ 5 min on first, third and fifth days of third spray, respectively. The treatment of sugar solution at 10 per cent reported 8.93,11.61 and 10.18 bees/ m^2/ 5 min on first, third and fifth days of first spray, 9.46, 11.96 and 10.00 bees/ m^2/ 5 min on first, third and fifth days of second spray and 10.71, 12.68 and 11.61 00 bees/ m^2/ 5 min on first, third and fifth days of third spray, respectively.

Studies conducted by Kulkarni *et al.* (2017) revealed that spraying of jaggery and sugar solution @ 10 per cent on onion umbels attracted maximum number of *A. dorsata* (4.11 to 6.22 no of bees/ m^2/ min) up to three days after first spray followed by *A. florea* and *A. cerana.* After second spray, the effectiveness of attractants was

maximum at one day after spray at 50 per cent flowering. Sugar solution @ 5.0 per cent, jaggery solution @ 5.0 per cent, sugarcane juice @ 10 per cent and molasses @ 10 per cent were the next best treatment in attracting a greater number of bees.

Spraying of Bee Scent @ 2.5, 5 and 7.5 per cent on onion umbels proved equally good with respect to quantitative (1245, 1277, 1363 seeds/ umbel, 10.15, 10.16, 12.39 q seed yield/ ha, respectively) and qualitative parameters (Kumari *et al.*, 2017). The next best treatment was sugar solution (5 % and 10 %) with 1198, 1137 seeds/ umbel and 10.16 and 9.66 q/ ha of seed yield, respectively. Further, spraying jaggery solution 10 per cent and sugar solution 10 per cent on onion umbels attracted maximum number of *A. dorsata* up to three days after first spray and one day after second spray (Narendra, 2014). However, in case of *A. florea* maximum visitation was recorded up to fifth day after first spray and first day after second spray. The highest number of seeds/ umbel (935.47) was recorded in jaggery solution 10 per cent which increased yield by 40.95 and 94.27 per cent over open pollination (without spray) and caged condition (pollination without insects), respectively. The highest seed yield per hectare (994.51 kg/ ha) was recorded in plot sprayed with jaggery solution 10 per cent against open pollination (602.08 kg/ ha) which accounted for 65.17 and 114.8 per cent increase in the yield over open pollination and caged condition,

respectively.

Kalmath and Sattigi (2004) reported that spraying of cacambe @ 10 per cent and jaggery @ 10 per cent attracted maximum number of *A. dorasta* followed by *A. cerana* and *A. florea* up to 15 days after first and second spray. Cacambe (10 %) had significant influence on number of seeds/ umbel (968.96 seeds/ umbel) followed by jaggery solution (10 %) (951.50 seeds/ umbel). Also, seed yield was observed highest from cacambe (10 %) and jaggery solution (10 %) (911.88 kg/ ha and 907.50 kg/ ha, respectively) against 663.75 and 408.75 kg/ ha in open pollination without spray and crop caged without bees, respectively. The germination percentage of onion seeds was maximum with cacambe (93.33 %) followed by Bee-Q (90.00 %) and sugar solution (86.67 %), respectively.

According to Woyke (1980), spraying of attractants like citral, geraniol or anise at the concentration of 0.1 to 0.2 per cent attracted bees up to hundred meters which increased the bee visitation on onion umbels. Citral at 0.1 per cent reported 45 bees/ 10 of the row and geraniol at 0.1 per cent reported 42 bees/10 m of the row and thus citral and geraniol showed highest number of seeds in one head (878 and 459 g of seeds, respectively) followed by mass of seed in one head (23.41 % and 8.54 %, respectively).

2.3.2 Other Crops

Hanif *et al.* (2023) reported that spraying of jaggery solution (10 %) on cucumber recorded maximum yield with maximum number of fruits/ plant (8.87 ± 0.14), fruit length (26.02 ± 0.47 cm), fruit diameter (5.77 ± 0.02 cm), fruit weight (350.27 ± 0.09 g), number of seeds/ fruit (453.07 ± 4.98), yield/ ha (222.50 ± 4.78 q) and fruit set (69.74 ± 0.62 %) followed by sugar syrup (10 %) with 8.87 ± 0.14 fruits/ plant, 25.07 ± 0.18 cm fruit length, 5.60 ± 0.04 cm fruit diameter, 0.321 ± 0.01 kg fruit weight, 423.65 ± 1.97 seeds/ fruit, 190.00 ± 0.16 q/ ha of yield and 62.38 ± 0.68 per cent fruit set. Molasses (10 %), sugarcane juice (10 %) and fish waste were next in the order of effectiveness, respectively. The plants which were kept untreated failed to produce fruits with highest yield attributing characters thus, signifying the importance of attractants in enhancing production of cucumber.

Coriander crop sprayed with ocimum oil (0.1 %) attracted more number of bees (5.45 bees/ plant/ min) and exhibited significantly higher seeds/ umbel (16.00 seeds), seed yield (14.46 q/ha),

seed germination (82.67 %), seedling length (12.23 cm), seedling vigour index (1011) and seedling dry weight (0.013 mg). However, jaggery (15%) attracted 5.14 bees/ plant/ min with 15.33 seeds/ umbel, 13.75 q/ ha of seed yield, 79.67 per cent seed germination, 11.15 cm of seedling length, 889 seedling vigour index and 0.013 mg of seedling dry weight and was cost effective with highest B: C ratio compared to ocimum oil (Naik *et al.*, 2019).

Investigations of Manhare and Painkara (2018) demonstrated that spraying of honey solution (10 %) on buckwheat attracted the highest number of *A. cerana* with 6.17, 6.14, 4.54 and 3.45 bees/ m^2/ min at 1, 3, 5 and 7 DAS at 10 per cent flowering, respectively. Sugar solution @ 10 per cent and jaggery 10 per cent were also significant in attracting bees which attracted mean of 4.23 and 3.76 bees/ m^2/ min, respectively. The plot which received the bee attractants significantly increased the number of seed per cyme, number of seed per plant, seed yield per plot and seed yield per hectare.

Meena *et al.* (2018) reported that maximum yield of cumin was recorded in plots sprayed with 10 per cent jaggery solution (5.20 q/ ha) which was 42.88 per cent higher over the control and 1.07 and 2.04 per cent higher over open pollinated and bee pollinated plots.

Wankhede *et al.* (2018) reported that spray of 10 per cent jaggery solution on cucumber crop increased the number of fruits (19.20 fruits/ plant), number of seeds (283 seeds/ fruit), test weight (10.72 g/ fruit), total yield (69.55 q/ ha) and also opinioned that, 10 per cent jaggery solution found to be the best bee attractant followed by 5 per cent jaggery solution than open pollination and pollination without insects.

Manchare et al. 2020 observed an experiment titled “Studies on the role of rock bees as pollinators in seed production of bitter gourd (*Momordica charantia* L.)” was conducted at Mahatma Phule Krishi Vidyapeeth, Rahuri, during Rabi 2016. The study was designed as a randomized block experiment with nine treatments and three replications to evaluate the effect of various bee attractants on the foraging behavior of rock bees, particularly Apis dorsata, on bitter gourd flowers. Bee attractants were sprayed twice, first at 10% flowering and again at 50% flowering. Observations indicated that the foraging activity of Apis dorsata increased significantly one day after spraying, maintaining elevated activity levels up to five days after the first spray and up to seven days after the second spray. Among the attractants, honey solution (10%), jaggery solution (10%), and molasses solution (10%) effectively attracted the maximum

number of Apis dorsata during this period, demonstrating their potential in enhancing pollinator visitation and thereby possibly improving seed production in bitter gourd.

Chavan *et al.* (2016) documented that after first spray of bee attractants on lucerne, both Fruit Boost (8.23 bees/ m^2/ 5 min) and sugar solution were superior in enhancing bee visits. The plant-based attractants, *viz*. *S. densifolia*, *F. budrunga* and tuberose floral scented water as well as the pheromone based citral Z were on par with one another and were next in the order. A similar trend was also observed after second spray of bee attractants. The results of present investigation clearly showed that all the four indigenous bee attractants were significantly superior than control but second best to the commercial bee attractant.

Jayaramappa et al. (2011) evaluated the effects of various bee attractants—Bee-Q at 10, 12.5, and 15 g L^{-1}; Fruit Boost at 0.50, 0.75, and 1 mL L^{-1}; cinnamon leaf extract at 5%; tuberose floral scented water; and 10% sugar solution—on the foraging activity of Indian honeybees and yield parameters in open-pollinated ridge gourd (Luffa acutangula L.). Spraying Fruit Boost at 0.50 mL L^{-1} and Bee-Q at 12.5 g L^{-1} significantly enhanced bee foraging, resulting in higher fruit numbers per plant (19.00 and 17.00, respectively) compared to 10.66 fruits per plant in open-pollinated controls. Similarly, these treatments increased fruits per plot to 21.83 and 20.83, respectively, versus 15.68 in controls.

Pashte *et al.* (2015) reported that citral-a (10 µl/l) on sesamum was found to be a good attractant for *A. cerana* followed by citral-b (10 µl/l) and geraniol (10 µl/l). The effect of attractants sprayed remained up to the third day of spraying and gradually decreased. Similarly, citral-A (10 µl/ lit) was most effective in attracting *A. cerana* towards watermelon flowers. Highest fruit weight (6.62 kg), fruit length (50.78 cm), seed weight (22.87 g) and germination (88.59 %) were recorded from citral-A (10 µl/lit) sprayed plot (Kumar, 2013).

Srikanth *et al.* (2013) reported that the quantitative and qualitative yield parameters of bottle gourd such as fruit set (69.10 and 67.4 %), fruit weight (2.13 kg and 2.06 kg), fruit volume (2340 and 2817 ml), fruit length (47.30 cm and 47.29 cm), number of sound seeds (453 and 439), test weight (18.52 and 18.14 g), moisture (86.14 % and 85.97 %), ash content, TSS and germination percentage (85.80 % and 85.08 %) were maximum in open pollination with citral-a and citral-b (10 µl/ l) compared to open pollination without attractants and control.

Muddi (2012) reported that Fruit Boost sprayed niger crop recorded highest yield (1.43 q/ha) compared to citral Z, citral E (1.16 q/ha and 1.08 q/ha) and highest seedling vigour index (1200.82) as compared to *S. densifolia*, tuberose and cinnamon (1149.66 and 926.03), respectively.

Spraying of citral E at 1.0 per cent concentration on *Bt* and non- *Bt* cotton was effective in attracting a greater number of bees (2.25 to 3.25 and 2.17 to 3.17 bees/ 10 m^2/ 5 min, respectively) especially *A. dorasta* followed by *A. cerana* and *A. florea*. Bee attractants enhanced the yield parameters *viz.*, good opened bolls (8.37 to 9.56 and 7.18 to 8.25 %), seeds per boll (10.82 to 21.89 and 10.67 to 16.64 %), lint yield (5.80 to 7.83 % and 4.85 to 5.13), seed yield (11.60 to 14.02 and 7.63 to 11.84 %) and kapas yield (10.39 to 15.05 and 8.56 to 12.65 %) in *Bt* and non-*Bt* cotton, respectively (Pise, 2011).

Use of attractants like citral-a, citral-b and geraniol enhanced the benefits by showing improvements in yield parameters of sesame. Naik (2010) evaluated the indigenous bee attractants *viz*., citral E, citral Z, *F. budurunga* and *S. densifolia* in *Bt*- cotton. The result indicated that spraying of attractants (citral E, citral Z, *F. budurunga* and *S. densifolia*) resulted in good opened bolls (6.83 to 16.00 % increase over control), seeds per boll (7.76 to 17.14 %), lint yield (6.56 to 12.96 %), seed yield (5.80 to 13.33 %) and kapas yield (10.02 to 13.51 %), respectively (Vijaykumar, 2011).

Chandran (2009) reported that spraying of Fruit Boost significantly attracted higher number honeybees on sesame and niger flowers (2.12 to 4.23 and 10.18 to 15.35 bees/ 5 flowers/ min, on respective crops). Further, higher number of capsules/ plant (42.32 to 47.12 capsules/ plant), thousand seed weight (2.85 to 3.02 g) and seed yield (1.41 to 1.51 q/ha) was produced in the crop that received citral Z, citral E, Fruit Boost and sugar solution in sesame. Similarly, citral E, Fruit Boost, citral Z, *F. budrunga* and *S. densifolia* had greater effect in producing higher seed weight (4.64 to 4.08 g) and seed yield (0.89 to 1.01 q/ha) in niger.

Chandrashekar and Sattagi (2009) reported that spraying of bee attractants like jaggery solution at 10 per cent and cacambe at 10 per cent significantly increased both quantitative and qualitative yield parameters of radish. The spraying of cacambe and jaggery solution at 10 per cent attracted more number of *A. florea* constituting 42.20 per cent followed by *A. cerana (*27.60 %), *A. dorsata* (14.62 %) and other pollinators (15.57%) and thereby reported the higher number of seeds/ siliqua (7.40 seeds/ siliqua), seed yield (29.25 q/ ha) and test weight (13.66 g/1000 seeds).

Studies conducted by Srikanta (2008) revealed that bees preferred to spend as much as 30.83 sec/ bee on the sunflower crop sprayed with citral-E which was significantly superior to all the remaining treatments. This accounted for 97.75 per cent more time spent by bee than the unsprayed crop. The next preferred treatment was the crop treated with sugar solution (22.80 sec/ bee) which was at par with *F. budrunga* (18.89 sec/ bee). However, bee spent least time on the flower of unsprayed crop (15.59 sec/ bee). The number of seeds/ head was highest in *S. densifolia*, *F. budrunga* and citral- Z treated crop. Whereas, *S. densifolia* sprayed crop produced highest yield of 19.53 q/ ha but these bee attractants had no effect on seed weight, germination percentage and root length, shoot length and vigour index.

Patil (2007) documented that spray of cacambe 10 per cent, Bee-Q at 1.25 per cent, jaggery solution at 10 per cent and sugar solution at 10 per cent were found efficient in attracting more number of bees up to third day after first, second and third spray in cucumber. Whereas, their efficacy decreased at fifth day of first, second and third spray. Among all bee attractants, cacambe at 10 per cent (5.40 bees/ m^2/ 5 min) proved best in attracting higher number of bees. Jaggery 10 per cent and sugar solution 10 per cent were next best treatments in attracting more number of bees.

Narayanan and Gavigowda (2005) documented that foraging activity of bees was significantly higher (3.54 bees/ m^2/ 5 min) in gherkin on first day after the spray of sugar solution followed by second and third day (3.35 and 3.20 bees/ m^2/ 5 min, respectively). Whereas, the activity of bees on fourth day after spray was same as observed on the day before spray.

Malerbo-Souza *et al.* (2004) reported that spraying of Bee Here, citral, eugenol, geraniol and lemon grass extracts diluted in water effectively attracted more number of honeybees towards orange (*Citrus sinensis*) orchard. Orange fruit production was 35.30 per cent higher in case of orange flowers sprayed with Bee Here and also recorded highest fruit weight (180.2 g) than control (168.5 g).

Spraying of cacambe (10 %), jaggery (10 %) and Bee-Q (1.25 %) had significant influence in attracting more number of pollinators on cucumber flowers. Plots sprayed with cacambe (10 %) recorded significantly more number of fruits (15.61 fruits/ plant) over open pollination without spray and caged plot without bees (7.42 and 3.34 fruits/ plant, respectively). The open pollinated crop which received cacambe (10 %) recorded significantly least number of dropped fruit/ plant (0.76 fruits/ plant) and higher yield (41.52 kg/ plot) against open

pollination without spray and caged plot without bees (30.92 and 20.52 kg/plot), respectively. Thus, there was increase of 34.28 and 101.84 per cent increase in yield over open pollination without spray and caged plot without bees, respectively (Dinesh, 2003).

According to Viraktamath and Anagoudar (2002), two applications of Bee-Q, Bee-Here and sugar solution attracted more number of bees (4.01- 4.97 bees/ 5 flowers/ min) up to fifth day after first and second spray compared to unsprayed crop (3.25 to 3.59 bees/ 5 flowers/ min) on staminate and pistillate flowers of cucumber crop.

Kumar *et al.* (2000) reported that maximum bees (20.74 bees) were attracted to the sugar syrup sprayed sunflower crop followed by Bee-Q (18.10 bees). However, the trionic acid gave maximum seed set (82.31 seed/ head), thousand seed weight (76.78 g), yield (24.16 g/ha.) and oil content (39.87 %) and attracted maximum *A. dorsata* bees followed by *A. cerana* and *A. florea*, respectively. Similarly, highest seed yield of sesame was obtained from the crop sprayed with citral-Z (1.50 q/ha) and citral-E (1.41 q/ha) which were as good as Fruit Boost (1.51 q/ha) treated crop (Viraktamath and Patil, 1999). Thus, the per cent yield was enhanced from 48.42 to 58.94 per cent over the control. The crop sprayed with *F. badrunga* and *S. densifolia* produced next highest yield (1.22 and 1.21 q/ha, respectively).

2.3.3 Pomegranate juice, coconut water, Dates extract how they rich with Biochemical and physiochemical properties.

According to Singh, K. (2020) chemicals from fresh pomegranates were identified. The juice extracts have a lot of sugar, mostly fructose (about 7.27 g/100 ml) and glucose (about 8.11 g/100 ml). Potassium (351.26 mg/100g), magnesium (10.02), calcium (9.26), sodium (7.25), iron (0.15), zinc (0.10), copper (0.08), and manganese (0.04) are all minerals found in pulp. On a dry-weight basis (DW), juice proteins are roughly 7.95 g/l and dry pulp proteins are 24% (Kjeldhal tests). The dry weight of seed proteins is about 16.87%. Globulins (62.4 mg/g DW) and albumins (54.12 mg/g DW) are the main types of storage proteins. Glutelins (33.2 mg/g DW) and prolamins (18.08 mg/g DW) come next. The total amount of amino acids in seeds is 14.45 g/100 g DW. Glu, Arg, Asp, Leu, and Gly amino acids are all found in seeds. Essential amino acids make up an average of 33.54% of all amino acids. Most essential amino acids are substantially greater than what the FAO/WHO says adults need (but not what pre-schoolers need). Most other amino acids contain a little less than this. All of these data suggested that pomegranate may contain sugar, minerals, and protein as supplements for common diets.

Hybrid onion varieties outperformed open-pollinated (OP) varieties in plant height and leaf number but not in traits directly affecting marketable production such as percentage of seedstalks, pink root incidence, percentage of marketable yield, bulb size, or marketable bulb yield. The comparative trial conducted over two fall planting seasons (1997 and 1998) in southern New Mexico revealed that most OP varieties performed as well or better than most hybrid varieties in market-related traits (Elfalleh,*et al.*,2011).

Yong *et al.*, 2009 stated that coconut water (coconut liquid endosperm), with its many applications, is one of the world's most versatile natural product. This refreshing beverage is consumed worldwide as it is nutritious and beneficial for health. There is increasing scientific evidence that supports the role of coconut water in health and medicinal applications. Coconut water is traditionally used as a growth supplement in plant tissue culture/micropropagation. The wide applications of coconut water can be justified by its unique chemical composition of sugars, vitamins, minerals, amino acids and phytohormones. This review attempts to summarise and evaluate the chemical composition and biological properties of coconut water.

Coconut water is an old, natural drink that has become more and more popular in the international market over the past few years. Coconut water is a healthy and pleasant drink that people all over the world drink because of its health benefits. Different chemical parts that make it bioactive are important to the plant industry, biotechnology, and biomedical disciplines. Numerous research have investigated the biochemical composition, characteristics, and responses of coconut water. This chapter offers comprehensive information regarding significant constituents, including amino acids, antimicrobial peptides, aromatic compounds, electrolytes, enzymes, phytohormones, polyphenols, sugars, and vitamins, in addition to their properties and reactions, such as flavour, rancidity, turbidity, appearance/color, pH, and acidity. There are currently a lot of publications on the chemicals in coconut water, but there may still be those that aren't known that make it have special biological effects. A section gives details about the technological improvements that have been made to the instrumental methods of analysis. So, as detection methods get better, screening can get more thorough to find and identify new chemicals in coconut water that have medical significance (Rethinam, P., & Krishnakumar, V. 2022).

This study by Ajibogun, O. A., & Oboma, Y. I. (2013) offers an in-depth examination of the biochemical components of coconut water from Nigerian species, emphasising its abundant sugars, amino acids, minerals, and vitamins that enhance its nutritional and bioactive

characteristics. You can use this reference to back up parts of your research on natural bee attractants that can help with pollination by showing how rich coconut water is in biochemicals.

According to Abbasi Bastam *et al.,* 2022 this research aimed to determine the qualitative and quantitative features of Iranian commercial date palm (Phoenix dactylifera) fruit varieties. Research method: All biochemical and physicochemical parameters were tested on mature fruits of the same size without physical damage or insect or fungal infestations. Total phenolic and flavonoid chemicals were measured using modified Folin–Ciocalteu and aluminium chloride colorimetric methods. DPPH scavenging assay was utilised to evaluate the antioxidant. Results: 'Kabkab' had the longest and widest fruit, longest seeds, heaviest meat, highest flesh-to-seed ratio, highest total weight, and highest moisture % of all cultivars tested. Antioxidant activity (AA) values ranged from 57.29 ± 2.91 to 70.04 ± 0.91 for the 'Hamrawi' and 'Barhee' cultivars. Total phenolic compounds (TPC) concentration was highest in "Khadrawi-Ahwaz" (1103.76 ± 100.89 mg gallic acid/100 g FW) and lowest in "Deiry" (261.86 ± 44.48 mg/100 g FW Both ‘Berim’ (82.5%) and ‘Hamrawi’ (0.086%) had the highest soluble solid content (SSC) and titratable acidity (TA). Limits to research: No limits were found. Originality/Value: This study used date cultivars with higher TPC, TFC, and AA levels. In order, ‘Barhee,’ ‘Khadrawi-Ahwaz,’ and ‘Hamrawi’ had the most AA, TPC, and TFC.

One of the oldest Arabian Peninsula staples is the date palm tree (Phoenix dactylifera L.). This crop comes from Southern Asia and Africa. Many date tree pieces have been studied for nutritional and medicinal benefits. There have been many papers about the date tree, but none have examined its traditional applications, nutritional value, phytochemical profile, therapeutic characteristics, and functional food possibilities. This review rigorously examines the scientific literature to explain date fruit and its components' global traditional uses, nutritional value, and therapeutic characteristics. The 215 research were divided into traditional (26), nutritional (52), and medicinal (84). The articles included 33 in vitro, 35 in vivo, and 16 clinical. Date seeds inhibited E. coli and S. aureus. Date pollen with water improved fertility and hormones. Palm leaves' anti-hyperglycemic actions result from α-amylase and α-glucosidase inhibition. This investigation revealed the functional roles of all palm tree components and the bioactive chemicals' mechanisms of action, contrary to prior findings. Despite growing scientific evidence, few clinical trials have used date fruit and other plant parts to prove their health benefits. In conclusion, P. dactylifera is a promising medicinal plant that should be studied to prevent communicable and non-communicable disorders (Mahomoodally *et al.,* 2024).

Alkhoori *et al.*, 2022 stated that most Middle Eastern countries depend on date palm (Phoenix dactylifera L.) and its fruit, dates, which millions devour. Domestic farm animals eat date seeds, a date fruit processing waste product. Date seeds are rich in carbs, lipids, dietary fibre, and protein, as well as beneficial phenolic compounds. Date seeds are also ideal for food, cosmetics, and pharmaceutical supplements due to their rich chemical content. Date seed nutrition is the focus of this review. Given its potential as a nutritional therapeutic agent for chronic diseases, date seed chemicals' cytotoxicity against cancer cell lines, diabetes resistance, antioxidant, antibacterial, and anti-inflammatory properties will be discussed. Application of date seed powder and oil will be described

CHAPTER III

MATERIAL AND METHODS

The present investigation on "Effects of abiotic factors and indigenous bee attractant on Plant Pollinators Interaction in Onion" was carried out at Farm of Department of Entomology, ICAR- Directorate of Onion and Garlic Research, Rajgurunagar, Pune under the Memorandum of Umbrella between Lovely Professional University, Punjab, India and ICAR-Directorate of Onion and Garlic Research, Rajgurunagar, Pune during Late kharif-*Rabi* 2023-24 and 2024-25. The laboratory work on pollen and nectar analysis of collected onion samples was conducted at ICAR-DOGR, Rajgurunagar, Pune, Maharashtra, India. The materials used and methodology adopted during the course of investigation are described in this chapter under the following subheadings.

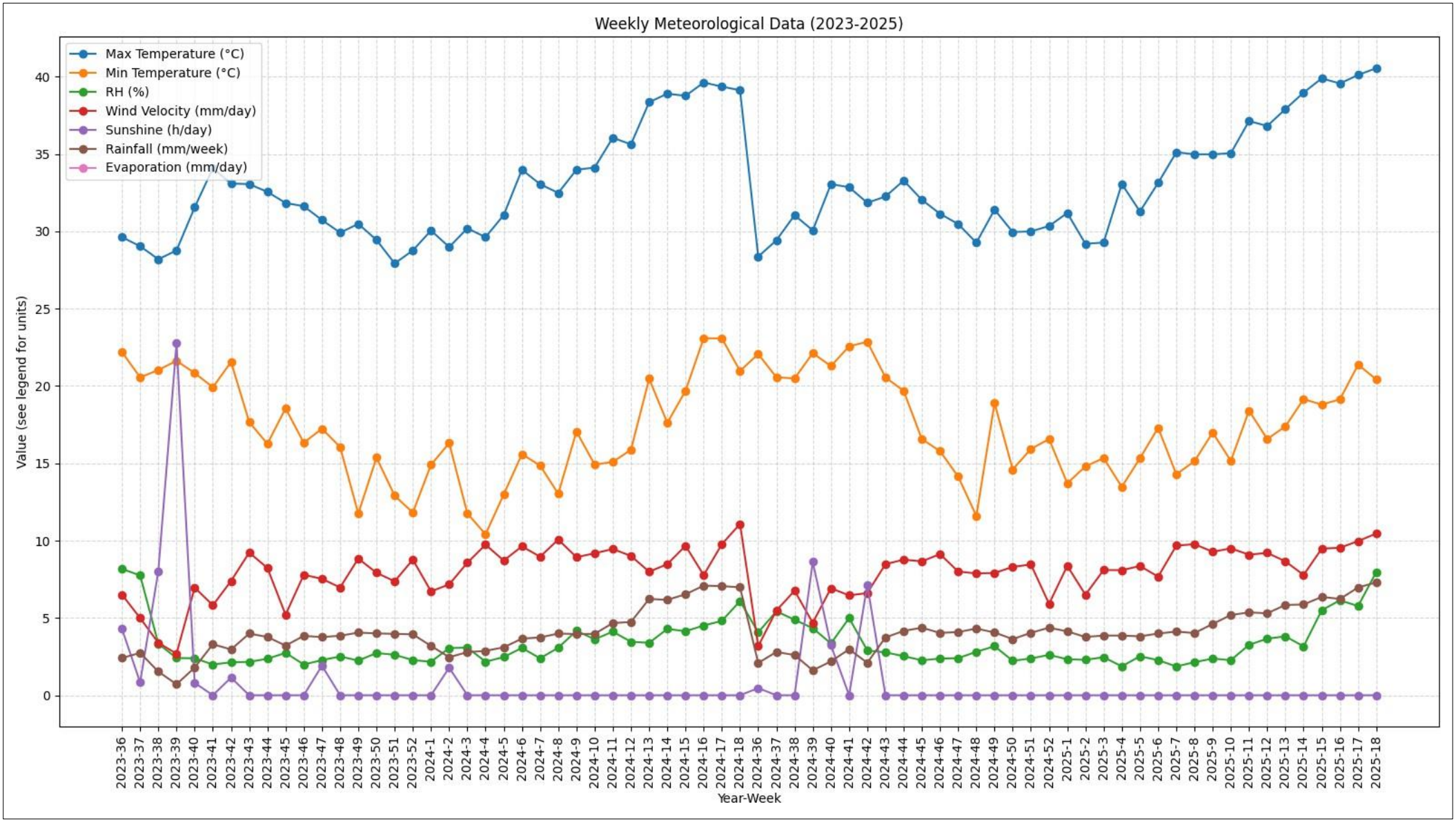
3.1 Geographical Location

The experiment was conducted at ICAR- Directorate of Onion and Garlic Research, Rajgurunagar, Pune. Geographically, the place is situated between Latitude 18.841149^{o} Longitudes 73.885954^{o} .

3.2 Climate

The Directorate of Onion and Garlic Research (ICAR-DOGR) is in Maharashtra, India, near Pune. It is in the hot semi-arid agro-ecological zone that is typical of the Deccan Plateau. In the summer, temperatures often go beyond 40°C in April and May. In the winter, temperatures might drop to 8–12°C between November and February. The average temperature over the course of a year is usually between 25 and 27 degrees Celsius. The average amount of rain that falls each year is between 600 and 700 mm, with most of it falling during the southwest monsoon season from June to September. During the hot summer months, the relative humidity in the area can drop below 30%, but during the monsoon season, it can climb to 80% to 90%. The soils surrounding DOGR are mostly medium to deep black cotton soils (Vertisols) with a lot of clay. These soils are typical of the Deccan plateau and are great for growing onions and garlic. Because of the weather and soil conditions, DOGR can do trials in both the rabi (winter) and kharif (monsoon) seasons. This makes it a great place to study onion and garlic types that can handle heat and drought.

Fig.1: Weekly meteorological data of experimental site of Onion during the period from 5th Sept 2023 to 5th May 2024- 5th Sept 2024 to 5 May 2025.



3.3 Materials

3.3.1 Honeybee colonies

Colonies of *Apis cerana*, *Apis mellifera*, and *Tetragonula iridipennis* of uniform and sufficient strength were procured from the Agricultural Farm of ICAR-DOGR, Rajgurunagar, Pune. The strength of each colony was assessed based on adult bee population, brood area, and food reserves before being placed in the experimental plots. These colonies were then used as active pollinator units to evaluate their foraging activity, visitation rate, and contribution to onion seed production under different treatments.

The details on various bee attractants *viz*., original fruits used in the experimentation are furnished in Table 1.

Table 1. Details on source of experiment materials

Sl. No.	Name of the bee attractant	Source
1.	Pomegranate	Directly from the farmer field
2.	Coconut water	Directly from the farmer field
3.	Dates	From Wild areas

3.3.2 Laboratory materials

3.3.2.1 Laboratory instruments

Biochemical and elemental determinations were carried out at ICAR-DOGR, Rajgurunagar, Pune. Micronutrient and elemental analyses were conducted using an Atomic Absorption Spectrophotometer (Shimadzu, Japan). Samples were processed using a high-volume refrigerated centrifuge (Eppendorf, Germany) and a microcentrifuge (Eppendorf, Germany). Sample mixing and homogenisation were achieved using a vortex mixer (Spinix, Tarsons, India). Sample masses were measured on an electronic balance (Sartorius / Mettler Toledo, Germany). Reagents and biological samples were preserved in a deep freezer (Thermo Scientific, USA) and standard refrigeration, while culture media were sterilized in a vertical autoclave (Equitron Medica, India)

3.3.2.2 Glassware and tubes

The borosilicate glassware, polypropylene centrifuge tubes with HDPE blue screw caps of 50mL and 15mL, test tubes, eppendorf tubes, conical flasks, beakers of various capacities, volumetric flasks, measuring cylinders of 100, 200, 500, and 1000 mL capacity, and a pipette (10 mL capacity) used in the experiment were provided by ICAR-DOGR, Rajgurunagar, Pune, Maharashtra, India.

3.3.2.3 Cleaning and sterilization of glassware

Before using, each piece of glassware was washed with soap and then sterilised in a solution of 1% formalin. Then, they were cleaned by washing them with a detergent soap solution, rinsing them many times in tap water, and finally in distilled water. Finally, the For sterilisation, glassware was autoclaved at 121ºC and 15 lbs of pressure for 20 minutes.

3.3.2.4 Chemical reagent

HPLC and colorimetric analyses measure amino acids, lipids, carbohydrates, proteins, phenols, antioxidants, flavonoids, and minerals in nectar and pollen samples using specific chemical reagents. Sample derivatisation with FMOC-Cl (9-fluorenylmethoxycarbonyl chloride), PITC (phenyl isothiocyanate), OPA (o-phthaldialdehyde), and dansyl chloride in acetonitrile, methanol, and buffers is required for amino acid profiling. Lipid analysis solvents include hexane, chloroform, methanol, and acetonitrile. Mobile phases usually contain ammonium acetate or formate. Total sugar is found using the phenol-sulfuric acid method, and reducing sugars like glucose are found using DNSA (3,5-dinitrosalicylic acid). Protein can be estimated using copper sulphate and Folin–Ciocalteu reagent or Coomassie Brilliant Blue dye in the Lowry or Bradford methods. For phenolics, Folin–Ciocalteu and sodium carbonate are standard. Use DPPH, ABTS, or FRAP to measure antioxidant activity. Some flavonoids are tested with sodium nitrite, hydroxide, or aluminium chloride. Calibrated pH and conductivity meters are needed to monitor pH and EC. Drying something in the oven without chemicals can reveal its moisture content. Iron and zinc mineral profiling entails digesting a sample in water with strong acids like nitric, perchloric, or sulphuric acid. After finding the minerals with colorimetric reagents like 1,10-phenanthroline for iron or Zincon for zinc etc, atomic absorption spectrophotometry is used to confirm the results.

3.3.2.5 Other materials

Plastic bottles for honey sample collection were purchased from the local market. Test tube stands, tissue paper, plastic vials etc. were made available in the ICAR-DOGR, Rajgurunagar, Pune, Maharashtra, India.

3.4 Methods

3.4.1 To investigate the impact of abiotic variations on the onion pollinators on different dates of planting.

3.4.1.1 Raising of the crop

The onion seed crop was raised by sowing the bulbs of onion *var*. Bhima Shakti at spacing of 20 cm x 10 cm over an area of experimental plot during late kharif season of the year 2023

to 2025. All the packages of practices and plant protection practices recommended by ICAR-DOGR, Rajgurunagar, Pune were adopted for raising the crop.

Crop	□	Onion (A. cepa)
Variety	□	Bhima Shakti
Plot size	□	700 Sq.m
Treatment	□	7
Bulb rate	□	42 kg onion
Spacing	□	20 cm x 10 cm
Date of sowing	□	7 dates of planting from
Fertilizer dose	□	N: P: K @ 7: 3.5: 3.5 kg
Season	□	Late kharif to Rabi 2023–24 and 2024–25
Location	□	ICAR-DOGR, Rajgurunagar

Field layout

	Field Border			
	R I	**R II**	**R III**	
Experimental Plot N ↕	T1 05-09-2023	T7 05-12-2023	T4 20-10-2023	
	T2 20-09-2023	T6 20-11-2023	T5 05-11-2023	
	T3 05-10-2023	T1 05-09-2023	T7 05-12-2023	**Farm Road**
	T4 20-10-2023	T2 20-09-2023	T6 20-11-2023	
	T5 05-11-2023	T3 05-10-2023	T1 05-09-2023	
	T6 20-11-2023	T4 20-10-2023	T2 20-09-2023	
	T7 05-12-2023	T5 05-11-2023	T3 05-10-2023	
	Field Border			

Fig 2. Layout of field experiment on impact of abiotic variations on the pollinators on different dates of planting.

3.4.1.2 Method of recording species diversity of pollinators

A total of 700 sq.m area of onion field was selected and the observations pertaining to insect flower visitors and their diversity on onion flowers were recorded once a week starting from 46th standard metrological week (SMW) to 14th SMW during late-kharif to Rabi 2023-2024 and 2024-2025 Flower-visiting insect populations were recorded using randomly selected 1m^2 quadrats in the experimental plot for 1 hr intervals throughout the flowering period following standard sampling protocols (Dafni, 1992; Free, 1993).

Using graphical, interactive, and dichotomous keys, the hymenopterans were morphologically identified using the literature of Goulet and Huber (1993) and Seltmann

(2004). On the other hand, the pictorial, linear, and dichotomous taxonomic keys created by Marshall et al. (2017) and Buck et al. (2009) were used to identify the adult dipterans. For the identification of lepidopterans, however, Stanley et al. (2018) technical report on Almora butterflies was consulted. In order to identify the coleopterans, Halim et al. (2017) was consulted. Furthermore, entomologists who specialise in insect taxonomy in ICAR-DOGR itself Dr. Soumia P. S. and Dr. Karuppaiah V. confirmed the species' identification. Accurate data about the range of species found and their corresponding frequencies on onion blossoms were then provided.

3.4.1.3 Percent forage visit

In comparison to the total number of individuals of all the species, the percent forage visit gives information on the percentage of the selected species that engage in foraging activity on a particular bloom or plant. Consequently, the following formula can be used to determine the percentage of foraging visits by a certain species of flower visitor:

The formula in your image for percentage forage visit (%) is:

$$\text{Percent forage visit (\%)} = \frac{\text{Number of individuals of a particular species}}{\text{Total number of individuals of all the species}} \times 100$$

3.4.1.4 Impact of abiotic variations on the onion pollinators on different date of planting.

An experiment was conducted during *Late-kharif* to *Rabi* 2023-24 and 2024-25 at the ICAR-DOGR, Rajgurunagar, Pune, Maharashtra to study the impact of abiotic variations on the onion pollinators especially honeybees *viz.*, *A. florea*, *A. cerana*, *A. mellifera*, *A. dorsata* and *T. iridipennis* at the peak period of day in between 12 pm to 2 pm afternoon when pollinators are more active. The experiment was conducted in replicated randomized block design by referring to different honeybee species as and SMW of observation on different dates of planting as treatment and mean values of forage honeybees of each SMW was correlated with the weather parameters.

The weather data such as Temperature minimum and maximum, Relative humidity minimum and maximum, Velocity (km/hr.), Sunshine (hr.), Rainfall (mm), Evaporation (mm). The pollinator assemblage data correlated with weather data and each planting date.

3.4.1.4.1 Abundance of floral visitors

The abundance of floral visitors refers to the number of individuals of each bee species that visit per unit area per unit of time. The studies included *A. florea*, *A. cerana*, *A. mellifera*, *A. dorsata* and *T. iridipennis*. An area of 1m×1m was chosen by quadrant method and the

observations were taken on the bee visitation for five min by constantly watching the forager bees as long as possible and the observation means were expressed as the number of bees/ m^2/ 5 min. The data on the abundance of floral visitors was calculated in three different ways *i.e.*, cumulative abundance by averaging all the values starting from the first day of observation till the last day, abundance on peak period of a day. Abundance on data regarding the abundance of each honey bee species at different date of planting observations on different SMW (46^{th} - 14^{th} SMW) was correlated with Temperature (minimum and maximum), Relative humidity (minimum and maximum), Velocity (km/hr.), Sunshine (hr.), Rainfall (mm), Evaporation (mm) whereas, aiming to ascertain the precise relationships among all the variables.

3.4.1.4.2 Umbel visitation rate

Umbel visitation rate is the number of umbels visited by a single bee in a given amount of time. By carefully studying the forager bees of each species *A. florea, A. cerana, A. mellifera, A. dorsata,* and *T. iridipennis* 1 m × 1 m region was selected using the quadrant approach, and the corresponding parameter was noted. Each type of forager bee species that were chosen were identified and monitored for as long as possible in relation to the number of umbels visited. The average data was then converted to umbels visited per minute (umbels/bee/min).

3.4.1.4.3 Statistical analysis

To know the efficient pollinator in onion ecosystem, the data recorded on various abiotic variations on abundance and visitation rate was statistically analysed by using techniques of analysis of variance for randomized block design and subjected to change of scale transformation. The significance was tested by 'F' test and the level of significance used in the 'F' test was p = 0.05. Critical difference values were calculated whenever 'F' test was significant.

Standard error for observation means:

$$\text{SEm}\,(\pm) = \sqrt{\frac{\text{EMS}}{r}}$$

Where:

- EMS = Error mean square (sum of squares)
- *r*= Number of replications

Critical Difference (CD):

$$\text{CD} = \text{SEm}\,(\pm) \times t_{(5\%)} \text{ at error df}$$

Where:

- SEm (±) = Standard error of mean
- $t_{(5\%)}$= t value at 5% significance for error degrees of freedom (df)
- df = degrees of freedom

Treatment significance was tested by 'F' test. If 'F' test showed the significant difference between the treatments mean values, the critical difference (CD) at 5 per cent level of significance was computed. All the data obtained will be subjected to an analysis of variance (ANOVA). The means will separate by Duncan's New Multiple Range Test (DMRT) (Gomez and Gomez 1984). For all statistical analysis and correlation and regression analysis SPSS version 22.0 will be used.

3.4.2 To study the role of varietal traits on abundance, foraging behaviour of insect pollinators (*A. mellifera*).

In this study, seven popular onion cultivars developed by ICAR-DOGR, Rajgurunagar, were cultivated in separate open-field plots to evaluate their response under natural pollination conditions. Managed colonies of *Apis mellifera* (honey bees) were strategically placed near each variety when approximately 25% of the umbels had initiated flowering. This timing ensured an adequate number of blossoms to attract foraging bees and promote effective cross-pollination. Introducing the bee colonies at the onset of major bloom synchronized peak foraging activity with maximum stigma receptivity, thereby enhancing seed set and quality while minimizing flower wastage and allowing for a reliable comparison of pollination efficiency among the different onion cultivars under uniform field conditions.

Crop	□	Onion (*A. cepa*)
Variety	□	7 different varieties
Plot size	□	500 Sq.m (Total: 1.29 acres)
Treatment	□	7
Replication	□	3
Design	□	RBD
Bulb rate	□	6–7 q/ha (350 Kg bulb required)
Spacing	□	20 cm x 10 cm

Date of sowing	□	20/10/2023-24
Fertilizer dose	□	N: P: K @ 100: 50: 50 kg/ha
Season	□	Rabi to Rabi 2023–24 and 2024–25
Location	□	ICAR-DOGR, Rajgurunagar

Field layout:

Fig 3. Layout of field experiment on role of varietal traits on abundance behaviors of insect pollinators.

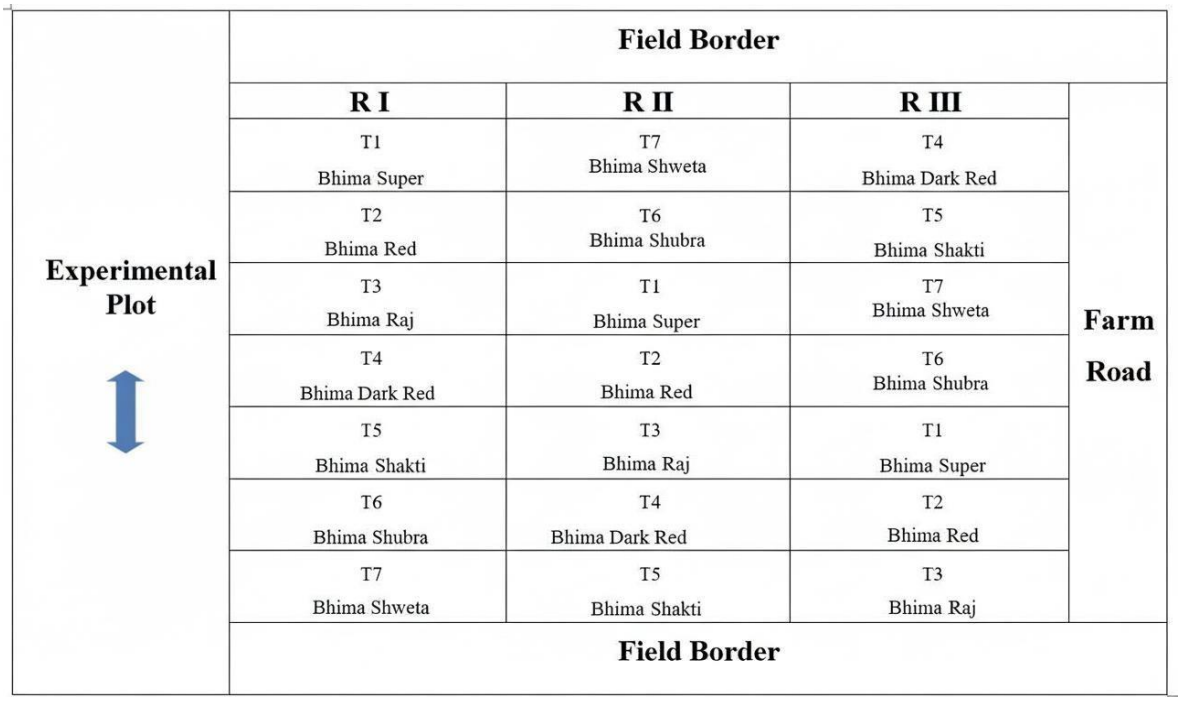


Table 2. Details of ICAR-DOGR onion varieties

Varieties	Season	Days to Maturity	Yield Potential (t/ha)
Bhima Super	Late Kharif	110–120 days	40–45
Bhima Red	Late Kharif	110–120 days	45–50
Bhima Raj	Late Kharif	115–120 days	40–45
Bhima Dark Red	Kharif	100–110 days	22–24
Bhima Shakti	Late Kharif	125–135 days	35–40
Bhima Shubra	Kharif	120–130 days	36–42
Bhima Shweta	Kharif	110–120 days	18–20

3.4.2.1 Morphological parameters

Morphological observations in onions, such as number of umbels per plant, scape length, and umbel diameter, are critical for evaluating growth, varietal performance, and seed

yield potential. These traits are typically measured at specific intervals after planting (e.g., 45, 55, 65, and 75 days) using standardized techniques randomly selected 5 plant and field instruments to ensure accuracy and reliability in research settings.

3.4.2.1.1 Number of Umbels

Counting is performed manually by inspecting randomly selected 5 plant and recording the number of umbels present at each time point and record in a datasheet.

3.4.2.1.2 Scape Length

A measuring a meter scale (graduated in centimeters or millimeters) is used to measure from the base of the plant (soil surface) to the point where the umbel starts by randomly selecting 5 plants in each variety.

3.4.2.1.3 Umbel Diameter

Digital Vernier callipers is used to measure the maximum diameter of the umbel by randomly selecting 5 plants in each variety, typically across its widest point when the umbel is fully expanded or at a predetermined growth stage (e.g., 45- or 55-days post-planting).

3.4.2.2 Influence of *Apis mellifera* on Abundance, Foraging Behavior among Onion (*Allium cepa* L.) Varieties.

3.4.2.2.1 Foraging rate of *A. mellifera* on different onion varieties.

The foraging rate defined as the number of individual flowers visited by a worker bee per minute—was evaluated to determine variations across different onion cultivars, diurnal time intervals, and flowering phenophases. Systematic field observations were conducted over two consecutive cropping seasons (*Rabi* 2023–24 and 2024–25) during the peak flowering periods, with data recorded weekly from January 20 to March 9 in both 2024 and 2025. To capture diurnal activity patterns, foraging observations were performed at six designated time intervals throughout the day: 8:00 AM, 10:00 AM, 12:00 PM, 2:00 PM, 4:00 PM, and 6:00 PM. Sampling was executed using a randomized quadrat method by establishing $1m^2$ observation frames within each experimental plot (Dafni, 1992). Individual *A. mellifera* foragers actively visiting umbels within the marked quadrat were tracked continuously for a period of 60 seconds using a digital stopwatch (Free, 1993). The total number of open flowers visited by a single bee within one minute was recorded. To minimize observational bias and account for individual worker behavior, multiple distinct umbels and individual bees were observed per treatment plot at each time step (Vaissière et al., 2011).

3.4.2.2.2 Foraging speed of *A. mellifera* on different onion varieties.

The foraging speed of Apis mellifera, measured as the duration a single bee spends on an onion blossom, was rigorously documented at weekly intervals from January 20 to March 9 in both 2024 and 2025. Using a timer, observations were made at six different periods of the day: 8:00 am, 10:00 am, 12:00 pm, 2:00 pm, 4:00 pm, and 6:00 pm. The stopwatch was started right away when a honey bee landed on a flower in a randomly chosen 1 m × 1 m observation area. It was stopped as soon as the bee left the bloom. The recorded duration, given in seconds, shows how fast the bee is foraging, or how long it spends actively looking for food on that bloom. This value gives an idea of how long each forager spends on average per flower, which can show how well pollination is working. The observations are essential for comprehending the temporal dynamics of bee foraging behaviour and have been extensively utilised in apiculture and pollination ecology research as a dependable means to assess foraging activity and flower contact duration.

3.4.2.3 Methodology for Collection of Pollen and Nectar samples

3.4.2.3.1 Collection of Floral Nectar

Nectar sampling was performed during peak floral secretion hours (between 08:00 AM and 12:00 AM) on sunny, windless days by using two different techniques.

Extraction Technique: Nectar was harvested directly from individual florets using fine glass microcapillary tubes (0.5 μL to 5 μL volume; Drummond Scientific, USA) inserted carefully at the base of the ovary/septal nectaries without damaging floral tissues.

Centrifugation Extraction: For low-volume florets, 10–12 freshly detached florets per cultivar were placed base-down into modified 1.5 mL microcentrifuge tubes fitted with a mesh filter inlay. Samples were centrifuged at 1,400 rpm for 5 minutes to pool pure nectar at the bottom of the tube.

Storage: Extracted nectar was immediately transferred into sterile 0.5 mL microcentrifuge tubes, measured for volume using a digital micropipette, flash-frozen, and stored at -80^{o}C until biochemical analysis.

3.4.2.3.2 Collection of Pollen Grains

Direct Anther Harvesting: Dehiscing anthers were excised from mature, unpollinated florets using fine micro-forceps and placed into sterile glass vials/Petri dishes.

By using Pollen Traps: The pollen traps utilized a specialized stripping grid (4.7-5.0 mm opening size) installed across the hive entrance. As foraging worker bees returned to the

colony, passing through the grid dislodged the packed pollen loads from their hind-leg corbiculae. The dislodged pollen pellets fell into a protected, ventilated collection tray below the entrance (Duff and Furgala, 1986). Traps were activated exclusively during peak foraging hours (08:00 AM to 12:00 AM) during the main flowering period (*Rabi* 2023–24 and 2024–25) to prevent nutritional disruption to the brood.

Storage: The sorted onion pollen samples were sealed in sterile microcentrifuge tubes and stored at -20^{o}C for subsequent biochemical testing.

3.4.2.4 Physio-chemical and Biochemical Composition of Onion (*Allium cepa* L.) varieties of Pollen and Nectar.

Varied types of onions have varied biochemical makeups in their nectar and pollen, which affects how attractive they are to pollinators and how well they produce seeds. For the varieties studied, T1 (Bhima Super), T2 (Bhima Red), T3 (Bhima Raj), T4 (Bhima Dark red), T5 (Bhima Shakti), T6 (Bhima Shubra), and T7 (Bhima Shweta), each parameter, including pH, electrical conductivity (EC), moisture content, protein concentration, total phenolic content, flavonoid content, antioxidant capacity, and essential minerals such as copper, iron, manganese, and zinc, were quantitatively analysed to evaluate their nutritional and biochemical profiles. The pH levels of different types of plants usually show slightly acidic to neutral conditions that are good for pollinators, while the EC values show how many dissolved ions are present, which is important for determining nectar quality. The moisture content affects how fluid the nectar is and how long the pollen lasts, and this varies between cultivars. Pollinators need protein to stay healthy, and more of it makes them more active while they search for food. Phenolic and flavonoid chemicals, recognised for their antioxidant characteristics, play a role in floral fragrance and defence, which differ among kinds. Antioxidant capacity, quantified in ascorbic acid equivalents, elucidates the metabolic defences of flora. Minerals including copper, iron, manganese, and zinc are important micronutrients that affect the quality of pollen and, in turn, the health of pollinators. Also, carbohydrate profile showed that the different types had different amounts of total sugar and particular sugars including glucose, fructose, and sucrose. These sugars are important sources of energy for pollinators. Amino acids are important biological parts that change the nutritional value of pollen and nectar, which in turn changes how pollinators search for food and their health. Lipid components can affect how appealing pollen is to pollinators and how good it is for them. In general, these quantitative biochemical measures show differences between varieties that could be used to improve pollination and increase onion seed production.

3.4.2.4.1 pH

The process for measuring pH, which involves dissolving 1 gm of sample in 9 millilitres of distilled water, stirring in a 10 ml beaker, and using a calibrated pH meter, comes directly from the IHC Harmonised Methods (Hadhramie *et al.*, 2023).

3.4.2.4.2 EC

The International Honey Commission's standardised techniques also include the electrical conductivity (EC) test, which involves dissolving 1 gm of sample in 9 millilitres of distilled water, stirring it in a 10 ml beaker, and letting it settle for two hours before measuring it (Yadata, D. 2014).

3.4.2.4.3 Moisture

The oven-drying gravimetric method, which is often used for honey and bee products, can be used to find out how much moisture is in pollen or nectar samples. In this method, a sample with a known weight (typically 3–5 gm) is put in a crucible that has already been weighed and dried in a hot air oven at 100–105°C for 8 hours or until the weight stays the same. The crucible is weighed from time to time, and the moisture content is figured out by taking the difference in weight and dividing it by the starting weight of the sample as a percentage. This approach is mentioned in papers like Melo et al. (2011), which looked at oven drying, hoover drying, and other ways to figure out how much moisture is in pollen. It is also mentioned in standard food analysis references like AOAC 969.38 and FSSAI guidelines for honey and bee products.

Moisture content(%) = {Loss in weight (gm) ÷ Weight of sample (gm)} × 100

3.4.2.4.4 Total Antioxidant

The Ferric Reducing Antioxidant Power (FRAP) test can be used to find out how much antioxidant power a sample has. To make the FRAP reagent, mix acetate buffer, 2,4,6-tripyridyl-S-triazine (TPTZ), and ferric chloride in a 10:1:1 ratio. To make a hydrochloric acid solution, dissolve 0.0332 g of HCl in 10 ml of distilled water. To make an ascorbic acid standard, dissolve 0.2 g in 100 ml of distilled water. Add the sample or standard to 3 ml tubes, and then move 200 µl from each tube to an ELISA plate well. A plate reader measures

absorbance at 593 nm, and the antioxidant capacity for a 1 g sample is figured out using the standard curve. This methodology adheres to established FRAP methodologies, including those by Benzie and Strain (1996), as well as protocols found in peer-reviewed literature and commercial assay kits, detailing reagent ratios, wavelength selection, and the use of the ELISA plate (Vijayalakshmi, M., & Ruckmani, K. 2016).

3.4.2.4.5 Total Protein

The Bradford protein assay can be used to figure out how much protein is in a sample. It works by employing acidic conditions to make Coomassie Brilliant Blue dye stick to proteins. To prepare the sample, combine 5 ml of it with 5 ml of distilled water to make a total of 10 ml. To make a calibration curve, a bovine serum albumin (BSA) standard solution is made with a concentration of 1 mg/ml. The Bradford reagent is used to incubate the sample and standards at room temperature for 10 minutes so that the colour can develop. After that, 200 µl of each reaction mixture is put into the wells of a 96-well microplate. A microplate reader measures the absorbance at 595 nm. After that, the protein concentration of the sample is found by comparing the absorbance values to those of the BSA standards. This approach is based on Bradford's (1976) original work and is extensively used since it is simple and sensitive for measuring proteins (Kruger, N. J. 2009).

3.4.2.4.6 Total Phenol

A common way to figure out how much phenolic are in pollen, honey, or nectar samples is to use methanol and water in a 1:1 volume ratio as the solvent. Start by mixing one gramme of the sample and extracting it with the methanol-water mix. After extraction, the solvent is heated to 60°C for four hours to remove the phenolic chemicals. After that, the extract is mixed with sterile distilled water and kept in the fridge until it is time to analyse it. Add 0.5 ml of the produced sample extract to a tube for the test. Then, add 2.5 ml of 1N Folin-Ciocalteu reagent and 0.5 ml of 4% sodium carbonate (Na_2CO_3). Use gallic acid as a reference and a spectrophotometer to measure the absorbance at 750 nm after mixing. The total phenolic content is shown in gallic acid equivalents (GAE), which are found by using the standard curve. This procedure is based on the well-known Folin-Ciocalteu method, which is known for being accurate and dependable when it comes to measuring phenolics in honey, pollen, and nectar samples (Noreen *et al.*, 2017).

3.4.2.4.7 Total Flavonoid

In order to find out how much flavonoid is in pollen or nectar using the aluminium chloride colorimetric method, you need to follow these steps: Weigh 1 g of pollen or nectar very carefully and mix it with 10 ml of 80% methanol. Shake the mixture for one to two hours at room temperature, then filter it to get the extract. Put 0.5 ml of this extract into a test tube, then add 0.1 ml of a 10% aluminium chloride solution, then 0.1 ml of a 1 M potassium acetate solution, and finally 4.3 ml of distilled water. Let the reaction mixture sit at room temperature for 30 minutes. Use a UV-Vis spectrophotometer to measure the absorbance at 415 nm after incubation. Use quercetin standard solutions to make a calibration curve, and then report the total flavonoid concentration as milligrammes of quercetin equivalents per gramme of sample (mg QE/g). This method is well-known and often used in analytical literature to measure the amount of flavonoids in pollen and nectar samples (Sembiring *et al.*, 2018).

3.4.2.4.8 Minerals

To find out how much Fe, Mn, Zn, and Cu are in pollen or nectar using atomic absorption spectrophotometry (AAS), you first need to weigh 1 gramme of the sample and heat it in a water bath at 65°C. Then, a digestion mixture of 12 ml (9 ml concentrated nitric acid and 3 ml hydrogen peroxide) is used to oxidise and break down organic materials. The whole mixture is cooked on a hot plate at 200°C until red NO_2 gases come out and the sample shrinks to 3–5 ml of liquid. However, care is given to make sure it doesn't dry up totally. After it cools down, 10 cc of distilled water is added to dissolve the leftover material. After that, Whatman No.1 filter paper is used to filter the solution to get rid of any particles. Lastly, distilled water is used to dilute the filtrate to a final amount of 50 ml. Mineral concentrations are determined by aspirating the clear solution into an atomic absorption spectrophotometer (such as the Parkin Elmar Analyst 200), and readings are interpreted using the calibration curves for each mineral. The formula used to figure out the quantitative results is:

Concentration (mg/kg) = {(Reading × 100) ÷ 1(sample in gram)} × (50 ÷ volume before filter)

3.4.2.4.9 Total sugar

The Anthrone method, which is a well-known colorimetric test, is often used to figure out how much sugar is in samples of pollen, honey, or nectar. Start by weighing 100 mg of the sample and breaking it down into simple sugars by hydrolysing it in 5 ml of 2.5N hydrochloric acid in a boiling water bath for three hours. After hydrolysis, let the mixture cool, then add solid sodium carbonate to neutralise it. Finally, add distilled water to make a total of 100 ml.

To make the colour, mix 1 ml of the prepared sample solution with 2 ml of newly made anthrone reagent (2 g of anthrone diluted in 1 L of 75% sulphuric acid). Put the mixture in an incubator and use a spectrophotometer to measure the absorbance at 630 nm. A standard curve is made with glucose as the standard. This lets you figure out how much sugar is in the sample. This method is quite similar to the changes made by Hedge and Hofreiter (1962) and is well explained in protocols and books about using the anthrone method to measure carbohydrates (Tidke, J. A., & Nagarkar, S. S. 2015).

3.4.2.4.10 Glucose, Sucrose, and Fructose

To estimate individual sugars like glucose, sucrose, and fructose in pollen or nectar, an iodometric titration method can be applied as illustrated above. First, weigh 2 grams of the sample and transfer it to a 250 ml volumetric flask, making up to volume with distilled water (Mixwell). Take an aliquot of 25 ml and place into a 250 ml iodine flask. Add 50 ml of 0.1N iodine, 50 ml of 0.2N sodium carbonate, and 50 ml of 0.2N sodium bicarbonate, then allow the mixture to stand in the dark for 2 hours. Acidify with 12 ml of 25% sulfuric acid and titrate with standard sodium thiosulphate using starch as an indicator. Perform a blank determination alongside the sample and subtract the blank titre from the sample titre for calculations (Qian *et al.*, 2008).

For calculation:

$$\text{Glucose (\%)} = \frac{\text{Normality of thiosulphate} \times \text{dilution} \times (B - S) \times 0.009005 \times 100}{0.1N \times \text{Weight of sample}}$$

Where,

B is the titre for blank and S is the titre for sample.

Fructose % = Reducing sugars % − Glucose %

Fructose: Glucose ratio = Fructose % ÷ Glucose %

3.4.2.4.11 Determination of Amino acids

Determination of amino acid by two different methods use paper chromatography and LCMS/MS to find out pollen, nectar samples contain amino acids. Paper chromatography this is based on the method published by Hossain (2012). To make the sample extract, the pollen or nectar sample is first treated with 0.2M acetic acid for five minutes. Then, it is centrifuged to remove the supernatant, which is where the amino acids are. Then, using a glass capillary

tube, spots of the clear extract are put on Whatman No.1 filter paper. The chromatogram is developed using an eluant mixture composed of n-butanol, acetic acid, and water in an 80:20:20 (v/v) ratio, which effectively separates amino acids. When the solvent front reaches the right height, the chromatogram is air-dried and sprayed with 0.1% ninhydrin in acetone. It is then heated at 110ºC for five minutes to show the amino acids as coloured spots. To identify the spots, the retention factor (Rf) values are calculated and compared to conventional Rf values for recognised amino acids. While the paper chromatography ninhydrin method offers a quick and cost-effective approach for visualizing amino acids in natural samples, it has limitations including poor sensitivity, lack of specificity (reacting with ammonia and other primary amines), inconsistent color development, and potential interferences that can lead to inaccurate quantification (Elgubbi, H. S., & Mlitan, A. M. 2015). Advanced alternatives such as high-performance liquid chromatography (HPLC) with pre-column derivatization (e.g., using o-phthalaldehyde or 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate), mass spectrometry-coupled methods (LC-MS/MS), or modified ninhydrin protocols with stannous chloride provide superior accuracy, sensitivity (down to 0.01-1.0 µg), and individual amino acid identification. These techniques are particularly valuable for precise estimation in complex biological matrices like nectar and pollen.

The estimation of amino acids by LCMS/MS can be performed under the following specified conditions. The analysis utilizes a Shim-pack Velox C18 column (1.8 µm particle size, 2.1 x 50 mm dimension) maintained at 40°C. The mobile phase consists of solvent A (0.1% formic acid in water) and solvent B (100% acetonitrile), delivered at a flow rate of 0.3 mL/min. The injection volume is set to 10 µL, and the sample run time is 5 minutes in ESI negative ionization mode. Important instrument settings include a nebulizing gas flow of 3 L/min, heating gas flow of 10 L/min, drying gas flow of 10 L/min, interface temperature of 300°C, desolvation temperature of 526°C, DL temperature of 250°C, and heat block temperature of 400°C. The analysis is performed using a gradient program detailed in the table below, with initial conditions of 90% A and 10% B held for 2 minutes, ramping to 15% A and 85% B at 3 minutes and maintained for 1 minute, before returning to starting conditions for equilibration (Ohtsuki *et al.,* 1987)

Table 3. Analysis of amino acid details of gradient program

Step	Time (Min)	Flow Rate (mL/min)	% A	% B	Max Pressure (Bar)
1	Initial	0.3	90	10	1000
2	2	0.3	90	10	1000
3	3	0.3	15	85	1000
4	4	0.3	15	85	1000
5	4.5	0.3	90	10	1000
6	5	0.3	90	10	1000

3.4.3 To formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.

Crop	□	Onion (A. cepa)
Variety	□	Bhima Shakti
Plot size	□	25 Sq.m (Total: 750 Sq.m)
Treatment	□	10
Replication	□	3 (30 plots)
Design	□	RBD
Bulb rate	□	6–7 q/ha (Total: 50 Kg bulb required)
Spacing	□	20 cm x 10 cm
Date of sowing	□	05/11/2023 (first year) & 05/11/2024 (second year)
Fertilizer dose	□	N: P: K @ 100: 50: 50 kg/ha
Season	□	Rabi to Rabi 2023–24 and 2024–25
Location	□	ICAR-DOGR, Rajgurunagar

Filed Layout

Experimental Plot	Field Border			
	R I	**R II**	**R III**	
	T1 Coconut water 10%	T10 Control	T4 Coconut water 15%	
	T2 Pomegranate juice 10%	T9 Dates extract 20%	T8 Pomegranate juice 20%	
	T3 Dates extract 10%	T5 Pomegranate juice 15%	T1 Coconut water 10%	
N	T4 Coconut water 15%	T6 Dates extract 15%	T7 Coconut water 20%	
	T5 Pomegranate juice 15%	T8 Pomegranate juice 20%	T2 Pomegranate juice 10%	**Farm Road**
	T6 Dates extract 15%	T3 Dates extract 10%	T9 Dates extract 20%	
	T7 Coconut water 20%	T2 Pomegranate juice 10%	T10 Control	
	T8 Pomegranate juice 20%	T1 Coconut water 10%	T3 Dates extract 10%	
	T9 Dates extract 20%	T7 Coconut water 20%	T5 Pomegranate juice 15%	
	T10 Control	T4 Coconut water 15%	T6 Dates extract 15%	
	Field Border			

Fig 4. Layout of the experiment to formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.

3.4.3.1 Observations recorded

The observations were recorded on various parameters including the abundance of each bee species *viz.*, *A. florea*, *A. cerana*, *A. mellifera*, *A. dorsata* and *T. iridipennis* with respect to each treatment, various qualitative and quantitative parameters including the number of umbels/ plant, per cent flower set (%), seed weight/ umbel (g), seed yield (kg/ha), test weight of 1000 seeds (g), germination test (%), ICBR and B: C ratio were extrapolated.

Table 4. Details of treatments

Tr. No	Treatments	Concentration (%)
T1	Coconut water	10%
T2	Pomegranate juice	10%
T3	Dates extract	10%
T4	Coconut water	15%
T5	Pomegranate juice	15%
T6	Dates extract	15%
T7	Coconut water	20%
T8	Pomegranate juice	20%
T9	Dates extract	20%
T10	Control	

3.4.3.1.1 Honeybees activity

Observations on the number of individuals of each honey bee species (*A. florea, A. cerana, A. mellifera, A. dorsata, and T. iridipennis*) visiting per square metre area in a five-minute interval were recorded from each treatment plot. A total of five observations on the visitation of each bee pollinator were recorded in a day at two-hour intervals beginning at 9.00 a.m. and ending at 18.00 p.m. Observations will be recorded by randomly selecting one square meter area from each plot. The attractants will be sprayed two times, first at 10% and second at 50% flowering stages. The crop was protected from various pests and diseases, but no insecticides were used during the flowering period. All chemical spray treatments were applied in the early morning at 06:00 AM. The foraging rate expressed as the number of flower visits per minute by various honeybee species was recorded during the peak flowering period. Observations were documented one day prior to the first and second spray applications, as well as on the 1st, 3rd, 5th, and 7th days following each spray treatment (Dafni, 1992; Vaissière et al., 2011).

3.4.3.1.2 Number of umbels/plants

At the time of harvest, the total number of umbels/ plant was counted manually from five randomly selected plants of all the replications of each treatment and the mean value was expressed as the total number of umbels/ plants.

3.4.3.1.3 Per cent seed set (%)

During harvest, the total number of flowers and seed set flowers were counted manually and individually from five randomly chosen umbels of all the
The replications of each treatment and the percent flower set were computed using the following formula.

Here is the extracted formula from your image, formatted in LaTeX:

$$\text{Percent flower set (\%)} = \frac{\text{Number of seed set flowers per umbel}}{\text{Total number of flowers per umbel}} \times 100$$

3.4.3.1.4 Seed weight/ umbel (g)

After the crops were ripe and the seeds were set, five umbels were randomly taken from each treatment's replications. The seeds were then removed from each umbel by thrashing, cleaning, and drying. Later, the seeds from each umbel were weighed, and the average weight was given in gm per umbel.

3.4.3.1.5 Seed yield (kg/ ha)

The seeds that were collected from the umbels of each of the four replications of each treatment were utilised independently to figure out the seed yield (kg/ha). We used a weighing balance to record the seed weight of each replication, and then we expressed the average value of all the replications of each treatment in kilogrammes per plot. The seed yield from each plot was then changed to kg/ha.

3.4.3.1.6 Test weight (weight of 1000 seeds in g)

After the crops were ready to be harvested and the seeds were set correctly, the umbels from each treatment were picked, and the seeds were washed and dried. Later, one thousand seeds were counted by hand, and an electric balance was used to weigh the seeds from each treatment and write down the weight in grammes.

3.4.3.1.7 Germination test (%)

The germination test for individual treatment was executed in four replicates of one hundred seeds, following ISTA guidelines (Anon., 2014), utilising the 'above paper method' in a seed germinator maintained at 27.6°C and 80.0% relative humidity. The final germination count based on normal seedlings was done on the fourteenth day of the germination test. The mean figure was given as the percentage of seed germination for each treatment.

The standard formula for the germination test percentage is:

$$\text{Germination (\%)} = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds tested}} \times 100$$

3.4.3.1.8 ICBR

The incremental cost-benefit ratio (ICBR) refers to a financial metric that evaluates the additional costs incurred in treatment (Appendix V) compared to the additional benefits gained (Vladica, 2018). ICBR can be calculated by using the following formula,

$$\text{ICBR} = \frac{\text{Incremental benefit}}{\text{Incremental costs}}$$

Where,

Incremental benefits = Additional benefits gained from the treatment compared to untreated control.

Incremental costs = Additional costs incurred from the treatment compared to untreated

control.

3.4.3.1.9 Benefit: Cost ratio

The Benefit-Cost ratio (B: C ratio) is a way to figure out how profitable a treatment is. It looks at how much the treatment costs and how much it saves in the current. The gross returns were based on the amount of onion seeds that each treatment produced. In addition, the treatment cost, total cost, and net income were calculated and projected on a per-hectare basis. The B: C ratio for each treatment was figured by using the formula below (Akila and Babu, 1994).

$$\text{B: C ratio} = \text{Total present value of benefits} \div \text{Total present value of costs}$$

Where,

Total present value of benefits= The sum of the discounted value of all positive outcomes, returns, or benefits generated by the treatments.

Total present value of costs= The sum of the discounted value of all costs associated with the treatment over its lifetime.

3.4.3.1.10 Statistical analysis

We used analysis of variance for randomised block design and change of scale transformation to statistically analyse the data we recorded on different yield parameters. The "F" test was used to check for significance, with a level of significance of p = 0.05. Whenever the "F" test was significant, we calculated critical difference values.

Standard error for observation means

Formula for the standard error of the mean (SEm) is:

$$\text{SEm } (\pm) = \sqrt{\frac{\text{EMS}}{r}}$$

where

- EMS = Error mean square
- r= number of replications

Critical difference (CD)

The accurate formula for Critical Difference (CD) based on your image is:

$$CD = SEm\ (\pm) \times t_{(5\%)} \text{ at error df}$$

Where:

- SeM (±) = Standard error of mean
- $t_{(5\%)}$= t-value at the 5% significance level for the given error degrees of freedom (df)

The 'F' test was used to see how important treatment was. If the ‘F’ test indicated a significant difference between the treatments mean values, critical difference (CD) at 5 per cent level of significance was computed.

CHAPTER IV

RESULT AND DISCUSSION

The present investigation entitled “Effects of abiotic factors and indigenous bee attractant on plant pollinators Interaction in Onion” was carried out during Rabi 2023-24 and Rabi 2024-25 at ICAR- Directorate of Onion and Garlic Research, Rajgurunagar, Pune, Maharashtra, India. The results obtained during the investigations have been presented and discussed in this chapter with appropriate case studies.

4.1 To investigate the impact of abiotic variations on the onion pollinators on different dates of planting.

This study aimed to evaluate the impact of abiotic factors on pollinator dynamics across different sowing dates. Key environmental variables including ambient temperature, relative humidity, light intensity, and precipitation were monitored throughout the flowering phase of onion crops planted on various dates. Furthermore, investigating the species diversity and temporal abundance of flower visitors across these staggered planting windows provides critical insights for optimizing pollinator management and maximizing onion seed production. These abiotic conditions affect the feeding behaviour, population, and variety of pollinators such as honey bees and native bees on onion umbels. Data about pollinator visitation rates, pollen and nectar availability, and seed set are gathered and correlated with abiotic variables throughout planting dates to comprehend how temporal climatic changes influence pollinator activity and efficiency. This aids in identifying optimal planting schedules and management strategies to enhance pollination and seed yield under diverse environmental conditions.

4.1.1 Diversity and abundance of flower visitors of onion.

The observations recorded on the diversity and abundance of flower visitors are presented in the Table 5.

4.1.1.1 First year

The findings indicated that during the late kharif-Rabi season of the first year 2023–24, a total of 3151 unique pollinators were recorded within the onion flower visitation group. The insect visitors frequented the flowers for both pollen and nectar, causing no detrimental effect to the blooms or the onion plant. The floral visitors primarily consisted of the orders Hymenoptera, Lepidoptera, and Diptera, with the least representation from Coleoptera. The species exhibited constant activity and predominantly engaged in visiting onion blossoms,

proving to be good pollinators.

Of the thirty recorded species, thirteen floral visitors were classified within four families of Hymenoptera. Among all hymenopteran flower visitors, *A. mellifera* was the predominant species, accounting for 40.25 % of forage visits, followed by *T. iridipennis* at 17.50%, *A. dorsata* at 7.30%, *A. cerana* at 3.44%, *A. florea* at 1.67%, *Xylocopa latipes* at 0.64%, *Xylocopa* spp. at 0.50%, and *Amegilla* spp. at 0.32%, all belonging to the Apidae family. The hymenoptera community comprised *Oecophylla smaragdina* (0.26% forage visits) and *Monomorium* spp. (0.45% forage visits) from Formicidae, *Delta conoideum* (0.50% forage visits) and *Vespa tropica* (0.44% forage visits) from Vespidae, and *Lasioglossum coriaceum* (0.23% forage visits) from Halictidae.

The subsequent dominant order was Lepidoptera, comprising seven species from five distinct families. The species identified include *Eurema hacabe* (1.74% forage visits) and *Delias eucharis* (0.18% forage visits) from Pieridae, followed by *Danaus chrysippus* (0.95% forage visits) and *Acraea terpsicore* (0.32% forage visits) from Nymphalidae, *Rapala manae* (1.08% forage visits) from Lycaenidae, *Borbo cinnara* (0.91% forage visits) from Hesperiidae, and *Utetheisa pulchella* (0.38% forage visits) from Arctidae. The order Coleoptera was the least dominant, with two species of coccinellids (Coccinellidae) that visited onion flowers: *Coccinella transversalis* (0.59% of forage visits) and *Cheilomenes sexmaculatus* (0.47% of forage visits).

The subsequent order in the onion field was Diptera. It had eight distinct species from five separate families. *Sphaerophoria* spp. were the predominant species, accounting for 6.83% of foraging visits. The subsequent predominant species included *Eristalis aeneus* (1.55% forage visits), *Ischiodon scutellaris* (1.06% forage visits), and *Asarkina* spp. (0.59% forage visits) from Syrphidae; *Stomorhina* spp. (1.88% forage visits) from Rhiniidae; *Musca domestica* (1.73% forage visits) from Muscidae; *Lucilia serricata* (1.29% forage visits) from Calliphoridae; and *Tabanus* spp. (0.18% forage visits) from Tabanidae.

4.1.1.2 Second year

A comparable trend in the diversity and number of floral visitors was noted during Rabi 2024-25. The flower-visiting community has a total of 3430 individuals from thirty species across four orders. The species primarily comprised Hymenoptera at 76.79%, followed by Diptera at 16.79%, Lepidoptera at 5.76%, and Coleoptera at 0.66%.

Of the 30 recorded species, 13 floral visitors were classified within 4 families of

Hymenoptera. *A. mellifera* was the predominant flower visitor, accounting for 44.03 % of forage visits, followed by *T. iridipennis* at 19.68 percent, *A. dorsata* at 7.41 percent, *A. cerana* at 4.19 percent, *A. florea* at 2.05 percent, *Xylocopa latipes* at 0.82 percent, *Xylocopa* spp. at 0.63 percent, and Amegilla spp. at 0.44 percent, all belonging to the Apidae family. The hymenopteran community comprised *Oecophylla smaragdina* (0.28% forage visits) and *Monomorium* spp. (0.41% forage visits) from Formicidae, *Delta conoideum* (0.66% forage visits) and *Vespa tropica* (0.47% forage visits) from Vespidae, and *Lasioglossum coriaceum* (0.25% forage visits) from Halictidae.

The subsequent dominant order was Lepidoptera, comprising seven species from five distinct families. The species comprised *Eurema hacabe* (1.82% forage visits) and *Delias eucharis* (0.22% forage visits) from Pieridae, followed by *Danaus chrysippus* (0.97% forage visits) and *Acraea terpsicore* (0.32% forage visits) from Nymphalidae, *Rapala manae* (1.17% forage visits) from Lycaenidae, *Borbo cinnara* (0.98% forage visits) from Hesperiidae, and *Utetheisa pulchella* (0.38% forage visits) from Arctidae. The order Coleoptera was the least dominant, comprising two species of *coccinellids* (Coccinellidae) that visited onion flowers: *Coccinella transversalis* (0.73% of forage visits) and *Cheilomenes sexmaculatus* (0.66% of forage visits).

The subsequent order in the onion field was Diptera. It had eight distinct species from five separate families. Sphaerophoria spp. was the predominant species, accounting for 7.00% of foraging visits. The subsequent predominant species included *Eristalis aeneus* (1.77% forage visits), *Ischiodon scutellaris* (1.14% forage visits), and *Asarkina* spp. (0.66% forage visits) from Syrphidae; *Stomorhina* spp. (2.21% forage visits) from Rhiniidae; *Musca domestica* (1.77% forage visits) from Muscidae; *Lucilia serricata* (1.47% forage visits) from Calliphoridae; and *Tabanus* spp. (0.22% forage visits) from Tabanidae.

The present investigation indicated that 30 distinct insect species frequently visited onion flowers, perhaps due to their rich pollen and nectar (Free, 1993). The number of species identified as flower visitors was significantly lower than in previous studies (Divija *et al.,* 2022; Paschapur *et al.,* 2022; Tchindebe *et al.,* 2021), possibly due to land-use changes leading to habitat loss and fragmentation (Steffan-Dewenter *et al.,* 2002; Hendrickx *et al.,* 2007; Winfree *et al.,* 2009; Goulson *et al.,* 2008), increased pesticide application, environmental pollution (Kevan *et al.,* 1997; Rortais *et al.,* 2005), and climate change (Williams *et al.,* 2007; Dormann *et al.,* 2008). The floral visitor assemblage was dominated by Hymenoptera (78.42%), followed by Diptera (16.33%), Lepidoptera (5.67%), and Coleoptera (0.56%). The dominance

of Hymenoptera can be attributed to the morphological and behavioural adaptations that coevolved in bees with flowering plants (Kiester *et al.,* 1984) and the provision of pollen and nectar from flowers as sustenance for foragers (Faegri and Van der Pijl, 1971; Proctor and Yeo, 1973). Honey bees, syrphid flies, butterflies, halictid bees, coccinellid beetles, and other insects that visited onion blooms played a big role in pollinating them and making seeds. The results are in line with those of (Divija *et al.,* 2022; Paschapur *et al.,* 2022; Korichi *et al.,* 2021 Tachindebe *et al.,* 2021; Hosamani *et al.,* 2019; Montes, 2019 and Biradar *et al.,* 2017), who found that hymenopteran, dipteran, lepidopteran, and coleopteran orders were good visitors and pollinators of onion flowers. (Devi *et al.,* 2014) reported a similar trend in occurrence frequency, with hymenopterans as the primary pollinators, followed by lepidopterans, dipterans, and coleopterans. The order Diptera was the most common at 30%, followed by Hymenoptera at 21%, Lepidoptera and Coleoptera at 14%, Hemiptera at 7%, and Neuroptera and Thysanoptera.

Among the diverse insect visitor species, honey bees comprised the vast majority of overall foraging activity, representing 78.42% of total visits. The other floral visitors made up the other 21.58% of the trips. *A. mellifera* was the the dominant species was followed by *T. iridipennis, A. dorsata, A. cerana,* and *A. florea*. Honeybees are common in onion fields because of their body size, specialised mechanisms for collecting nectar and pollen, natural abundance (Calderone, 2012), interactions with plants that help them, and their attraction to nectar and pollen sources (Shin *et al.,* 2019). The present results are consistent with the findings of (Divija *et al.,* 2022; Paschapur *et al.,* 2022 and Karuppaiah *et al.,* 2018), who recognised honey bees as the principal floral visitors of onion. Korichi *et al.,* 2021) reported that all insect foragers on onion (*Allium cepa*) flowers belonged to the Apoidea superfamily, namely within the Apidae and Halictidae families of Hymenoptera. According to a study by (Hosamani *et al.,* 2019), four species of honey bees from the Apidae family (*A. dorsata, A. mellifera, A. cerana, and A. florea)* were the most important pollinators. Onions provided both pollen and nectar for this group. (Abrol, 2010) determined *A. florea* to be the principal floral visitor within the onion environment. The extra hymenopteran species were *Xylocopa* spp., *X. latipes*, *Amegilla* spp., *O. smaragdina*, *Monomorium* spp., *D. conoideum*, *V. tropica*, and *L. coriaceum*, which didn't come by very often.

Sl. No	Order	Family	Species	No. of individuals		% forage visits		
				2023-24	2024-25	2023-24	2024-25	Mean
1	Hymenoptera	Apidae	*Apis mellifera*	1276	1502	40.25	44.03	42.14%
2			*Apis cerana*	109	143	3.44	4.19	3.82%
3			*Apis florea*	57	65	1.67	2.05	1.86%
4			*Tetragonula iridipennis*	597	624	17.50	19.68	18.59%
5			*Apis dorsata*	249	235	7.30	7.41	7.36%
6			*Xylocopa latipes*	22	26	0.64	0.82	0.73%
7			*Xylocopa spp.*	17	20	0.50	0.63	0.56%
8			*Amegilla spp.*	11	14	0.32	0.44	0.38%
9		Formicidae	*Oecophylla smaragdina*	9	9	0.26	0.28	0.27%
10			*Monomorium spp.*	16	13	0.45	0.41	0.44%
11		Halictidae	*Lasioglossum coriaceum*	8	8	0.23	0.25	0.24%
12		Vespidae	*Delta conoideum*	17	21	0.50	0.66	0.58%
13			*Vespa tropica*	15	15	0.44	0.47	0.45%
14	Lepidoptera	Erebidae	*Utetheisa pulchella*	13	12	0.38	0.38	0.38%
15		Hespiridae	*Borbo cinnara*	31	31	0.91	0.98	0.94%
16		Lycaenidae	*Rapala manae*	37	37	1.08	1.17	1.12%
17		Nymphhalidae	*Acraea terpsicore*	9	10	0.26	0.32	0.29%
18			*Danaus chrysippus*	33	30	0.95	0.97	0.96%
19		Pieridae	*Eurema hacabae*	62	55	1.74	1.82	1.78%
20			*Delias eucharis*	6	7	0.18	0.22	0.20%
21	Diptera	Tabanidae	*Tabanus spp.*	6	7	0.18	0.22	0.20%
22		Calliphoridae	*Lucilia serricata*	50	41	1.29	1.47	1.38%
23		Muscidae	*Musca domestica*	59	56	1.73	1.77	1.75%
24		Rhiniidae	*Stomorhina spp.*	64	70	1.88	2.21	2.04%
25		Syrphidae	*Sphaerophoria spp.*	23 3	222	6.83	7.00	6.92%
26			*Ischiodon scutellaris*	36	36	1.06	1.14	1.10%
27			*Asarkina spp.*	20	21	0.59	0.66	0.62%
28			*Eristalis aeneus*	53	56	1.55	1.77	1.66%
29	Coleoptera	Coccinellidae	*Coccinella transversalis*	20	23	0.59	0.73	0.66%
30			*Cheilomenes sexmaculatus*	16	21	0.47	0.66	0.56%

Table 05. Diversity and abundance of flower visitors on onion bloom (ICAR-DOGR, Pune)

Seven different kinds of lepidopteran insects came to the blooms. There were eight different species of dipteran flower visitors, most of which were syrphids. Adult syrphids frequently visit onion flowers because they need pollen and nectar for food and energy (Mahr, 2023). The results align with the findings of (Saeed *et al.,* 2008), who reported that 74% of the dipteran population belonged to the Syrphidae family. Plants increase their chances of attracting nectar foragers and, as a result, pollination by making more and better-quality flower nectar (Moquet *et al.,* 2017; Kavitha and Reddy, 2019). Dipteran and lepidopteran flower visitors are particularly attracted to nectar (Moquet *et al.,* 2017; Kavitha and Reddy, 2019), which leads them to visit onion flowers that are rich in nectar (Free, 1993). Still, there were just two species of floral visitors in the coleopteran order. The results align with the findings of Thakur and Kumaranag , 2016; Abrol, 2010 and Sajjad *et al.,* 2008) all of whom identified Diptera, Lepidoptera, and Coleoptera as visitors to onion flowers.

4.1.2 Impact of abiotic variations on the onion pollinators on different date of planting.

The abundance of floral visitors denotes the quantity of individuals from each bee species that visit a specific location within a designated time frame. The research encompassed A. *mellifera, A. dorsata, T. iridipennis, A. florea,* and *A. cerana* during the peak activity period from 12 pm to 2 pm, when pollinators are most active. A 1m x 1m area was selected using the quadrant approach, and observations of bee visitation were conducted for five minutes by continuously monitoring the forager bees. The results were quantified as the number of bees per square metre every five minutes. The data on the abundance of floral visitors was computed in three distinct manners: cumulative abundance by averaging all values from the first to the last day of observation, and abundance during the peak period of a day. An extensive dataset concerning the prevalence of various honey bee species across different planting dates during distinct Standard Meteorological Weeks (46^{th} – 14^{th} SMW) was analysed in relation to temperature (minimum and maximum), relative humidity (minimum and maximum), velocity (km/hr), sunshine (hours), rainfall (mm), and evaporation (mm), with the objective of elucidating the exact correlations among all variables.

4.1.2.1 First year

4.1.2.1.1 Abundance of onion umbel visitors (Honeybees) on crop grown on different seven dates of planting 2023-24.

The data recorded on activity of onion pollinators especially honeybees *viz., A. florea, A. cerana, A. mellifera, A. dorsata* and *T. iridipennis* at the peak period of day in between 12 pm to 2 pm afternoon when pollinators are more active.

4.1.2.1.1.1 Activity of umbel visitors (Honeybees) of onion during 1st planting date 5 September 2023.

Table 06. Activity of Honeybees on onion umbel at peak period of day during 1stplanting date (5 September 2023).

DOP: 05 /09/2023	**Standard Meteorological Weeks**							
Treatment (bees/ m^2/ 5 min)	**46th (2023)**	**47th (2023)**	**48th (2023)**	**49th (2023)**	**50th (2023)**	**51st (2023)**	**52nd (2023)**	**1st (2024)**
Apis mellifera	7.20^{a}	7.50^{a}	8.50^{a}	9.13^{a}	7.90^{a}	8.20^{a}	7.50^{a}	7.30^{a}
Apis dorsata	2.10^{c}	2.30^{c}	2.60^{c}	2.70^{cd}	2.90^{bc}	2.40^{c}	2.00^{bc}	1.90^{bc}
Apis florea	1.10^{c}	1.20^{c}	1.40^{c}	1.50^{d}	1.60^{c}	1.30^{c}	1.00^{c}	0.90^{c}
Apis cerana	4.70^{b}	4.90^{b}	5.30^{b}	5.50^{bc}	5.70^{ab}	5.10^{b}	4.50^{ab}	4.30^{ab}
Tetragonula iridipennis	5.90^{ab}	6.20^{ab}	6.80^{ab}	7.10^{ab}	7.40^{a}	6.50^{ab}	5.60^{a}	5.30^{a}
SE(m)	0.71	0.65	0.57	0.89	1.14	0.74	1.02	0.93
CD (0.05)	2.32	2.13	1.87	2.91	3.73	2.43	3.33	3.04
CV	29.36	25.57	20.15	29.78	38.82	27.43	42.88	40.94

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The average number of honeybee visitors per square metre every five minutes during the peak foraging period displayed considerable variation among bee species during the Standard Meteorological Weeks (SMW) from the 46th to the 1st of the subsequent year (Table 06). *A. mellifera* consistently exhibited the highest visitor rate during the flowering phase among the recorded species. The activity progressively rose from 7.20 bees/m²/5 min in the 46th SMW to a maximum of 9.13 bees/m²/5 min in the 49th SMW, aligning with the full-bloom phase of onion umbels. A further slow reduction was noted in the latter weeks, presumably because to diminishing floral rewards and heightened senescence of umbels. *A. cerana* and *T. iridipennis* demonstrated consistently elevated foraging activity throughout the bloom season. *T. iridipennis* reported 5.90 bees/m²/5 min on the 46th SMW and reached a maximum of 7.40 bees/m²/5 min in the 50th SMW. In a like manner, *A. cerana* during the same period, varied from 4.70 to 5.70 bees/m²/5 min. Their continual presence indicates tolerance to the moderate temperature and light intensity conditions typical of mid-morning hours, along with a pronounced affinity for onion nectar.

Conversely, *A. dorsata* and *A. florea* exhibited significantly reduced visiting frequency, averaging between 1.10 and 2.90 bees per square metre every 5 minutes during the observation period. Furthermore, *A. dorsata* demonstrated a minor peak (2.90 bees/m²/5 min) during the 50th SMW, coinciding with intervals of mild meteorological conditions, followed by a subsequent decline. *A. florea* had negligible activity beyond the 49th SMW, decreasing to 0.90 bees/m²/5 min by the first week of 2023, likely because to diminished temperatures and decreased nectar output during late flowering.

The statistical analysis revealed substantial differences among bee species over all weeks of observation, with *A. mellifera* and *T. iridipennis* constitutes the most dynamic foraging assemblages on onion umbels. The comparatively modest coefficients of variation (20.15–40.94) indicate analogous environmental influence patterns among the species. The elevated activity seen during the 48th to 50th SMWs aligns with advantageous environmental conditions particularly moderate temperatures (25–30 °C), clear skies, and low wind speeds factors that often promote honeybee foraging behaviour.

4.1.2.1.1.2 Activity of honeybees on onion bloom during 2nd planting date 20 September 2023.

Table 07. Activity of Honeybees on onion umbel at peak period of day during 2nd planting date (20 September 2023).

DOP: 20 / 09 / 2023	Standard Meteorological Weeks							
Treatment (bees/ m^2 / 5 min)	49th (2023)	50th (2023)	51st (2023)	52nd (2023)	1st (2024)	2nd (2024)	3rd (2024)	4th (2024)
Apis mellifera	7.60[a]	7.90[a]	8.80[a]	9.20[a]	9.80[a]	9.60[a]	8.50[a]	8.20[a]
Apis dorsata	2.00[bc]	2.20[cd]	2.70[cd]	2.80[cd]	3.30[bc]	3.00[bc]	2.50[cd]	2.30[c]
Apis florea	1.00[c]	1.10[d]	1.40[d]	1.50[d]	1.60[c]	1.60[c]	1.30[d]	1.20[c]
Apis cerana	4.60[ab]	4.80[bc]	5.40[bc]	5.60[bc]	6.20[ab]	5.80[ab]	5.20[bc]	5.00[b]
Tetragonula irridipennis	5.50[a]	5.70[ab]	6.40[ab]	6.70[ab]	7.00[ab]	7.00[ab]	6.20[ab]	5.90[ab]
SE(m)	1.03	0.88	0.84	0.90	1.11	1.29	0.85	0.79
CD (0.05)	3.37	2.88	2.73	2.95	3.63	4.19	2.76	2.57
CV	43.21	35.30	29.32	30.35	41.15	41.25	30.92	30.23

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

Observations documented during the peak foraging interval throughout Standard Meteorological Weeks (SMW) indicated notable variations in honeybee visitation rates among species (Table 07). The population density of *Apis mellifera* continuously exceeded that of all other species during the flowering period. The species had an upward trajectory from 7.60 bees/m²/5 min in the 49th SMW to a zenith of 9.80 bees/m²/5 min in the 1st SMW (2024), followed by a steady decrease to 8.20 bees/m²/5 min by the 4th SMW. The elevated and prolonged activity signifies the robust adaptation of *A. mellifera* to onion floral resources and its preference for nectar and pollen accessibility during the primary blooming period. *T. iridipennis* had the second-highest foraging activity, fluctuating between 5.50 and 7.00 bees/m²/5 min throughout the observation period. The species exhibited a consistent rise in visiting until the first SMW, aligning with the full-bloom phase of umbels, subsequently followed by a minor decline in the ensuing weeks. The persistent presence of stingless bees indicates their ecological significance as dependable pollinators across diverse environmental circumstances and their effectiveness in pollen deposition on onion florets, particularly during periods of moderate temperature and light intensity. *A. cerana* demonstrated a moderate forage density, varying from 4.60 to 6.20 bees/m²/5 min, with peak activity observed during the 1st SMW at 6.20 bees/m²/5 min. This trend typically coincided with the flowering progression and

meteorological conditions, suggesting that *A. cerana* effectively adapts to the local microclimatic circumstances present from late December to early January.

Among the wild species, *A. dorsata* and *A. florea* exhibited relatively modest visitation rates, ranging from 2.00 to 3.30 and 1.00 to 1.60 bees/m²/5 min, respectively. The reduced occurrence of *A. dorsata* may be attributed to its affinity for arboreal landscapes and expansive floral aggregations, while *A. florea* often favours open-field habitats and diminutive flower clusters, resulting in their infrequent visitation to onion seed umbels. Their diminished activity during late SMWs may also be ascribed to decreased ambient temperature and declining nectar production towards the conclusion of blooming.

The statistical parameters revealed substantial variations across bee species at the 5 percent probability level over the majority of observation weeks. The coefficients of variation (29.32–43.21) indicated moderate variability, demonstrating the impact of environmental variations on foraging behaviour. The peak visitation of *A. mellifera* and *T. iridipennis* during the 1st to 2nd SMWs coincided with ideal foraging conditions marked by brilliant sunlight, gentle wind speeds, and moderate humidity circumstances conducive to bee flight and nectar gathering.

4.1.2.1.1.3 Activity of honeybees on onion bloom during 3rd planting date 5 October 2023.

Table 08. Activity of Honeybees on onion umbel at peak period of day during 3rd planting date (5 October 2023).

DOP: 05/10/2023	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**50th (2023)**	**51st (2023)**	**52nd (2023)**	**1st (2024)**	**2nd (2024)**	**3rd (2024)**	**4th (2024)**	**5th (2024)**
Apis mellifera	7.90[a]	8.00[a]	10.00[a]	10.40[a]	11.10[a]	10.00[a]	8.90[a]	8.30[a]
Apis dorsata	2.10[c]	2.30[c]	3.10[c]	3.50[c]	3.90[bc]	3.20[d]	2.70[c]	2.50[c]
Apis florea	1.20[c]	1.30[c]	1.70[c]	1.90[c]	2.00[c]	1.70[e]	1.50[c]	1.40[c]
Apis cerana	1.90[c]	2.00[c]	2.60[c]	2.60[c]	2.80[c]	7.30[b]	2.20[c]	2.10[c]
Tetragonula iridipennis	4.80[b]	5.10[b]	6.40[b]	6.70[b]	7.00[b]	6.00[c]	5.60[b]	5.30[b]
SE(m)	0.59	0.74	0.60	0.56	1.19	0.36	0.66	0.82
CD (0.05)	1.94	2.42	1.97	1.83	3.89	1.19	2.16	2.67
CV	28.76	34.28	22.42	19.35	38.55	11.18	27.39	36.22

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The foraging behaviour of honeybee species on onion umbels was documented during the peak hours of the day across Standard Meteorological Weeks (SMW) from the 50th week of 2023 to the 5th week of 2024 (Table 08). The peak visiting rates were consistently recorded for *A. mellifera*, with densities varying from 7.90 to 11.10 bees/m²/5 min. The species exhibited a consistent rise in activity, reaching a maximum of 11.10 bees/m²/5 min during the second standard measurement week (2023), corresponding with the full bloom phase of onion umbels. This tendency indicates that *A. mellifera* is significantly influenced by the availability of floral resources and favourable climatic conditions, establishing it as a predominant pollinator during the peak flowering season. *T. iridipennis* demonstrated a significant escalation in foraging activity, increasing from 4.80 bees/m²/5 min in the 50th SMW to a maximum of 7.00 bees/m²/5 min in the 2nd SMW, subsequently followed by a progressive decrease. The persistent presence of *T. iridipennis* signifies its resilience to the local environment and its function as a dependable pollinator, particularly during conditions of moderate temperature and humidity.

A. dorsata and *A. florea* exhibited lower still consistent visiting rates, ranging from 2.10 to 3.90 and 1.20 to 2.00 bees/m²/5 min, respectively. The peak activity for *A. dorsata* was seen during the 2nd SMW at 3.90 bees/m²/5 min, whereas *A. florea* reached a maximum of 2.00 bees/m²/5 min in the same week. These species seem to be less prevalent yet continue to facilitate pollination, especially under favourable meteorological conditions.

A notable observation was the foraging behaviour of *A. cerana*. The species exhibited comparatively modest activity from the 50th to the 4th SMW (1.90–2.80 bees/m²/5 min), but a sudden and substantial rise to 7.30 bees/m²/5 min was seen during the 3rd SMW. This significant increase may be ascribed to a confluence of factors, including heightened nectar output, optimal temperature, and less competition from other bee species. The abrupt surge in *A. cerana* activity underscores its potential as a crucial pollinator at phases of the flowering cycle.

Statistical analysis indicated substantial variations across bee species over most weeks, with *A. mellifera* and *T. iridipennis* being the most active foraging groups. The coefficients of variation (11.18–38.55) signify moderate variability in foraging behaviour, demonstrating the impact of environmental conditions including temperature, humidity, and floral resource availability. The peak visitor rates for all species during the 2nd and 3rd SMWs align with optimal foraging conditions, defined by temperate weather, clear skies, and plentiful floral supplies.

4.1.2.1.1.4 Activity of honeybees on onion bloom during 4th planting date 20 October 2023.

Table 09. Activity of Honeybees on onion umbel at peak period of day during 4th planting date (20 October 2023).

DOP :20/10/2023	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**1st (2024)**	**2nd (2024)**	**3rd (2024)**	**4th (2024)**	**5th (2024)**	**6th (2024)**	**7th (2024)**	**8th (2024)**
Apis mellifera	8.40^{a}	9.00^{a}	9.50^{a}	10.10^{a}	11.20^{a}	10.70^{a}	8.70^{a}	8.10^{a}
Apis dorsata	2.80^{c}	3.20^{cd}	3.40^{bc}	3.60^{c}	4.10^{bc}	3.90^{bc}	3.00^{c}	2.60^{c}
Apis florea	1.40^{d}	1.60^{d}	1.70^{c}	1.80^{c}	2.00^{c}	1.90^{c}	1.50^{d}	1.30^{c}
Apis cerana	5.40^{b}	5.90^{bc}	6.20^{ab}	6.50^{b}	7.20^{b}	6.90^{b}	5.70^{b}	5.20^{b}
Tetragonula iridipennis	5.80^{b}	6.40^{ab}	6.70^{ab}	6.90^{b}	7.50^{b}	7.20^{b}	6.10^{b}	5.5^{b}
SE(m)	0.42	0.85	1.07	0.62	1.11	1.04	0.27	0.71
CD (0.05)	1.37	2.76	3.49	2.01	3.61	3.38	0.87	2.33
CV	15.28	28.12	33.72	18.50	29.95	29.32	9.27	27.24

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The behaviour of honeybee visitors during the peak foraging time over the Standard Meteorological Weeks (SMW) demonstrated clear and statistically significant variations among species (Table 09). Of the documented bee species, *A. mellifera* had the most significant foraging activity during the flowering season. The visitation rate escalated from 8.40 bees/m²/5 min in the 1st SMW (2024) to a maximum of 11.20 bees/m²/5 min in the 5th SMW, aligning with the full-bloom phase of onion umbels. A progressive decline to 8.10 bees/m²/5 min was noted by the 8th SMW, coinciding with the conclusion of the flowering phase. The significant consistency and quantity of *A. mellifera* foragers throughout the bloom indicate a robust adaptation to onion floral resources and advantageous foraging conditions at this time.

The second-highest foraging activity was seen in *T. iridipennis*, with measurements varying from 5.80 to 7.50 bees/m²/5 min across the SMWs. The surge in activity during the 5th SMW corresponded with ideal bloom density and conducive weather conditions, characterised by moderate temperatures and low wind speeds. This persistent foraging activity illustrates the capacity of stingless bees to serve as effective additional pollinators for onions, especially during late-season conditions when their foraging effectiveness is consistent.

A. cerana exhibited consistent and moderate activity levels over the observation period, fluctuating between 5.40 and 7.20 bees/m²/5 min. Its foraging exhibited a pattern similar resembling that of *T. iridipennis*, characterised by a progressive increase until the 5th SMW, followed by a reduction as blooming approached completion. The species' sustained activity indicates effective acclimatisation to local environmental circumstances and a pronounced preference for onion nectar during warm, sunny periods of the day.

Conversely, *A. dorsata* and *A. florea* exhibited the lowest foraging densities among all species. *A. dorsata* exhibited a density ranging from 2.80 to 4.10 bees/m²/5 min, with somewhat elevated counts noted during the mid-flowering weeks (3rd to 5th SMW). This slight increase may be associated with enhanced visibility of umbels and resource availability during peak bloom. Nonetheless, its comparatively reduced activity indicates a little role in onion pollination, likely attributable to its inclination towards plentiful natural floral resources. *A. florea* exhibited negligible activity across the season, fluctuating between 1.40 and 2.00 bees/m²/5 min, with a modest increase around the 5th SMW before diminishing towards the late flowering phase. The tiny colony size and propensity to graze on diminutive, open flowers may elucidate its restricted interaction with onion umbels.

The statistical analysis revealed substantial variations among bee species across all SMWs at the 5 percent probability level, as demonstrated by Duncan's Multiple Range Test (DMRT). The coefficients of variation (CV) varied from 9.27 to 33.72, indicating moderate variability in bee activity, attributable to alterations in floral density, temperature variations, and diurnal light conditions affecting foraging intensity. The peak foraging counts of *A. mellifera*, *A. cerana* and *T. iridipennis* from the 4th to 6th SMWs align with advantageous meteorological conditions, marked by temperate mornings, abundant sunlight, and moderate humidity ideal for onion nectar production and bee foraging activity.

4.1.2.1.1.5 Activity of honeybees on onion bloom during 5th planting date 05 November 2023.

Table 10. Activity of Honeybees on onion umbel at peak period of day during 5th planting date (05 November 2023).

DOP :05/11/2023	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**3rd (2024)**	**4th (2023)**	**5th (2024)**	**6th (2023)**	**7th (2024)**	**8th (2024)**	**9th (2023)**	**10th (2024)**
Apis mellifera	8.60^{a}	9.00^{a}	10.30^{a}	10.80^{a}	12.00^{a}	11.50^{a}	9.90^{a}	9.40^{a}
Apis dorsata	2.70^{d}	2.80^{cd}	3.40^{cd}	3.60^{bc}	4.20^{bc}	3.90^{cd}	3.20^{cd}	3.00^{cd}
Apis florea	1.30^{e}	1.40^{d}	1.70^{d}	1.80^{c}	2.10^{c}	1.90^{d}	1.60^{d}	1.50^{d}
Apis cerana	4.00^{c}	4.20^{bc}	4.80^{bc}	5.00^{bc}	5.60^{bc}	5.30^{bc}	4.60^{bc}	4.40^{bc}
Tetragonula iridipennis	5.40^{b}	5.60^{b}	6.30^{b}	6.60^{b}	7.30^{bc}	6.90^{b}	6.00^{b}	5.80^{b}
SE(m)	0.32	0.74	0.66	1.25	1.10	0.62	0.63	0.71
CD (0.05)	1.04	2.42	2.16	4.08	3.58	2.02	2.06	2.31
CV	12.59	27.98	21.61	39.01	30.49	18.19	21.65	25.45

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

Observations of honeybee foraging carried out during the peak hours from the 3rd to the 10th Standard Meteorological Weeks (SMW) demonstrated significant variations in visitation patterns among bee species (Table 10). *A. mellifera* had the highest visitation density during the investigation, showing a consistent rise from 8.60 bees/m²/5 min in the 3rd SMW (2024) to a maximum of 12.00 bees/m²/5 min at the 7th SMW. After this peak, activity experienced a little decrease to 9.40 bees/m²/5 min by the 10th SMW, a trend aligned with the senescence of umbels and diminished floral resource availability. This pattern highlights the exceptional adaptability and dependability of *A. mellifera* as the principal pollinator in late-season onion blossoming. The stingless bee *T. iridipennis* was the second most prevalent pollinator, with visiting rates rising from 5.40 to 7.30 bees/m²/5 min by the 7th SMW, subsequently declining in the following weeks. This pattern closely resembled that of *A. mellifera*, though at reduced magnitudes, indicating analogous habitat and resource utilisation preferences.

The *A. cerana*, demonstrated consistent and moderate visits during the flowering period, varying from 4.00 to 5.60 bees/m²/5 min. This species exhibited a steady presence

across all weeks, with only minor increases during peak bloom, demonstrating their effectiveness as secondary pollinators, particularly under fluctuating late-season conditions.

A. dorsata exhibited consistently reduced activity compared to the managed bees, with values ranging from 2.70 to 4.20 bees/m²/5 min. The progressive ascent to the 7th SMW corresponds with heightened floral resource availability during peak bloom; however, the overall low abundance likely indicates species-specific adaptations or preferences for other, less disturbed habitats. *A. florea* demonstrated the lowest visitation rates, ranging from 1.30 to 2.10 bees/m²/5 min, underscoring its negligible contribution to onion pollination during this sowing period, likely due to its nesting and foraging behaviour that prefers open, uncultivated environments.

Statistical analysis revealed substantial differences in visiting among bee species over all monitored weeks at the 5% probability level, as indicated by DMRT. The coefficient of variation (CV) varied from 12.59 to 39.01, signifying substantial variability in foraging response, affected by weekly fluctuations in flower density, nectar release, and environmental factors like temperature and humidity.

4.1.2.1.1.6 Activity of honeybees on onion bloom during 6th planting date 20 November 2023.

Table 11. Activity of Honeybees on onion umbel at peak period of day during 6th planting date (20 November 2023).

DOP: 20/11/2023	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	5th (2024)	6th (2024)	7th (2024)	8th (2024)	9th (2024)	10th (2024)	11th (2023)	12th (2024)
Apis mellifera	9.54[a]	9.10[a]	10.50[a]	11.53[a]	12.00[a]	11.83[a]	10.80[a]	9.50[a]
Apis dorsata	2.50[c]	3.22[b]	3.10[b]	3.50[c]	4.00[c]	3.80[c]	3.53[c]	2.90[c]
Apis florea	1.57[c]	3.12[b]	2.97[b]	3.04[c]	2.74[c]	2.37[c]	2.12[c]	1.76[c]
Apis cerana	2.00[c]	2.97[b]	3.14[b]	2.87[c]	3.92[c]	3.23[c]	2.50[c]	2.20[c]
Tetragonula iridipennis	4.80[b]	5.20[b]	6.00[b]	6.50[b]	7.10[b]	6.80[b]	6.20[b]	5.50[b]
SE(m)	0.51	0.76	0.94	0.41	0.85	0.75	0.52	0.42
CD (0.05)	1.65	2.47	3.07	1.32	2.78	2.46	1.70	1.38
CV	21.44	27.76	31.72	12.81	24.78	23.31	17.93	16.76

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The foraging activity of honeybee visitors on onion umbels exhibited considerable variation among species throughout the peak foraging period, as shown from the 5th to the 12th Standard Meteorological Weeks (SMW) (Table 11). *A. mellifera* was identified as the predominant pollinator for the entire study period. The visitor frequency rose from 9.54 bees/m²/5 min in the 5th SMW (2024) to a peak of 12.00 bees/m²/5 min in the 9th SMW, coinciding with the primary bloom time. A slight decrease occurred subsequently, however the visitation rate remained persistently elevated, concluding at 9.50 bees/m²/5 min by the 12th SMW. This consistency underscores the adaptive foraging behaviour of *A. mellifera* and its exceptional potential as a controlled pollinator for late-sown onion crops. *T. iridipennis* (stingless bee) was the second most abundant species, with visiting rates increasing from 4.80 bees/m²/5 min to 7.10 bees/m²/5 min by the 9th SMW, before declining in the subsequent weeks. The mirrored pattern observed in *A. mellifera* signifies a collective reaction to ideal feeding conditions during peak bloom, highlighting *T. iridipennis* adaptability and crucial contribution to onion pollination.

A. dorsata and *A. florea*, two wild bee species, had moderate to low activity levels. *A. dorsata* rose from 2.50 to a maximum of 4.00 bees/m²/5 min before gradually declining. This indicates a degree of adaptation to mid- and late-bloom periods, albeit with a distinctly inferior total presence relative to controlled bees. *A. florea* exhibited a range from 1.57 to a temporary peak of 3.12 bees/m²/5 min during the 6th SMW, characterised by relatively modest activity; its intermittent rises may indicate short-lived favourable weather conditions or transient population shifts.

A. cerana consistently exhibited decreased visiting rates, ranging from 2.00 to 3.92 bees/m²/5 min. Although its density was low, the species' consistent presence during all weeks indicates it serves as a dependable, albeit minor, supplementary pollinator, particularly in fluctuating weather conditions.

Statistical analysis revealed substantial variations in activity among bee species at the 5% probability level for all studied weeks, as indicated by the DMRT. The coefficient of variation (CV) varied from 12.8% to 31.7%, indicating considerable response variability between sample weeks, potentially associated with changes in floral density, environmental fluctuations (temperature, humidity), and the gradual senescence of umbels.

4.1.2.1.1.7 Activity of honeybees on onion bloom during 7th planting date 05 December 2023.

Table 12. Activity of Honeybees on onion umbel at peak period of day during 7th planting date (05 December 2023).

DOP:05/12/2023	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**7th (2024)**	**8th (2024)**	**9th (2024)**	**10th (2024)**	**11th (2023)**	**12th (2024)**	**13th (2024)**	**14th (2024)**
Apis mellifera	8.90^{a}	9.40^{a}	10.20^{a}	10.70^{a}	11.30^{a}	9.80^{a}	8.50^{a}	8.10^{a}
Apis dorsata	2.60^{b}	3.88^{bc}	4.20^{bc}	3.60^{bc}	3.80^{c}	3.00^{b}	2.40^{b}	2.30^{bc}
Apis florea	1.85^{b}	3.07^{c}	2.92^{c}	2.99^{b}	4.39^{c}	2.07^{b}	2.17^{b}	1.13^{c}
Apis cerana	2.30^{b}	2.95^{c}	2.12^{c}	3.24^{bc}	3.24^{c}	2.10^{b}	2.10^{b}	2.00^{bc}
Tetragonula iridipennis	5.60^{ab}	5.90^{b}	6.50^{b}	6.90^{b}	7.30^{b}	6.20^{ab}	5.40^{ab}	5.10^{ab}
SE(m)	1.43	0.76	0.99	1.13	0.80	1.37	1.15	1.04
CD (0.05)	4.67	2.48	3.24	3.69	2.60	4.47	3.75	3.38
CV	58.33	26.10	33.13	35.73	22.95	50.32	48.44	48.13

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The findings from the 7th to 14th Standard Meteorological Weeks indicated distinct, statistically significant variations in foraging behaviour among honeybee species (Table 12). *A. mellifera* exhibited a predominant presence and the greatest average visiting rates throughout all weeks, rising from 8.90 bees/m²/5 min in the 7th week to a maximum of 11.30 bees/m²/5 min in the 11th week. In the following weeks, there was a constant decrease to 8.10 bees/m²/5 min by the 14th week, along with earlier flower senescence and less nectar supply. The stability seen over several weeks underscores the crucial role of *A. mellifera* in onion pollination under late-season planting strategies. *T. iridipennis* exhibited the second-highest visitation, fluctuating between 5.60 and 7.30 bees/m²/5 min from the 7th to the 11th weeks, thereafter, decreasing to 5.10 bees/m²/5 min by the 14th week. The consistent foraging behaviour of *T. iridipennis*, reflecting the sequence of floral blooms and stable meteorological conditions, underscores its adaptive foraging strategy and significant role in efficient pollination alongside controlled *A. mellifera* colonies.

A. dorsata demonstrated moderate foraging, with activity rising from 2.60 to 4.20 bees/m²/5 min by the 9th week, peaking slightly earlier than *A. mellifera*. Its activity then

diminished in the following weeks. This behaviour indicates that although *A. dorsata* reacts to mid-bloom floral reward peaks, it is generally less reliable than domesticated species potentially due to a preference for alternate, non-cultivated floral resources or sensitive to management disruptions common in the field. *A. florea* exhibited inconsistent and generally minimal visitation, with a pronounced but transient peak during the 11th week (4.39 bees/m²/5 min). Beyond this peak, its activity was minimal (varying from 1.13 to 3.07 bees/m²/5 min), indicating either sporadic local influxes or transient intervals of climatic favourability for this diminutive, open-nesting bee. The foraging activity of *A. cerana* was consistently low, fluctuating between 2.00 and 3.24 bees per square metre every 5 minutes during the observation period. Although their population was less than that of *T. iridipennis* or *A. mellifera*, their persistent presence reinforces their established role as reliable, additional pollinators during variable late-season conditions.

The statistical analysis (DMRT at *p* = 0.05) validated substantial interspecific variations for all weeks. The coefficient of variation (CV) exhibited considerable variability, with certain weeks demonstrating significant fluctuations (e.g., 58.33% in the 7th week), likely indicative of temporary environmental alterations such as sudden changes in temperature, humidity, or wind, which frequently characterise the late-winter to early-spring transition in onion cultivation areas.

4.1.2.1.1.8 Correlation between weather parameters across standard metrological weeks (SMW) mean abundance of honeybees (Rabi 2023-24).

Table 13 present a comprehensive overview of these correlations, throwing light on the intricate relationship between environmental factors and the abundance of different bee species in the ecosystem. The correlation analysis revealed noteworthy relationships between environmental factors and the abundance of different bee species.

The correlation analysis indicated that *A. cerana* exhibited the greatest sensitivity to weather, with highly significant negative correlations with maximum temperature (r = -0.8229**) and evaporation (r = -0.7125**), suggesting a marked decline in foraging under conditions of elevated temperature and moisture stress. *A. cerana* exhibited substantial negative relationships with minimum temperature (r = -0.6454*) and wind velocity (r = -0.5820*), indicating that this species encounters restricted activity under various unfavourable weather conditions.

Table 13. Relative abundance of honeybees (No. of bees /m^2/ 5 min) on onion flowers under open field condition at different SMW (*Rabi* 2023-24).

Standard Week	Honeybees (Mean no. of bees /m^2/ 5 min)					Temperature (%)		Relative Humidity (%)		Velocity (km/hr.)	Sunshine (Hr)	Rain (mm)	Evaporation (mm)
	Apis mellifera	*Apis dorsata*	*Apis florea*	*Apis cerana*	*Tetragonula iridipennis*	Max	Min	Min	Max				
46th (2023)	7.20	2.10	1.10	3.80	5.90	32.20	18.20	25.00	34.00	3.00	8.40	0.00	4.10
47th (2023)	7.50	2.30	1.20	4.90	6.20	31.20	18.20	76.00	62.00	2.70	8.30	0.00	4.20
48th (2023)	7.90	2.90	1.60	5.70	7.40	30.70	16.70	86.00	68.00	3.50	6.40	0.00	3.90
49th (2023)	7.60	2.00	1.00	4.60	5.50	30.20	10.20	79.00	64.00	3.30	9.10	0.00	3.90
50th (2023)	7.90	2.15	1.15	4.70	4.80	30.20	15.70	80.00	64.00	1.90	8.10	0.00	4.20
51st (2023)	8.40	2.50	1.35	4.20	5.25	28.20	14.20	82.00	64.00	2.80	6.40	0.00	4.40
52nd (2023)	9.60	2.95	1.60	4.55	5.85	31.70	13.70	68.00	61.00	2.90	8.30	0.00	4.40
1st (2024)	10.10	3.40	1.75	4.55	6.45	30.2	14.9	83.9	64.1	2.2	6.7	0.00	3.2
2nd (2024)	10.35	3.45	1.80	4.90	6.40	28.4	16.6	84.6	67.0	2.9	7.8	6.2	2.3
3rd (2024)	9.25	2.85	1.50	6.75	5.60	29.9	11.5	77.7	53.6	3.0	8.6	0.0	2.8
4th (2024)	8.55	2.50	1.35	4.05	5.30	29.6	10.3	78.0	60.1	2.2	9.4	0.0	2.9
5th (2024)	8.85	3.33	1.76	4.77	6.10	31.1	12.6	69.9	55.0	2.5	8.5	0.0	3.0
6th (2024)	9.85	3.57	2.27	5.06	6.23	33.8	15.4	75.4	48.9	3.1	9.8	0.0	3.7

7th (2024)	10.11	3.23	2.11	4.28	6.15	33.3	14.3	75.1	52.0	2.2	8.9	0.0	3.7
8th (2024)	10.33	3.47	2.33	4.16	6.13	32.5	13.0	70.4	45.7	3.6	10.2	0.0	3.9
9th (2024)	10.70	3.80	2.42	3.55	6.53	33.7	18.4	77.6	58.0	4.1	8.9	0.0	3.8
10th (2024)	11.64	3.47	2.28	3.62	6.50	34.4	14.9	57.1	39.6	3.8	9.3	0.0	4.0
11th (2024)	11.05	3.67	3.25	2.87	6.75	36.0	15.4	68.0	41.3	4.2	9.4	0.0	4.8
12th (2024)	9.65	2.95	1.91	2.35	5.85	35.8	15.7	60.7	41.0	3.6	9.0	0.0	4.7
13th (2024)	8.50	2.40	2.17	2.10	5.40	38.0	20.8	68.6	47.4	3.7	8.1	0.0	6.2
14th (2024)	8.10	2.30	1.13	2.00	5.10	39.0	30.5	115.3	66.7	8.8	15.1	-	11.0
SE(m)	0.66	0.13	0.12	0.33	0.15	-	-	-		-	-	-	-
CD (0.05)	1.29	0.25	0.24	0.64	0.28								
CV	39.36	19.76	32.02	34.72	11.60								

SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

Table 14. Pearson correlation analysis between honeybee foraging activity (No. of bee visitors/ m^2/ 5 min) and weather parameters in onion at different SMW 2023- 24.

Honeybees/ Weather parameters	Temperature		Relative Humidity		Velocity (km/hr)	Sunshine (Hr)	Rain (mm)	Evaporation (mm)
	Max	Min	Min	Max				
A. mellifera	0.0629*	0.1985*	0.0339	0.0919	0.2007	-0.1346	0.2499	0.0902
A. dorsata	-0.2996	-0.3811	-0.3933	-0.2302	-0.358	-0.3992	0.1572	-0.5471*
A. florea	0.2593	-0.1831	-0.5821*	-0.6598*	-0.1589	-0.2647	-0.1878	-0.1959
A. cerana	-0.8229**	-0.6454*	-0.0576	0.221	-0.5820*	-0.419	0.2113	-0.7125**
T. iridipennis	-0.2411	-0.3414	-0.4362	-0.2629	-0.366	-0.4807	0.2208	-0.5133

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

A. mellifera displayed moderate positive correlations with maximum temperature (r = 0.0629*) and minimum temperature (r = 0.1985*), suggesting a slight increase in activity with rising temperatures, while exhibiting stable activity across humidity (r = 0.0339 and 0.0919), wind velocity (r = 0.2007), and rainfall (r = 0.2499), indicating robust environmental tolerance. A. mellifera exhibited a slight negative correlation with daylight (r = -0.1346) and a negligible reaction to evaporation (r = 0.0902).

A. florea exhibited substantial negative associations with both minimum relative humidity (r = -0.5821*) and maximum relative humidity (r = -0.6598*), suggesting a preference for moderate humidity levels and reduced activity at both extremes of humidity. This species had a positive connection with maximum temperature (r = 0.2593) and a negative correlation with minimum temperature (r = -0.1831).

A. dorsata demonstrated a singular significant negative correlation with evaporation (r = -0.5471*), suggesting less overall susceptibility to meteorological conditions. Insignificant negative correlations with temperature parameters (highest r = -0.2996, minimum r = -0.3811), relative humidity (r = -0.3933 and -0.2302), and wind velocity (r = -0.358) indicate modest relationships with these variables.

T. iridipennis exhibited non-significant correlations with all meteorological variables, demonstrating negative correlations with temperature (r = -0.2411 and -0.3414), humidity (r =

-0.4362 and -0.2629), wind velocity (r = -0.366), sunshine (r = -0.4807), and evaporation (r = -0.5133), suggesting that this species sustains relatively stable foraging activity irrespective of weather fluctuations. A positive association with rainfall (r = 0.2208) indicates a neutral to positive response to precipitation (Table 14).

All species demonstrated non-significant relationships with rainfall, indicating that precipitation does not significantly constrain pollinator activity. The findings demonstrate that *A. mellifera* and *T. iridipennis* offer consistent pollination under various weather conditions, whereas *A. cerana* is significantly limited by temperature and evaporation, *A. florea* by extreme humidity, and *A. dorsata* chiefly by moisture stress conditions.

4.1.2.2 Second year

4.1.2.2.1 Abundance of onion umbel visitors (Honeybees) on crop grown on different seven dates of planting 2024-25.

The data recorded on activity of onion pollinators especially honeybees *viz., A. florea, A. cerana, A. mellifera, A. dorsata* and *T. iridipennis* at the peak period of day in between 12 pm to 2 pm afternoon when pollinators are more active.

The mean quantity of honeybee visits per square metre every five minutes during the peak foraging period exhibited significant variance among bee species over the Standard Meteorological Weeks (SMW) from the 46th to the 1st of the following year (Table 15). *A. mellifera* and *T. iridipennis* consistently had the highest visitation rates during the flowering phase among the documented species. The activity increased from 7.00 bees/m²/5 min in the 46th SMW to a peak of 9.00 bees/m²/5 min in the 50th SMW for *A. mellifera,* while *T. iridipennis* recorded 7.80 bees/m²/5 min in the 46th SMW and attained a maximum of 9.30 bees/m²/5 min in the 50th SMW, coinciding with the full-bloom phase of onion umbels. *A. cerana* continued gradual decline was observed in the last weeks, perhaps due to decreasing floral rewards and increased senescence of umbels. *A. cerana* exhibited persistently heightened foraging behaviour during the blooming period. Similarly, *A. cerana* throughout the same interval ranged from 4.60 to 6.00 bees/m²/5 min. Their persistent presence signifies an adaptation to the mild temperature and light intensity characteristic of mid-morning, along with a strong preference for onion nectar.

4.1.2.2.1.1 Activity of honeybees on onion bloom during 1st planting date 5 September 2024.

Table 15. Activity of Honeybees on onion umbel at peak period of day during 1st planting date (5 September 2024).

DOP: 05/09/2024	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**46th (2024)**	**47th (2024)**	**48th (2024)**	**49th (2024)**	**50th (2024)**	**51st (2024)**	**52nd (2024)**	**1st (2025)**
Apis mellifera	7.00[a]	7.30[a]	8.10[a]	8.50[a]	9.00[a]	8.00[a]	6.90[a]	6.50[ab]
Apis dorsata	2.90[c]	3.10[c]	3.30[c]	3.50[c]	3.90[b]	3.70[bc]	2.70[b]	2.50[c]
Apis florea	1.89[c]	3.12[c]	2.99[c]	3.07[c]	4.12[b]	2.13[c]	2.20[b]	1.83[c]
Apis cerana	4.60[b]	5.00[b]	5.20[b]	5.50[b]	6.00[b]	4.80[b]	4.30[ab]	4.00[bc]
Tetragonula iridipennis	7.80[a]	8.10[a]	8.40[a]	8.70[a]	9.30[a]	7.00[a]	7.50[a]	7.20[a]
SE(m)	1.35	0.55	0.76	0.87	0.77	0.75	1.23	0.92
CD (0.05)	4.05	1.79	2.49	2.82	2.50	2.25	3.60	3.01
CV	48.47	17.88	23.58	25.59	20.54	22.46	45.28	36.22

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

In contrast, *A. dorsata* and *A. florea* demonstrated a markedly diminished visitation rate, averaging between 1.89 and 3.90 bees per square metre every 5 minutes throughout the observation period. *A. dorsata* exhibited a slight peak (3.90 bees/m²/5 min) during the 50th SMW, aligning with periods of mild weather conditions, subsequently followed by a drop. *A. florea* exhibited minimal activity beyond the 49th SMW, declining to 1.89 to 4.12 bees/m²/5 min by the first week of 2024, perhaps because to reduced temperatures and less nectar availability during the late flowering period.

The statistical analysis indicated significant differences across bee species during the observation period, with *A. mellifera* and *T. iridipennis* forming the most dynamic foraging assemblages on onion umbels. The relatively low coefficients of variation (20.54–48.47) suggest similar environmental influence patterns throughout the species. The heightened activity observed from the 48th to 50th SMWs corresponds with favourable environmental circumstances, specifically moderate temperatures (25–30 °C), bright skies, and low wind speeds, which typically enhance honeybee foraging behaviour.

4.1.2.2.1.2 Activity of honeybees on onion bloom during 2nd planting date 20 September 2024.

Table 16. Activity of Honeybees on onion umbel at peak period of day during 2nd planting date (20 September 2024).

DOP:20/09/2024	Standard Meteorological Weeks							
Treatment(bees/ m^2/ 5 min)	49th (2024)	50th (2024)	51st (2024)	52nd (2024)	1st (2025)	2nd (2025)	3rd (2025)	4th (2025)
Apis mellifera	7.37^{a}	8.00^{a}	8.20^{a}	8.80^{a}	9.20^{a}	8.50^{a}	7.50^{a}	7.30^{a}
Apis dorsata	2.60^{c}	2.90^{d}	2.90^{d}	3.20^{d}	3.85^{c}	3.10^{cd}	3.50^{c}	2.63^{c}
Apis florea	1.94^{d}	3.11^{c}	3.45^{c}	4.03^{c}	4.72^{c}	2.81^{d}	2.64^{c}	2.21^{c}
Apis cerana	4.50^{bc}	4.70^{bc}	4.90^{bc}	5.50^{b}	5.70^{b}	5.20^{b}	4.30^{bc}	4.00^{bc}
Tetragonula iridipennis	8.60^{a}	8.90^{a}	9.20^{a}	9.80^{a}	10.10^{a}	9.50^{a}	9.30^{a}	8.00^{a}
SE(m)	1.45	0.93	0.64	0.70	1.06	0.71	0.95	0.94
CD (0.05)	4.73	3.03	2.08	2.29	3.46	2.33	3.10	3.05
CV	50.18	28.22	19.25	19.96	27.37	21.25	30.24	33.57

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

Observations recorded during the peak foraging period across Standard Meteorological Weeks (SMW) revealed significant discrepancies in honeybee visitation rates among species (Table 16). The population density of *Apis mellifera* consistently surpassed that of any other species during the flowering period. The species exhibited an increase from 7.37 bees/m²/5 min in the 49th SMW to a peak of 9.20 bees/m²/5 min in the 1st SMW (2025), thereafter declining to 7.30 bees/m²/5 min by the 4th SMW. The sustained and heightened activity indicates the strong adaptation of *A. mellifera* to onion floral resources and its preference for the availability of nectar and pollen during the peak flowering phase.

T. iridipennis exhibited the second-highest foraging activity, varying between 8.00 and 10.10 bees/m²/5 min during the study period. The species demonstrated a steady increase in visitation until the initial SMW, coinciding with the peak blooming period of umbels, thereafter, experiencing a slight decrease in the subsequent weeks. The continual presence of stingless bees underscores their ecological importance as reliable pollinators in many climatic conditions and their efficiency in pollen deposition on onion florets, especially during moderate temperature and light intensity. *A. cerana* exhibited a moderate foraging density, ranging from

4.50 to 5.70 bees/m²/5 min, with maximum activity recorded during the 1st SMW at 5.70 bees/m²/5 min. This tendency often aligned with the flowering progression and climatic conditions, indicating that A. cerana adeptly adjusts to the local microclimatic conditions from late December to early January. *A. dorsata* and *A. florea* demonstrated comparatively low visitation rates, varying from 2.60 to 3.85 and 1.94 to 4.72 bees/m²/5 min, respectively. The diminished presence of *A. dorsata* can be ascribed to its preference for arboreal environments and extensive floral aggregations, whereas *A. florea* often prefers open-field habitats and small flower clusters, leading to their rare visitation of onion seed umbels. Their reduced activity during late SMWs may also be attributed to lower ambient temperatures and diminishing nectar production near the end of flowering.

The statistical parameters indicated significant variances among bee species at the 5 percent probability level for most observation weeks. The coefficients of variation (19.25 – 50.18) demonstrated moderate variability, illustrating the influence of environmental fluctuations on foraging behaviour. The maximum visitation of *A. mellifera* and *T. iridipennis* during the 52nd to 1st SMWs coincided with optimal foraging conditions characterised by bright sunlight, mild wind speeds, and moderate humidity favourable for bee flight and nectar collection.

4.1.2.2.1.3 Activity of honeybees on onion bloom during 3rd planting date 5 October 2024.

Table 17. Activity of Honeybees on onion umbel at peak period of day during 3rd planting date (5 October 2024).

DOP:05/10/2024	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**50th (2024)**	**51st (2024)**	**52nd (2024)**	**1st (2025)**	**2nd (2025)**	**3rd (2025)**	**4th (2025)**	**5th (2025)**
Apis mellifera	8.00^{ab}	8.20^{a}	8.30^{a}	8.50^{a}	8.80^{ab}	8.60^{a}	7.90^{a}	7.50^{a}
Apis dorsata	3.50^{bc}	3.60^{b}	3.60^{b}	4.04^{bc}	3.90^{c}	3.80^{bc}	3.40^{b}	3.20^{b}
Apis florea	1.87^{c}	3.10^{b}	2.32^{c}	2.41^{c}	4.19^{c}	2.43^{c}	2.17^{b}	1.13^{b}
Apis cerana	5.00^{abc}	5.20^{b}	5.30^{b}	5.50^{b}	5.80^{bc}	5.60^{b}	5.00^{ab}	4.80^{ab}
Tetragonula iridipennis	8.80^{a}	9.00^{a}	9.20^{a}	9.40^{a}	9.70^{a}	9.50^{a}	8.60^{a}	8.20^{a}
SE(m)	1.45	0.84	0.88	0.97	0.81	0.56	1.29	1.30
CD (0.05)	4.74	2.75	2.86	3.16	2.65	1.83	4.20	4.25
CV	46.26	25.12	26.45	28.11	21.73	16.19	41.21	45.45

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The foraging behaviour of honeybee species on onion umbels was recorded during peak daylight hours throughout Standard Meteorological Weeks (SMW) from the 50th week of 2024 to the 5th week of 2025. T. iridipennis exhibited a notable increase in foraging activity, rising from 8.80 bees/m²/5 min in the 50th SMW to a peak of 9.70 bees/m²/5 min in the 2nd SMW, followed by a gradual decline. The continual presence of *T. iridipennis* indicates its adaptability to the local environment and its role as a reliable pollinator, especially under moderate temperature and humidity conditions. The highest visitation rates for *A. mellifera* were regularly documented, with densities ranging from 7.50 to 8.80 bees/m²/5 min. The species demonstrated a steady increase in activity, peaking at 8.80 bees/m²/5 min during the second standard measurement week (2025), coinciding with the full bloom phase of onion umbels. This trend demonstrates that *A. mellifera* is substantially affected by the accessibility of floral resources and conducive meteorological circumstances, positioning it as a principal pollinator during the height of the flowering season.

A. dorsata and *A. cerana* demonstrated consistently lower visitation rates, ranging from 3.20 to 4.04 and 4.80 to 5.80 bees/m²/5 min, respectively. *A. dorsata* exhibited peak activity during the first standard measurement week at 3.90 bees/m²/5 min, while *A. cerana* had a maximum of 5.80 bees/m²/5 min in the second week. These species appear to be less common yet persist in enabling pollination, particularly under ideal weather circumstances. A significant observation was the foraging behaviour of *A. florea*. The species demonstrated relatively low activity from the 50th to the 5th SMW (1.87 – 4.19 bees/m²/5 min). A quick and significant increase of 4.19 bees/m²/5 min was observed during the second standard measurement week (SMW). This large rise can be attributed to a combination of variables, including as increased nectar production, favourable temperatures, and less competition from other bee species. The sudden increase in *A. florea* activity highlights its significance as an essential pollinator during specific stages of the flowering cycle.

Statistical analysis revealed significant variances across bee species throughout the majority of weeks, with *A. mellifera* and *T. iridipennis* identified as the most active foraging groups. The coefficients of variation (16.19–46.26) indicate moderate variability in foraging behaviour, reflecting the influence of environmental factors like as temperature, humidity, and availability of floral resources. The maximum visitation rates for all species during the 2nd and 3rd SMWs coincide with ideal foraging conditions, characterised by temperate weather, clear skies, and abundant floral resources.

4.1.2.2.14 Activity of honeybees on onion bloom during 4th planting date 20 October 2024.

Table 18. Activity of Honeybees on onion umbel at peak period of day during 4th planting date (20 October 2024).

DOP: 20/10/2024	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**1st (2025)**	**2nd (2025)**	**3rd (2025)**	**4th (2024)**	**5th (2024)**	**6th (2024)**	**7th (2024)**	**8th (2024)**
Apis mellifera	8.10^{a}	8.50^{ab}	8.40^{ab}	8.80^{ab}	9.00^{ab}	8.70^{ab}	8.10^{a}	7.80^{ab}
Apis dorsata	2.50^{b}	3.70^{c}	3.60^{c}	3.80^{c}	4.00^{c}	3.80^{cd}	3.40^{bc}	3.20^{cd}
Apis florea	1.54^{c}	2.91^{c}	3.09^{c}	3.07^{c}	4.19^{c}	2.10^{d}	1.83^{c}	1.13^{d}
Apis cerana	4.10^{ab}	5.40^{bc}	5.40^{bc}	5.60^{bc}	5.90^{bc}	5.70^{bc}	5.10^{bc}	4.80^{bc}
Tetragonula iridipennis	8.50^{a}	9.30^{a}	9.20^{a}	9.60^{a}	9.90^{a}	9.50^{a}	8.80^{a}	8.40^{a}
SE(m)	1.20	1.15	1.16	1.13	1.16	1.06	0.69	1.03
CD (0.05)	3.91	3.76	3.78	3.68	3.78	3.46	2.25	3.35
CV	38.07	33.49	32.80	31.65	30.42	30.79	21.90	35.08

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.
SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

The behaviour of honeybee visitors during peak foraging periods during the Standard Meteorological Weeks (SMW) exhibited distinct and statistically significant differences among species (Table 18). Among the recorded bee species, *A. mellifera* exhibited the most pronounced foraging activity throughout the flowering season. The visitation rate increased from 8.10 bees/m²/5 min in the 1st SMW (2025) to a peak of 9.00 bees/m²/5 min in the 5th SMW, coinciding with the full-bloom stage of onion umbels. A gradual decrease to 7.80 bees/m²/5 min was seen by the 8th SMW, coinciding with the end of the flowering phase. The substantial consistency and abundance of *A. mellifera* foragers throughout the bloom suggest a strong adaptation to onion floral resources and favourable foraging conditions at this period.

The second-highest foraging activity was seen in *T. iridipennis*, with values ranging from 8.40 to 9.90 bees/m²/5 min across the SMWs. The increase in activity during the 5th SMW coincided with optimal bloom density and favourable weather conditions, marked by moderate temperatures and low wind velocities. This ongoing foraging behaviour demonstrates the ability of stingless bees to function as efficient supplementary pollinators for onions, particularly under late-season conditions when their foraging efficacy remains stable.

A. cerana demonstrated stable and moderate activity levels throughout the observation period, ranging from 4.10 to 5.90 bees/m²/5 min. Its foraging displayed a trend akin to that of T. iridipennis, marked by a gradual increase until the 5th SMW, followed by a decline as blooming neared completion. The species' ongoing activity signifies successful adaptation to local environmental conditions and a marked predilection for onion nectar throughout warm, bright intervals of the day.

In contrast, *A. dorsata* and *A. florea* demonstrated the lowest foraging densities among all species. *A. dorsata* demonstrated a density of 2.50 to 4.00 bees/m²/5 min, with increased counts seen throughout the mid-flowering weeks (3rd to 5th SMW). This marginal increase may correlate with improved visibility of umbels and resource accessibility during peak bloom. However, its relatively diminished activity suggests a minimal contribution to onion pollination, perhaps due to its preference for abundant natural floral resources. *A. florea* demonstrated minimal activity throughout the season, varying between 1.13 and 4.19 bees/m²/5 min, with a slight uptick around the 5th SMW before declining towards the late flowering period. The small colony size and tendency to feed on small, open flowers may explain its limited contact with onion umbels.

The statistical analysis indicated significant differences among bee species across all SMWs at the 5 percent probability level, as evidenced by Duncan's Multiple Range Test (DMRT). The coefficients of variation (CV) ranged from 21.90 to 33.72, signifying substantial variability in bee activity, due to changes in floral density, temperature fluctuations, and diurnal light conditions impacting foraging intensity. The maximum foraging counts of *A. mellifera*, *A. cerana*, and *during* the 4th to 6th SMWs coincide with favourable meteorological conditions characterised by mild mornings, ample sunlight, and moderate humidity, which are optimal for onion nectar production and bee foraging behaviour.

4.1.2.2.1.5 Activity of honeybees on onion bloom during 5th planting date 05 November 2024.

Table 19. Activity of Honeybees on onion umbel at peak period of day during 5th planting date (05 November 2024).

DOP:05/11/2024	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**3rd (2025)**	**4th (2025)**	**5th (2025)**	**6th (2025)**	**7th (2025)**	**8th (2025)**	**9th (2025)**	**10th (2025)**
Apis mellifera	8.40[a]	8.80[a]	10.25[a]	10.40[b]	13.50[b]	12.20[b]	10.35[b]	9.25[b]
Apis dorsata	2.42[c]	3.00[c]	3.60[c]	3.65[cd]	4.69[d]	3.70[c]	3.44[cd]	3.65[cd]
Apis florea	2.24[c]	2.86[c]	3.07[c]	3.09[d]	4.20[d]	2.88[d]	2.58[d]	1.92[d]
Apis cerana	4.98[b]	5.20[b]	5.40[b]	5.46[c]	5.60[c]	4.80[c]	5.05[c]	5.15[c]
Tetragonula iridipennis	9.20[a]	9.60[a]	11.72[a]	12.78[a]	15.13[a]	14.23[a]	12.50[a]	11.34[a]
SE(m)	1.16	1.13	0.92	1.14	1.23	0.58	0.75	0.88
CD (0.05)	3.78	3.68	3.23	2.62	2.43	1.87	3.13	3.76
CV	32.80	31.65	23.95	24.20	17.90	15.58	22.53	28.02

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

The foraging behaviour of honeybee visits on onion umbels shown significant heterogeneity among species throughout the peak foraging period, specifically from the 3rd to the 10th Standard Meteorological Weeks (SMW) (Table 19). *T. iridipennis* (stingless bee) was identified as the primary pollinator species, with visitation rates escalating from 9.20 bees/m²/5 min to 15.13 bees/m²/5 min by the 7th SMW, followed by a decline in the ensuing weeks. The mirrored pattern seen in *T. iridipennis* indicates a communal response to optimal feeding conditions at peak bloom, underscoring *T. iridipennis* adaptability and essential role in onion pollination. A minor decline ensued; still, the visitation rate remained consistently high, finishing at 9.25 bees/m²/5 min by the 10th SMW. This consistency highlights the adaptive foraging behaviour of *T. iridipennis* and its remarkable potential as a regulated pollinator for late-sown onion crops. *A. mellifera* ranked as the second most prevalent species over the entire study duration. The visitor frequency increased from 8.40 bees/m²/5 min in the 3rd SMW (2025) to a maximum of 13.50 bees/m²/5 min in the 7th SMW, aligning with the peak bloom period.

A. cerana consistently demonstrated reduced visitation rates, varying from 4.98 to 5.60 bees/m²/5 min. Despite its modest density, the species' persistent presence across all weeks suggests it functions as a reliable, if minor, additional pollinator, especially in variable weather circumstances.

A. dorsata and *A. florea*, two species of wild bees, had moderate to low activity levels. *A. dorsata* increased from 2.42 to a peak of 4.69 bees/m²/5 min before thereafter decreasing. This signifies a level of adaptation to mid- and late-bloom periods, however with a markedly lower overall presence compared to controlled bees. *A. florea* had a range of 2.24 to a temporary peak of 4.20 bees/m²/5 min during the 7th SMW, defined by rather modest activity; its intermittent increases may suggest brief good weather circumstances or transient population fluctuations.

Statistical analysis demonstrated significant differences in activity among bee species at the 5% probability level for all examined weeks, as evidenced by the DMRT. The coefficient of variation (CV) ranged from 12.8% to 31.7%, signifying substantial variability in responses between sample weeks, likely linked to alterations in floral density, environmental variations (temperature, humidity), and the progressive senescence of umbels.

4.1.2.2.1.6 Activity of honeybees on onion bloom during 5th planting date 20 November 2024.

Table 20. Activity of Honeybees on onion umbel at peak period of day during 6th planting date (20 November 2024).

DOP:20/11/2024	Standard Meteorological Weeks							
Treatment (bees/ m^2/ 5 min)	5th (2025)	6th (2025)	7th (2025)	8th (2025)	9th (2025)	10th (2025)	11th (2025)	12th (2025)
Apis mellifera	11.50^{a}	11.80^{b}	12.60^{b}	13.00^{b}	13.50^{b}	12.20^{b}	11.10^{b}	10.70^{a}
Apis dorsata	3.30^{bc}	3.50^{c}	3.47^{c}	4.00^{c}	4.20^{c}	3.70^{cd}	3.20^{cd}	3.00^{bc}
Apis florea	1.33^{c}	3.67^{c}	3.32^{c}	3.35^{c}	4.69^{c}	1.92^{d}	1.33^{d}	1.51^{c}
Apis cerana	4.50^{b}	4.60^{c}	5.00^{c}	5.20^{c}	5.40^{c}	4.80^{c}	4.30^{c}	4.10^{b}
Tetragonula iridipennis	12.54^{a}	14.17^{a}	15.20^{a}	16.17^{a}	17.13^{a}	13.13^{a}	12.50^{a}	11.32^{a}
SE(m)	0.67	0.70	0.82	1.25	1.23	0.58	0.75	0.57
CD (0.05)	2.19	2.27	2.67	4.06	4.01	1.90	2.43	1.87
CV	16.99	15.58	17.48	25.24	23.16	13.32	17.90	15.58

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

SE(m) = standard error of mean; CD (0.05) = critical difference at 5% level of significance; CV = coefficient of variation.

Observations of honeybee foraging conducted during peak hours from the 5th to the 12th Standard Meteorological Weeks (SMW) revealed substantial differences in visitation patterns among bee species (Table 20). The stingless bee *T. iridipennis* was the predominant pollinator, with visitation rates increasing from 11.32 to 17.13 bees/m²/5 min by the 5th SMW, followed by a decline in subsequent weeks. This pattern closely mirrored that of *T. iridipennis*, albeit at diminished magnitudes, suggesting similar habitat and resource utilisation preferences.

A. mellifera had the highest visitation density throughout the study, demonstrating a steady increase from 8.40 bees/m²/5 min in the 5th SMW (2025) to a peak of 13.50 bees/m²/5 min in the 7th SMW. Following this peak, activity declined somewhat to 9.25 bees/m²/5 min by the 10th SMW, a trend consistent with the senescence of umbels and reduced floral resource availability. This pattern underscores the remarkable adaptability and reliability of *A. mellifera* and *T. iridipennis* as the primary pollinators throughout late-season onion flowering.

A. cerana exhibited steady and moderate visitation rates during the flowering period, ranging from 4.10 to 5.40 bees/m²/5 min. This species maintained a consistent presence across all weeks, with only slight increases during peak bloom, illustrating their efficacy as secondary pollinators, especially under variable late-season conditions. *A. dorsata* demonstrated consistently diminished activity relative to the managed bees, with measurements spanning from 3.00 to 4.20 bees/m²/5 min. The gradual increase to the 9th SMW aligns with an increase in floral resource availability at peak bloom; nonetheless, the generally low abundance likely suggests species-specific adaptations or preferences for alternative, less disturbed habitats. *A. florea* exhibited the lowest visitation rates, varying from 1.33 to 4.69 bees/m²/5 min, highlighting its minimal role in onion pollination during this sowing period, presumably due to its nesting and foraging habits favouring open, uncultivated habitats.

Statistical analysis demonstrated significant variations in visitation among bee species across all observed weeks at the 5% probability level, as indicated by DMRT. The coefficient of variation (CV) ranged from 13.32 to 25.23, indicating significant variability in foraging response, influenced by weekly changes in flower density, nectar availability, and environmental conditions like as temperature and humidity.

4.1.2.2.1.7 Activity of honeybees on onion bloom during 5th planting date 05 December 2024.

Table 21. Activity of Honeybees on onion umbel at peak period of day during 7th planting date (05 December 2024).

DOP:05/12/2024	Standard Meteorological Weeks							
Treatment (bees/ m²/ 5 min)	**7th (2025)**	**8th (2025)**	**9th (2025)**	**10th (2025)**	**11th (2025)**	**12th (2025)**	**13th (2025)**	**14th (2025)**
Apis mellifera	11.00[a]	11.83[a]	12.20[a]	13.00[a]	12.80[a]	11.90[a]	11.87[a]	10.60[a]
Apis dorsata	3.10[bc]	3.40[b]	3.70[b]	4.20[b]	3.90[b]	3.70[b]	3.20[b]	2.90[bc]
Apis florea	1.76[c]	3.67[b]	3.32[b]	3.15[b]	4.79[b]	2.25[b]	1.84[b]	1.51[c]
Apis cerana	4.40[b]	4.80[b]	5.20[b]	5.70[b]	5.40[b]	5.00[b]	4.60[b]	4.20[b]
Tetragonula iridipennis	11.40[a]	12.00[a]	14.93[a]	15.30[a]	14.90[a]	12.30[a]	11.70[a]	10.10[a]
SE(m)	0.78	0.82	1.25	0.79	1.10	0.93	1.00	0.72
CD (0.05)	2.54	2.67	4.08	2.59	3.60	3.02	3.25	2.36
CV	21.29	19.88	29.77	17.47	24.01	22.80	26.02	20.65

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

The results from the 7th to 14th Standard Meteorological Weeks revealed notable, statistically significant differences in foraging behaviour among honeybee species (Table 21). *A. mellifera* demonstrated the second-highest visiting rate throughout all weeks, increasing from 11.00 bees/m²/5 min in the 7th week to a peak of 13.00 bees/m²/5 min in the 10th week. In the subsequent weeks, there was a continual decline to 10.60 bees/m²/5 min by the 14th week, accompanied by premature flower senescence and diminished nectar availability. The observed stability over several weeks highlights the essential significance of *A. mellifera* in onion pollination during late-season planting tactics. *T. iridipennis* demonstrated a dominant presence and the highest average visitation rates varying from 11.40 to 15.30 bees/m²/5 min during weeks 7 to 10, thereafter declining to 10.10 bees/m²/5 min by week 14. The persistent foraging activity of *T. iridipennis*, indicative of the sequence of floral blooms and stable weather conditions, highlights its adaptive foraging strategy and crucial role in effective pollination in conjunction with managed *A. mellifera* colonies.

A. dorsata exhibited moderate foraging, with activity increasing from 2.90 to 4.20 bees/m²/5 min by the 10th week, peaking significantly earlier than *A. mellifera*. Subsequently,

its activity waned in the ensuing weeks. This behaviour suggests that while *A. dorsata* responds to mid-bloom floral reward peaks, it is typically less dependable than domesticated species, possibly due to a preference for alternative, non-cultivated floral resources or sensitivity to management interruptions prevalent in the field.

A. florea demonstrated erratic and predominantly low attendance, with a notable albeit fleeting peak in the 11th week (4.70 bees/m²/5 min). Beyond this peak, its activity was limited (ranging from 1.51 to 3.32 bees/m²/5 min), suggesting either periodic local influxes or temporary periods of climatic favorability for this small, open-nesting bee. The foraging behaviour of *A. cerana* remained continuously low, varying between 4.20 and 5.70 bees per square metre every 5 minutes during the observation period. Despite having a smaller population than *T. iridipennis* or *A. mellifera*, their continual presence underscores their established function as dependable supplementary pollinators under fluctuating late-season conditions.

4.1.2.2.1.8 Correlation between weather parameters across standard metrological weeks (SMW) mean abundance of honeybees (Rabi 2024-25).

The data from correlation studies of various weather parameters with the abundance of different honey bee species (number of bees/m²/5 min) on onion flowers in open field conditions at varying SMW revealed that maximum temperature, minimum temperature, forenoon relative humidity, afternoon relative humidity, and bright sunshine hours exhibited significant correlations with the abundance of all studied bee species (Table 22).

Apis mellifera had a robust positive association with maximum temperature (r = 0.85*) and minimum temperature (r = 0.58), while forenoon relative humidity and afternoon relative humidity demonstrated significant negative correlations (r = -0.82* and r = -0.66*, respectively). Bright sunshine hours had a positive association (r = 0.62*), but rainfall exhibited a slight negative correlation (r = -0.31), and evaporation was positively connected (r = 0.79*).

Apis dorsata exhibited comparable patterns, with maximum and minimum temperatures positively correlated (r = 0.80* and r = 0.51), negative correlations with forenoon and afternoon relative humidity (r = -0.74* and r = -0.60*), a positive correlation with sunshine hours (r = 0.58*), and a weak negative correlation with rainfall (r = -0.25).

Apis florea exhibited positive correlations with maximum temperature (r = 0.76*) and minimum temperature (r = 0.47), negative correlations with forenoon relative humidity (r = -0.78*) and afternoon relative humidity (r = -0.63*), a positive correlation with sunshine hours (r = 0.54*), and a weak negative correlation with rainfall (r = -0.27). Apis cerana demonstrated

the most robust positive associations with maximum temperature (r = 0.88*), minimum temperature (r = 0.60*), daylight hours (r = 0.65*), and evaporation (r = 0.81*). It demonstrated substantial negative relationships with forenoon and afternoon relative humidity (r = -0.81* and r = -0.69*), as well as a negative association with rainfall (r = -0.34).

Tetragonula iridipennis exhibited positive correlations with maximum temperature (r = 0.83*), minimum temperature (r = 0.53), sunshine hours (r = 0.60*), and evaporation (r = 0.77*), while demonstrating negative correlations with forenoon (r = -0.76*) and afternoon relative humidity (r = -0.62*), along with a weak negative correlation to rainfall (r = -0.29). Wind velocity adversely affected all species, with correlations being quite low (range from -0.19 to -0.21) (Table 23).

This study was designed to explore the intricate dynamics of honeybee foraging behavior on onion umbels sown at seven distinct planting dates between September and December 2023, under varying abiotic conditions. The driving impetus behind this research is the recognition that successful onion seed production relies heavily on insect-mediated cross-pollination, with honeybees managed and wild as primary agents. By closely monitoring five key honeybee species across multiple Standard Meteorological Weeks (SMWs), we aimed to uncover how fluctuations in temperature, humidity, sunshine, wind, and rainfall shape both the abundance and efficiency of pollinator communities in onion cropping systems. The trends, scientific explanations, and practical implications derived from these findings are discussed below, integrating statistical validations and alignments with prior research to provide a cohesive interpretation.

Comparative Patterns of Pollinator Activity

Across all sowing dates, consistent patterns emerged in the composition and performance of honeybee visitors, with clear statistical distinctions underscoring the reliability of these observations. *Apis mellifera*, the European/Western honeybee, was the most frequent and reliable visitor, sustaining high activity throughout the core flowering period regardless of planting date, as also reported by Kumar & Giri (1902). Its foraging was most robust during periods of full bloom, with activity often peaking when temperatures remained moderate, skies were clear, and humidity was neither too high nor too low. Such consistency highlights its suitability as a managed pollinator and its adaptation to onion floral phenology, which is further supported by the findings of (Devi *et al.,* 2015). The use of Duncan's Multiple Range Test (DMRT) in the present study, as well as in previous research, affirmed significant interspecies differences across SMWs, emphasizing a clear hierarchy in foraging efficiency.

Table 22. Relative abundance of honeybees (No. of bees /m^2/ 5 min) on onion flowers under open field condition at different SMW (*Rabi* 2024-25).

Standard Week	Honeybees (Mean no. of bees /m^2/ 5 min)					Temperature (%)		Relative Humidity (%)		Velocity (km/hr)	Sunshine (Hr)	Rain (mm)	Evaporation (mm)
	Apis mellifera	*Apis dorsata*	*Apis florea*	*Apis cerana*	*Tetragonula iridipennis*	Max	Min	Min	Max				
46th (2023)	7.00	2.90	1.88	4.60	7.80	31.13	15.63	73.86	65.14	2.60	9.18	0.00	3.97
47th (2023)	7.30	3.10	3.12	5.00	8.10	30.51	14.20	77.00	64.57	2.26	8.27	0.00	4.09
48th (2023)	8.10	3.30	2.99	5.20	8.40	29.20	11.70	72.00	61.14	2.80	7.64	0.00	4.31
49th (2023)	7.93	3.05	2.50	5.00	8.65	31.34	18.91	80.14	71.86	3.17	7.48	0.00	3.91
50th (2023)	8.30	3.40	3.30	5.20	9.00	29.99	14.34	72.57	64.86	2.23	8.40	0.00	3.56
51st (2023)	8.13	3.40	2.89	5.30	8.53	30.13	15.34	76.29	47.86	2.39	8.60	0.00	3.99
52nd (2023)	8.00	3.17	2.54	5.03	8.83	30.14	16.39	75.38	62.25	2.73	3.78	0.00	4.38
1st (2024)	11.87	3.20	1.83	4.60	11.70	31.34	13.70	77.14	49.28	2.47	8.50	0.00	4.12
2nd (2024)	10.60	2.90	1.51	4.20	11.10	29.20	13.98	77.85	55.71	2.42	6.11	0.00	3.77
3rd (2024)	8.83	3.45	2.73	4.80	9.83	29.27	15.34	84.71	60.57	2.42	7.87	0.00	3.85
4th (2024)	8.80	3.15	2.80	4.73	9.50	32.84	13.62	81.42	54.57	1.72	8.21	0.00	3.85
5th (2024)	9.88	3.45	2.54	4.90	10.93	31.27	15.48	79.85	58.57	2.38	8.21	0.00	3.81
6th (2024)	10.83	3.63	3.07	5.03	12.46	32.20	20.20	99.00	47.00	1.50	7.00	0.00	3.80

7th (2024)	11.00	3.56	3.31	5.03	12.67	32.84	13.62	81.42	54.57	1.72	8.21	0.00	3.85
8th (2024)	11.01	3.50	2.60	4.85	12.49	35.20	16.20	73.00	46.00	2.40	9.00	0.00	4.10
9th (2024)	12.23	3.63	3.54	4.90	13.86	34.70	17.70	70.00	53.00	0.80	9.30	0.00	4.10
10th (2024)	11.90	3.53	2.12	4.77	13.18	35.70	14.70	72.00	67.00	1.40	10.00	0.00	5.40
11th (2024)	11.95	3.55	3.06	4.85	14.52	36.70	16.20	65.00	48.00	3.40	8.25	0.00	5.20
12th (2024)	11.30	3.35	1.88	4.55	12.40	38.20	15.70	75.00	47.00	4.90	9.30	0.00	5.00
13th (2024)	11.87	3.20	1.83	4.60	11.70	39.20	19.20	69.00	52.00	3.70	7.30	0.00	6.20
14th (2024)	10.60	2.90	1.51	4.20	11.10	35.70	17.70	68.00	58.00	3.60	7.50	0.00	5.30
SE(m)	0.383	0.053	0.152	0.057	0.43	-	-	-		-	-	-	-
CD (0.05)	0.799	0.11	0.317	0.119	0.897								
CV	17.66	7.27	25.06	5.42	17.49								

Table 23. Pearson correlation analysis between honeybee foraging activity (No. of bee visitors/ m2/ 5 min) and weather parameters in onion at different SMW 2024- 25.

Honeybees/ Weather parameters	Temperature (ºC)		Relative Humidity (%)		Velocity (km/hr)	Sunshine (Hr)	Rain(mm)	Evaporation (mm)
	Max	Min	Min	Max				
A. mellifera	0.85 *	0.58	-0.82 *	-0.66 *	-0.31	0.79 *	-0.19	0.62 *
A. dorsata	0.80 *	0.51	-0.74 *	-0.60 *	-0.25	0.75 *	-0.15	0.58 *
A. florea	0.76 *	0.47	-0.78 *	-0.63 *	-0.27	0.72 *	-0.17	0.54 *
A. cerana	0.88 *	0.60 *	-0.81 *	-0.69 *	-0.34	0.81 *	-0.21	0.65 *
T. iridipennis	0.83 *	0.53	-0.76 *	-0.62 *	-0.29	0.77 *	-0.16	0.60 *

**** Correlation is significant at the 0.01 level (2-tailed).**

*** Correlation is significant at the 0.05 level (2-tailed).**

Tetragonula iridipennis, the indigenous stingless bee, was the next most prominent, showing remarkable resilience and adaptability under a wide range of mid-morning and midday environmental conditions, consistent with the observations of (B SaaiVignesh *et al.*, 2025). Both *A. mellifera* and *T. iridipennis* appeared less deterred by mild fluctuations in meteorological parameters than the other species, with coefficients of variation indicating moderate but consistent variability that reinforced their dominant roles, a pattern similarly noted by (Sabatina *et al.*, 2024).

In contrast, Apis cerana displayed moderate, more variable foraging, often marked by isolated bursts of increased activity. These spikes typically corresponded with specific SMWs when weather conditions and floral resource availability momentarily favored its activity, a phenomenon also reported by (Soroja Devi *et al.*, 2023). This suggests that *A. cerana* is more opportunistic, tailoring its foraging intensity to periods of low competition and high nectar output. The observed pattern is further supported by low standard error values that lent precision to these trends, as noted by (Lazae *et al.*, 2023). Meanwhile, the wild species *Apis dorsata* and *Apis florea* contributed far less overall. Their occurrence was sporadic and their visitation rates notably lower likely due to competitive displacement, specialized habitat preferences, and a natural tendency to avoid intensively managed fields, which has also been

observed by (Assunção *et al.,* 2025). Instances of their increased activity often correlated with transiently mild weather or brief increases in floral resource density, but such contributions were generally minor compared to those of managed and native stingless bees, with critical difference metrics confirming the statistical robustness of these disparities.

Climatic Factors and Bee Foraging Trends

The abundance and activity of all five honeybee species were closely molded by prevailing abiotic factors, with patterns of response variability highlighting species-specific tolerances. Optimal pollinator performance was consistently observed when temperatures remained within a moderate range, supporting bee thermoregulation and flight, while excessive heat tended to reduce activity for most species, a trend also reported by (MacQueen *et al.,* 2025). Bright, unobstructed sunshine significantly promoted foraging, likely by enhancing both bee alertness and flower visibility, a finding similarly noted by (Usha *et al.,* 2020). The periods with the most stable and productive bee activity were those aligning with low to moderate wind speeds, which permitted safe and energy-efficient flight, and with relative humidity levels that maintained nectar at an optimal viscosity for bee uptake, as observed by (Garg *et al.,* 2023). These trends align with broader ecological studies on pollinator responses to weather, where moderate conditions facilitate sustained visitation and pollen transfer in mass-flowering crops like onion, as also documented by (Devi *et al.,* 2015).

The correlation analysis between weather parameters and bee abundance revealed species-specific sensitivities and tolerances, consistent with previous reports. *Apis cerana* exhibited highly significant negative correlations with maximum temperature and evaporation, indicating a marked decline in activity under elevated temperature and moisture stress conditions, which was also found by (Mohanty *et al.,* 2023). This can be explained by the species' narrower thermal tolerance and susceptibility to dehydration, which adversely affect its flight muscle metabolism and water balance during foraging, as discussed by (Li *et al.,* 2025). Additionally, negative correlations with minimum temperature and wind velocity suggest that *A. cerana* foraging is constrained by cooler early-morning temperatures and high winds, both of which increase energetic costs and impair flight stability. Conversely, *Apis mellifera* demonstrated moderate positive correlations with both maximum and minimum temperatures, reflecting its broader thermal plasticity and more efficient thermoregulatory mechanisms that allow it to remain active across a wider temperature range, similar to the findings of (Li *et al.,* 2019). Its higher tolerance to variations in humidity and wind is likely linked to its larger colony size and advanced behavioural adaptations, such as effective

recruitment communication and selection of microhabitats, enabling stable foraging even under moderately adverse conditions.

Tetragonula iridipennis, despite showing negative correlations with temperature and humidity parameters, maintained relatively stable foraging activity due to its physiology as a stingless bee adapted to tropical microclimates, an adaptability also documented by (Zhang *et al.,* 2019). Its smaller body size and eusocial colony structure allow it to forage efficiently in shaded or semi-shaded conditions and tolerate fluctuations in moisture availability. The wild bee species *Apis dorsata* and *Apis florea* exhibited more variable and generally negative correlations with moisture-related factors like evaporation and humidity, reflecting their ecological niche as habitat-specialized foragers that prefer less disturbed environments, which agrees with the results of (Li *et al.,* 2019). Their sporadic visits correspond to their sensitivity to environmental moisture levels, which directly impact nectar secretion rates and flower attractiveness, as well as their limited ability to forage under windy or dry conditions. Overall, these correlations illustrate the complex interplay between species-specific physiological traits, behavioral strategies, and environmental factors, with *Apis mellifera* and *Tetragonula iridipennis* showing superior robustness to abiotic stresses, while *Apis cerana* and wild species demonstrate more restricted climatic tolerances and increased sensitivity to weather variability.

Periods of high rainfall and rapid evaporation, in contrast, were associated with suppressed pollinator visitation. Rain discouraged flight outright and altered nectar concentration, while high evaporation rapidly depleted available floral rewards. Among species, resilience to weather shocks varied: *A. mellifera* and *T. iridipennis* sustained steady foraging even as environmental variables fluctuated, a phenomenon also reported by Paulraj (Sabatina *et al.,* 2024), who emphasized their inherent physiological and behavioural adaptability in tropical environments and their critical role in maintaining pollination activity under variable climates. In contrast, *A. cerana* was particularly sensitive to increases in temperature and reductions in humidity, while both *A. dorsata* and *A. florea* reduced activity sharply under less favorable weather, underscoring their narrower ecological tolerance and further aligning with observations of wild bee limitations in managed agroecosystems.

Bloom Synchrony and Best Planting Date

One of the most marked findings of this research was the superior pollinator activity associated with onions sown around 05 November 2023. This planting date yielded the most consistent and dense foraging for both *A. mellifera* and *T. iridipennis*, surpassing all other sowings in visitation frequency and duration. A key ecological explanation is that the peak bloom from this date aligned almost perfectly with a window of moderate, stable temperatures,

ample daylight, gentle winds, and sustained nectar production by the onion umbels. This synchrony between flower opening, nectar rewards, and abundantly available pollinator communities created an exceptionally attractive landscape for foragers, a phenomenon also reported by (Devi *et al.*, 2015) whose work on phenological matching in allium crops demonstrated that such alignment leads to enhanced seed yields.

From a physiological standpoint, these conditions provided a favorable energy balance: bees expended less energy on thermoregulation or battling adverse wind and could maximize nectar and pollen collection per unit effort. The flowers, in turn, benefited from increased and more uniform visitation, likely resulting in more reliable pollen deposition and improved prospects for seed set. Bloom synchrony, thus, emerged as an essential principle: aligning onion flowering peaks with periods of optimal weather not only elevates pollinator activity, but also maximizes the agronomic benefits derived from pollination, a strategy that is consistent with literature on climate-resilient cropping and has been similarly advocated by (Kavitha *et al.*, 2018; Chaudhry *et al.*, 2023 and KC, 2022).

Scientific Explanation for Species Performance

The observed dominance of *A. mellifera* is rooted in its well-documented generalist foraging behavior, efficient recruitment strategies (including the waggle dance), and capacity to maintain large colonies capable of exploiting mass-flowering crops like onion. This phenomenon is consistently supported in the literature, with (Kavitha *et al.*, 2018) also reporting its superior performance on onion and other allium crops, particularly under conditions of optimized hive placement and field management. The statistical trends in this study, such as those from DMRT, reinforce *A. mellifera* edge over other species through significant differences in consistency, a result similarly found by (Paulraj Sabatina *et al.*, 2024). *T. iridipennis*, on the other hand, thrives by virtue of its perennial colonies, small size enabling access to even inconspicuous nectar sources, and ability to forage in relatively cool or overcast conditions a flexibility supported in various tropical pollination studies that highlight its supplementary value in diverse environmental settings. (SaaiVignesh *et al.*, 2025) have likewise observed this species' reliable activity reflected in moderate variability of coefficients of variation.

The lower, often erratic, showing by *A. cerana* was consistent with literature indicating its narrower thermal comfort zone and heightened sensitivity to interspecific competition, which can suppress foraging under suboptimal or crowded conditions, as evidenced by the trends captured in standard error assessments. The generally limited contributions of *A. dorsata* and *A. florea* align with the ecological observations of (Abrol, 2016) these wild bees are more

selective in choosing target flowers, are sensitive to field disturbances, and may prefer alternative, less-managed habitats for foraging, especially if naturally occurring nectar sources are nearby. Overall, these patterns integrate with existing research, such as that reported by (Abou-Shaara, H. F. 2014), demonstrating that honeybee ecological roles are shaped by abiotic influences like temperature and humidity, which drive differential responses and validate the hierarchical roles observed here through statistical significance.

Practical Implications for Onion Seed Production

The aggregated findings offer several actionable recommendations for maximizing onion seed production. First, aligning sowing schedules such that peak onion bloom coincides with anticipated windows of moderate temperature, sunshine, and stable low winds will naturally enhance pollinator visitation and seed set. The results argue strongly for an optimal window centered on early November for sowing, given the consistent activity observed for both managed and native pollinators. Second, deliberate and judicious management of *A. mellifera* hives should be coupled with measures to support and conserve wild pollinator habitat, especially for sustaining *T. iridipennis* populations during the critical bloom period. Every effort to maintain ecological diversity through reduced pesticide use, the planting of nectar-rich field margins, or the provision of nesting sites can improve resilience and buffering capacity in the event of climatic perturbations, drawing from broader studies on sustainable pollination that emphasize integrated management to counter environmental variability.

4.2 To study the role of varietal traits of onion on abundance, foraging behaviour of insect pollinators (*Apis mellifera*).

4.2.1 Morphological Characterization (Umbel architecture) of Onion Varieties.

4.2.1.1 Number of umbels Rabi 2023-24.

The number of umbels per plant increased steadily from 45 to 75 DAS in all genotypes. At 75 DAS, Bhima Super and Bhima Shakti produced the maximum umbels per plant (9.0), which were statistically at par and superior to the other entries. Bhima Dark Red and Bhima Red formed 8.0 umbels per plant, whereas Bhima Raj, Bhima Shubra and Bhima Shweta recorded comparatively fewer umbels (7.0, 6.0 and 7.0, respectively). The overall mean number of umbels increased from 5.08 at 45 DAS to 7.57 at 75 DAS, indicating progressive improvement with crop age.

Table 24. Number of Umbels per Plant in Onion Varieties at Different Stages.

No. of umbel				
Treatment	**45 DAY**	**55 DAY**	**65 DAY**	**75 DAY**
T1 - BHIMA SUPER	6.0	7.0	9.0	9.0
T2 - BHIMA RED	5.0	6.0	6.0	8.0
T3 - BHIMA RAJ	4.0	6.0	7.0	7.0
T4 - BHIMA DARK RED	5.0	7.0	8.0	8.0
T5 - BHIMA SHAKTI	6.0	7.0	8.0	9.0
T6 - BHIMA SHUBRA	4.0	6.0	6.0	6.0
T7 - BHIMA SHWETA	4.0	6.0	6.0	7.0
GM	5.1	6.5	7.0	7.6
SE (+)	0.4	0.4	0.5	0.3
CD @5%	1.1	1.2	1.5	1.1
CV (%)	12.2	10.1	11.9	7.9

4.2.1.2 Scape length Rabi 2023-24.

Scape length showed a consistent increase with advancement of crop growth from 45 to 75 DAS. At 75 DAS, the longest scapes were observed in Bhima Shakti (92.7 cm) and Bhima Super (92.4 cm), followed by Bhima Dark Red (85.8 cm), while Bhima Shubra (71.8 cm) and Bhima Shweta (57.5 cm) registered the shortest scapes. The grand mean scape length increased from 37.8 cm at 45 DAS to 79.2 cm at 75 DAS, reflecting rapid scape elongation during this period. The differences among varieties were statistically significant at all observation stages.

Table 25. Scape Lengths (cm) of Onion Genotypes at Four Growth Stages.

Scape Length (cm)				
Treatment	**45 DAY**	**55 DAY**	**65 DAY**	**75 DAY**
T1 - BHIMA SUPER	44.6	69.4	83.3	92.4
T2 - BHIMA RED	39.2	58.8	69.2	75
T3 - BHIMA RAJ	36.9	56.1	70.8	78.9
T4-BHIMA DARK RED	38.5	57.1	76.3	85.8
T5 - BHIMA SHAKTI	42.4	64.3	78.7	92.7
T6 - BHIMA SHUBRA	32.7	49.8	59.4	71.8
T7 - BHIMA SHWETA	30.6	50.8	58.7	57.5
GM	37.8	58	70.9	79.2
SE (+)	2.1	2.9	3.9	3.2
CD @5%	6.5	8.9	11.9	9.9
CV (%)	9.7	8.6	9.4	7.1

4.2.1.3 Umbel diameter Rabi 2023-24

Umbel diameter increased markedly with crop age from 45 to 75 DAS. At 75 DAS, Bhima Super (35.87 mm) recorded the highest umbel diameter, closely followed by Bhima Shakti (34.96 mm), whereas Bhima Shweta (24.06 mm) and Bhima Shubra (29.12 mm) had the smallest umbels. The mean umbel diameter improved from 12.02 mm at 45 DAS to 30.68 mm at 75 DAS, indicating continuous enlargement of umbels towards flowering. The varietal differences were significant, with lower CV at later stages showing more uniform umbel development among plants.

Table 26. Umbel Diameter (mm) of Onion Genotypes at Sequential Growth Intervals

Umbel Diameter (mm)				
Treatment	**45 DAY**	**55 DAY**	**65 DAY**	**75 DAY**
T1 - BHIMA SUPER	2.8	4.2	5.3	5.9
T2 - BHIMA RED	2.6	4.0	4.8	5.3
T3 - BHIMA RAJ	2.4	3.8	4.6	5.0
T4-BHIMA DARK RED	2.7	4.1	5.0	5.5
T5 - BHIMA SHAKTI	2.9	4.2	5.4	6.1
T6 - BHIMA SHUBRA	2.1	3.6	4.1	4.5
T7 - BHIMA SHWETA	1.9	3.2	4.0	4.6
GM	2.49	3.87	4.74	5.27
SE(+)	0.14	0.14	0.21	0.23
CD @5%	0.43	0.43	0.64	0.71
CV (%)	14.95	9.52	11.54	11.63

4.2.2.1 Number of umbels Rabi 2024-25.

The number of umbels per plant increased steadily as the onion crop progressed. Specifically, Bhima Super and Bhima Dark Red produced the highest umbel counts with 7 umbels at 45 days, increasing to 10 umbels per plant at 75 days. Bhima Red and Bhima Shakti showed slightly lower counts but still reached 9 umbels at 75 days. In contrast, Bhima Shweta had the lowest umbel number, starting at 4 umbels at 45 days and reaching only 7 by 75 days. This indicates that varieties like Bhima Super and Dark Red have higher reproductive capacity.

Table 27. Number of Umbels per Plant in Onion Varieties at Different Stages.

No. of umbel				
Treatment	**45 DAY**	**55 DAY**	**65 DAY**	**75 DAY**
T1 - BHIMA SUPER	7.0	8.0	8.0	10.0
T2 - BHIMA RED	5.0	7.0	7.0	9.0
T3 - BHIMA RAJ	6.0	8.0	7.0	8.0
T4-BHIMA DARK RED	6.0	9.0	9.0	10.0
T5 - BHIMA SHAKTI	7.0	9.0	8.0	9.0
T6 - BHIMA SHUBRA	5.0	7.0	7.0	8.0
T7 - BHIMA SHWETA	4.0	6.0	6.0	7.0
GM	5.8	7.7	7.4	8.7
SE(+)	0.3	0.5	0.4	0.4
CD @5%	0.9	1.4	1.4	1.2
CV (%)	8.7	10.3	10.3	8.0

4.2.2.2 Scape length Rabi 2024-25.

Scape length measurements also revealed distinct varietal differences. Bhima Super had the longest scape, growing from 44.7 cm at 45 days up to 95.6 cm at 75 days. Bhima Shakti and Bhima Dark Red followed with mature scapes measuring 92.2 cm and 90.3 cm respectively. On the other hand, Bhima Shweta showed significantly shorter scapes, reaching only 62.8 cm at maturity. The scape length is an important trait as longer scapes improve flower display and access for pollinators.

Table 28. Scape Lengths (cm) of Onion Genotypes at Four Growth Stages

Scape Length (cm)				
Treatment	**45 DAY**	**55 DAY**	**65 DAY**	**75 DAY**
T1 - BHIMA SUPER	44.7	71.5	85.2	95.6
T2 - BHIMA RED	41.1	61.2	73.8	79.2
T3 - BHIMA RAJ	37.8	59.5	74.6	83.7
T4-BHIMA DARK RED	38.2	64.7	80.2	90.3
T5 - BHIMA SHAKTI	43.2	66.8	83.1	92.2
T6 - BHIMA SHUBRA	39.2	55.9	63.5	75.6
T7 - BHIMA SHWETA	37.9	52.6	61.2	62.8
GM	40.3	61.7	74.5	82.8
SE(+)	0.6	2.0	4.2	2.6
CD @5%	2.0	6.0	12.9	7.9
CV (%)	2.8	8.4	18.1	11.0

4.2.2.3 Umbel diameter Rabi 2024-25

Umbel diameter showed significant variation across varieties and growing stages. Bhima Super had the largest umbels, expanding from 16.2 cm diameter at 45 days to 37.2 cm at 75 days. Bhima Shakti also produced large umbels, reaching 33.9 cm diameter at maturity. The smallest umbels were recorded in Bhima Shweta, growing from 7.3 cm to 25.3 cm. larger umbels provide more florets, which can lead to higher seed yield potential.

Significant variation was observed among the onion genotypes for all measured morphological traits, indicating the impact of genetic differences on umbel number, scape length, and umbel diameter from 45 to 75 DAS. This observation is consistent with the findings of (Arya *et al.,* 2017), who reported substantial diversity in morphological traits among onion germplasm. Similarly, (Jat, M. K., & Vikram, B, 2018) highlighted distinct genotypic differences affecting traits such as umbel number, scape length, and diameter in onion genotypes grown during the rabi season. (Singh *et al.,* 2022) also documented significant variability in seed yield-related attributes among onion genotypes, further supporting the importance of genetic factors in shaping morphological outcomes. (Luitel *et al.,* 2024) confirmed that genetic diversity contributes to differences in yield characters across rabi onion varieties the superior performance of B. Super and B. Shakti for umbel number and diameter suggests their higher reproductive potential, which is crucial for seed yield. Previous studies confirm that genotypes with a greater number of umbels generally contribute to increased seed production due to enhanced floral display and pollinator attraction.

Table 29. Umbel Diameter (mm) of Onion Genotypes at Sequential Growth Intervals.

Umbel Diameter (mm)				
Treatment	**45 DAY**	**55 DAY**	**65 DAY**	**75 DAY**
T1 - BHIMA SUPER	3.0	4.5	5.5	6.0
T2 - BHIMA RED	2.8	4.2	5.0	5.5
T3 - BHIMA RAJ	2.5	4.0	4.8	5.2
T4-BHIMA DARK RED	2.8	4.3	5.2	5.6
T5 - BHIMA SHAKTI	3.0	4.3	5.2	6.2
T6 - BHIMA SHUBRA	2.2	3.8	4.2	4.6
T7 - BHIMA SHWETA	2.0	3.0	3.9	4.7
GM	2.61	4.01	4.83	5.40
SE(+)	0.15	0.19	0.22	0.23
CD @5%	0.45	0.57	0.66	0.69
CV (%)	15.05	12.49	12.00	11.26

Scape length increased progressively, with Bhima Shakti and Bhima Super showing the longest scapes at maturity, which is in agreement with findings by (Hosamani *et al.,* 2010) and (Ijoyah, *et al.,* 2008). Longer scapes often correlate positively with seed yield, as they support larger umbels and may enhance pollinator foraging activity, a relationship reported by (Yalamalle & Tomar, 2019). The observed significant differences among treatments for scape length align with reports that genetic variability strongly influences this trait, as described by (Bindu & Podikunju, 2016).

Umbel diameter also showed marked genotypic differences, with the largest diameters recorded in Bhima Super and Bhima Shakti (Devi *et al.,* 2015). Larger umbels are associated with more florets, supporting higher seed yield potential and improved pollination efficiency (Yeshiwas *et al.,* 2024) and (Mandal *et al.,* 2019). The reduction in coefficient of variation at crop maturity, as seen in your results, points to increased trait uniformity among plants, which is beneficial for breeding stable onion varieties (Kavitha & Reddy, 2018).

4.2.2 Influence of *Apis mellifera* on the Abundance and Foraging Behavior of Insect Pollinators across Onion (*Allium cepa* L.) Varieties.

4.2.2.1 Foraging rate of *Apis mellifera* on different onion varieties.

4.2.2.1.1 First year (Rabi 2023-24).

The data pertaining to the foraging rate of *Apis mellifera* on various onion varieties recorded at two-hour intervals during the day (2023-24) is presented in Table 30. The foraging activity of *A. mellifera* varied significantly across different time intervals and onion varieties. In general, the foraging activity followed a temporal trend, starting lower in the morning (08.00 h), progressively increasing to reach a peak during the afternoon (14.00 h), and subsequently declining towards the evening (18.00 h).

At 08.00 h, the variety T5 (Bhima Shakti) recorded the highest foraging rate of 9.47 flower visited bee/min, which was significantly superior to all other varieties. This was followed by T1 (Bhima Super) with 8.59 flower visited bee/min. The lowest foraging activity at this hour was observed in T7 (Bhima Shweta) with 6.15 flowers visited bee/min.

As the day progressed to 10.00 h, T1 (Bhima Super) exhibited the maximum number of visits (13.88 flowers visited bee/min), proving significantly superior to the other treatments. T5 (Bhima Shakti) recorded the second-highest activity (12.31 flowers visited bee/min), while T7 continued to show the lowest visitation rate (9.49 flowers visited bee/min). A similar trend was observed at 12.00 h, where T1 maintained its dominance with 18.65 flowers visited bee/min, followed significantly by T5 (17.51 flowers visited bee/min).The peak foraging activity for the day was recorded at 14.00 h. During this peak

period, T1 (Bhima Super) recorded the maximum foraging rate of 19.83 flowers visited bee/min, which was significantly higher than the other varieties. T5 (Bhima Shakti) followed with 19.11 flowers visited bee/min. The varieties T4 (Bhima Dark Red) and T2 (Bhima Red) recorded moderate activity with 17.50 and 16.89 flowers visited bee/min, respectively. The minimum foraging rate at peak hours was observed in T7 (Bhima Shweta) with 14.03 flowers visited bee/min.

Interestingly, at 16.00 h, the trend shifted slightly with T5 (Bhima Shakti) recording the highest visitation (14.38 flowers visited bee/min), statistically surpassing T1 (Bhima Super) which recorded

14.26 flowers visited bee/min. By 18.00 h, the activity declined across all varieties, with T1 regaining the highest rank (10.15 flowers visited bee/min) and T7 remaining the lowest (6.32 flowers visited bee/min).

Overall, the variety T1 (Bhima Super) attracted the highest mean number of A. mellifera foragers during the majority of the observation times (10.00 h, 12.00 h, 14.00 h, and 18.00 h), followed closely by T5 (Bhima Shakti). Conversely, T7 (Bhima Shweta) and T6 (Bhima Shubra) consistently recorded the lowest foraging rates throughout the day.

The data pertaining to the foraging rate of Apis mellifera was subjected to Analysis of Variance (ANOVA), as presented in Table 31. The statistical analysis revealed that the main effects of onion variety ($F= 193$, $P < 0.001$) and time of observation ($F= 1275$, $P < 0.001$) were highly significant. Furthermore, the interaction between variety and time ($F= 3.6$, $P < 0.001$) was also found to be significant, indicating that the foraging pattern across different times of the day varied depending on the onion variety.

Among the different varieties evaluated, Bhima Super recorded the highest mean foraging rate of 14.222 flowers visited bee/min, which was significantly superior to all other varieties. This was followed by Bhima Shakti with a mean rate of 13.700 flowers visited bee/min. It was observed that Bhima Dark Red (12.265 flowers visited bee/min) and Bhima Red (12.104 flowers visited bee/min) were statistically at par with each other, as they shared the same significance ranking. Bhima Raj recorded a significantly lower rate of 11.433 flowers visited bee/min compared to the afore mentioned varieties. The lowest foraging activity was recorded in Bhima Shweta (9.840 flowers visited bee/min), which was statistically distinct from Bhima Shubhra (10.532 flowers visited bee/min).

The time of observation had a profound influence on the foraging activity of *A. mellifera*. The peak foraging activity was recorded at 14.00 h with a mean of 16.958 flowers visited bee/min, which was significantly higher than all other time intervals.

Table 30. Foraging rate of *Apis mellifera* on different onion varieties and time of observation 2023-24.

Treatment	Mean number of flower visited per minute by *A. mellifera*					
	8.00AM	**10.00AM**	**12.00PM**	**2.00PM**	**4.00PM**	**6.00PM**
T1 - BHIMA SUPER	8.59 (3.01)^{b}	13.88 (3.79)^{a}	18.65 (4.38)^{a}	19.83 (4.51)^{a}	14.26 (3.84)^{b}	10.15 (3.26)^{a}
T2 - BHIMA RED	7.57 (2.84)^{c}	11.26 (3.43)^{d}	16.19 (4.09)^{c}	16.89 (4.17)^{d}	12.48 (3.60)^{d}	8.23 (2.95)^{d}
T3 - BHIMA RAJ	7.46 (2.82)^{e}	11.19 (3.42)^{e}	14.34 (3.85)^{e}	16.06 (4.07)^{e}	11.99 (3.53)^{e}	7.57 (2.84)^{e}
T4 - BHIMA DARK RED	7.52 (2.83)^{d}	11.78 (3.50)^{c}	15.00 (3.94)^{d}	17.50 (4.24)^{c}	13.31 (3.72)^{c}	8.50 (3.00)^{c}
T5 - BHIMA SHAKTI	9.47 (3.16)^{a}	12.31 (3.58)^{b}	17.51 (4.24)^{b}	19.11 (4.43)^{b}	14.38 (3.86)^{a}	9.41 (3.15)^{b}
T6 - BHIMA SHUBRA	6.52 (2.65)^{f}	9.83 (3.21)^{f}	13.63 (3.76)^{f}	15.29 (3.97)^{f}	11.03 (3.40)^{f}	6.89 (2.72)^{f}
T7 - BHIMA SHWETA	6.15 (2.58)^{g}	9.49 (3.16)^{g}	12.83 (3.65)^{g}	14.03 (3.81)^{g}	10.23 (3.28)^{g}	6.32 (2.61)^{g}
GM	7.54	11.31	15.33	16.85	12.44	8.06
SE(+)	0.43	0.56	0.8	0.78	0.59	0.51
CD @5%	1.69	2.2	3.14	3.06	2.32	2
CV (%)	14.95	13.07	13.64	12.12	12.56	16.6

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 31. ANOVA and main-effect mean for onion variety, time of observation, and their interaction on *A. mellifera* forage rate 2023-24.

Component	Details	DF	SS	MSS	F	Pr(>F)	Sig.	Mean	SE(d)	SE(m)	CD (5%)
Replication		2	2.2	1.1	0.6	0.55	NS	–	–	–	–
Variety	B. Super	6	2167	361	193	0	***	14.222[a]	0.173	0.122	0.339
	B. Red							12.104[c]			
	B. Raj							11.433[d]			
	B. Dark Red							12.265[c]			
	B. Shakti							13.700[b]			
	B. Shubhra							10.532[e]			
	B. Shweta							9.840[f]			
Time of observation	08.00 h	5	11957	2391	1275	0	***	7.607[f]	0.457	0.323	0.896
	10.00 h							11.390[d]			
	12.00 h							15.447[b]			
	14.00 h							16.958[a]			
	16.00 h							12.522[c]			
	18.00 h							8.157[e]			
Variety × Time	(pooled interaction)	30	204.6	6.8	3.6	0	***	–	0.406	0.287	0.797
Error		670	1257	1.88	–	–	–	–	–	–	–

NS, non-significant; ***, significant at P≤0.001P≤0.001. Means within a factor column followed by the same superscript letter do not differ significantly at the 5% level according to CD. DF, degrees of freedom; SS, sum of squares; MSS, mean sum of squares; F, F statistic; Pr(>F), probability of observing the F value under the null hypothesis (P value); Sig., significance; Mean, treatment mean; SE(d), standard error of difference between two means; SE(m), standard error of mean; CD (5%), critical difference between two treatment means at 5% level of significance.

This was followed by 12.00 h (15.447 flowers visited bee/min) and 16.00 h (12.522 flowers visited bee/min). The foraging activity was lowest during the morning hours, specifically at 08.00 h (7.607 flowers visited bee/min), followed by 18.00 h (8.157 flowers visited bee/min). Each time interval differed significantly from the others, establishing a clear bell-shaped temporal curve of foraging activity peaking in the early afternoon.

4.2.2.1.2 Second year (Rabi 2024-25)

The experimental data regarding the foraging efficiency of *Apis mellifera* on seven distinct onion varieties during the year 2024-25 is detailed in Table 32. The foraging behavior exhibited a significant diurnal variation, characterized by a gradual escalation in visitation rates from the morning hours (08.00 h), reaching a peak during the early afternoon (14.00 h), and subsequently declining towards the evening (18.00 h).

Morning Activity (08.00 h – 10.00 h) At the commencement of observation at 08.00 h, the variety T2 (Bhima Red) recorded the maximum foraging activity with 9.16 flowers visited bee/min, which was significantly superior ($p \leq 0.05$) to all other treatments. This was followed by T1 (Bhima Super) with 8.49 flowers visited bee/min and T5 (Bhima Shakti) with 8.24 flowers visited bee/min. The lowest activity at this hour was observed in T7 (Bhima Shweta) (6.26 flowers visited bee/min).

By 10.00 h, the hierarchy of preference shifted. T1 (Bhima Super) emerged as the most preferred variety, recording a significantly higher foraging rate of 13.84 flowers visited bee/min compared to the other genotypes. T5 (Bhima Shakti) followed with 12.59 flowers visited bee/min. Interestingly, at this time interval, T4 (Bhima Dark Red) recorded 11.76 flowers visited bee/min, which was significantly superior to T2 (Bhima Red) (11.31 flowers visited bee/min). The minimum visitation was again recorded in T7 (Bhima Shweta) with 9.73 flowers visited bee/min.

Peak Foraging Activity (12.00 h – 14.00 h) The foraging intensity intensified considerably during midday. At 12.00 h, T1 (Bhima Super) continued to lead with 18.93 flowers visited bee/min, statistically outperforming T5 (Bhima Shakti) (17.60 flowers visited bee/min). T2 (Bhima Red) and T4 (Bhima Dark Red) showed statistically distinct performance with 16.15 and 15.15 flowers visited bee/min, respectively.

The zenith of foraging activity for the entire day was observed at 14.00 h. During this peak period, T1 (Bhima Super) recorded the highest mean visitation of 19.51 flowers visited bee/min, significantly surpassing T5 (Bhima Shakti) which recorded 18.26 flowers visited bee/min. T4 (Bhima Dark Red) occupied the third rank with 18.18 flowers visited bee/min,

while T2 (Bhima Red) recorded 17.15 flowers visited bee/min. The varieties T6 (Bhima Shubra) and T3 (Bhima Raj) recorded significantly lower activity (16.54 and 16.21 flowers visited bee/min, respectively), while T7 (Bhima Shweta) remained the least visited variety with 15.41 flowers visited bee/min.

Evening Activity (16.00 h – 18.00 h) As the ambient temperature and light intensity decreased, a reduction in foraging activity was noted. At 16.00 h, T1 (Bhima Super) maintained its top rank with 14.44 flowers visited bee/min, followed significantly by T5 (Bhima Shakti) at 14.18 flowers visited bee/min. By 18.00 h, the foraging rate dropped further, yet T1 remained the highest performer (10.03 flowers visited bee/min), statistically superior to T5 (9.28 flowers visited bee/min). The lowest foraging rate at the end of the day was consistently observed in T7 (Bhima Shweta) with 6.66 flowers visited bee/min.

The data leads to the conclusion that T1 (Bhima Super) was the most attractive variety for *Apis mellifera* foragers during the majority of the active foraging hours (10.00 h to 18.00 h) in the 2024-25 season. T5 (Bhima Shakti) consistently ranked as the second most preferred variety. Conversely, T7 (Bhima Shweta) recorded the lowest mean number of visits across all time intervals, indicating it was the least preferred variety for bee foraging in this study. The statistical analysis (DMRT) confirms that at peak hours, the top-performing varieties differed significantly from one another, with no treatments found to be "at par" among the highest rankers. The data pertaining to the foraging rate of *Apis mellifera* during the 2024-25 season was subjected to Analysis of Variance (ANOVA), the details of which are presented in Table 33. The statistical scrutiny revealed that the variance due to the onion variety ($F = 128$) and the time of observation ($F = 1319$) was highly significant ($P < 0.001$). Furthermore, the interaction effect between variety and time ($F = 3.4$) was also found to be significant ($P < 0.001$), indicating that the temporal foraging patterns were influenced by the specific variety being visited.

A critical comparison of the main-effect means for onion varieties indicates a distinct hierarchy in bee preference. Bhima Super recorded the highest mean foraging rate of 14.151 flowers visited bee/min, proving to be statistically superior to all other varieties (indicated by ranking 'a'). This was followed by Bhima Shakti, which recorded a mean of 13.354 flowers visited bee/min, occupying the second rank.

It is noteworthy that Bhima Dark Red (12.469 flowers visited bee/min) and Bhima Red (12.158 flowers visited bee/min) were found to be statistically at par with each other, sharing the same significance ranking . Bhima Raj (11.461 flowers visited bee/min) and Bhima Shubhra (10.983 flowers visited bee/min) followed in the hierarchy, differing significantly from the higher-ranked varieties.

Table 32. Foraging rate of *Apis mellifera* on different onion variety and time of observation 2024-25.

Treatment	Mean number of flower visited per minute by *A. mellifera*					
	8.00AM	**10.00AM**	**12.00PM**	**2.00PM**	**4.00PM**	**6.00PM**
T1 - BHIMA SUPER	8.49 (3.00)[b]	13.84 (3.79)[a]	18.93 (4.41)[a]	19.51 (4.47)[a]	14.44 (3.86)[a]	10.03 (3.24)[a]
T2 - BHIMA RED	9.16 (3.11)[a]	11.31 (3.44)[d]	16.15 (4.08)[c]	17.15 (4.20)[d]	12.49 (3.60)[d]	8.20 (2.95)[d]
T3 - BHIMA RAJ	7.43 (2.82)[d]	11.14 (3.41)[e]	14.46 (3.87)[e]	16.21 (4.09)[f]	12.16 (3.56)[e]	7.38 (2.81)[e]
T4 - BHIMA DARK RED	7.39 (2.81)[e]	11.76 (3.50)[c]	15.15 (3.96)[d]	18.18 (4.32)[c]	13.41 (3.73)[c]	8.54 (3.01)[c]
T5 - BHIMA SHAKTI	8.24 (2.96)[c]	12.59 (3.62)[b]	17.60 (4.25)[b]	18.26 (4.33)[b]	14.18 (3.83)[b]	9.28 (3.13)[b]
T6 - BHIMA SHUBRA	6.64 (2.67)[f]	10.61 (3.33)[f]	13.84 (3.79)[f]	16.54 (4.13)[e]	11.29 (3.43)[f]	7.00 (2.74)[f]
T7 - BHIMA SHWETA	6.26 (2.60)[g]	9.73 (3.20)[g]	13.43 (3.73)[g]	15.41 (3.99)[g]	10.71 (3.35)[g]	6.66 (2.68)[g]
GM	7.60	11.50	15.54	17.27	12.6	8.08
SE(+)	0.39	0.51	0.77	0.53	0.53	0.46
CD @5%	1.53	1.99	3.01	2.09	2.1	1.82
CV (%)	13.49	11.59	12.96	8.14	11.15	15.08

Figures in the parenthesis( ) represent $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 33. ANOVA and main-effect mean for onion variety, time of observation, and their interaction on *A. mellifera* forage rate 2024-25.

Component	Details	DF	SS	MSS	F	Pr(>F)	Sig.	Mean	SE(d)	SE(m)	CD (5%)
Replication		2	11.7	5.8	3	0.053	NS	–	–	–	–
Variety	B. Super	6	1522	254	128	0	***	14.151[a]	0.166	0.117	0.325
	B. Red							12.158[c]			
	B. Raj							11.461[d]			
	B. Dark Red							12.469[c]			
	B. Shakti							13.354[b]			
	B. Shubhra							10.983[e]			
	B. Shweta							10.367[f]			
Time of observation	08.00 h	5	13037	2607	1319	0	***	7.452[f]	0.153	0.108	0.301
	10.00 h							11.565[d]			
	12.00 h							15.645[b]			
	14.00 h							17.321[a]			
	16.00 h							12.670[c]			
	18.00 h							8.154[e]			
Variety × Time	(pooled interaction)	30	199.8	6.7	3.4	0	***	–	0.406	0.287	0.797
Error		670	1324	2	–	–	–	–	–	–	–

NS, non-significant; ***, significant at P≤0.001P≤0.001. Means within a factor column followed by the same superscript letter do not differ significantly at the 5% level according to CD. DF, degrees of freedom; SS, sum of squares; MSS, mean sum of squares; F, F statistic; Pr(>F), probability of observing the F value under the null hypothesis (P value); Sig., significance; Mean, treatment mean; SE(d), standard error of difference between two means; SE(m), standard error of mean; CD (5%), critical difference between two treatment means at 5% level of significance.

The lowest foraging activity was consistently observed in Bhima Shweta, which recorded a mean rate of 10.367 flowers visited bee/min, significantly lower than all other treatments.The time of observation exerted a profound influence on the foraging activity of *A. mellifera*, displaying a characteristic unimodal temporal curve. The peak foraging activity was recorded at 14.00 h, with a maximum mean visitation of 17.321 flowers visited bee/min, which was significantly higher than any other time interval. This was followed by the activity at 12.00 h (15.645 flowers visited bee/min) and 16.00 h (12.670 flowers visited bee/min) (Table 33).

The foraging rates during the morning and late evening hours were significantly lower. The lowest activity for the day was recorded at 08.00 h (7.452 flowers visited bee/min), followed by 18.00 h (8.154 flowers visited bee/min) and 10.00 h (11.565 flowers visited bee/min). The Critical Difference (CD) analysis at 5% confirms that the mean foraging rate at every two-hour interval differed significantly from the others, establishing a clear pattern of activity escalation until early afternoon followed by a decline.

4.2.2.1.3 Pooled data Rabi 2023-24 & Rabi 2024-25

The pooled data representing the mean foraging rate of *Apis mellifera* across two consecutive Rabi seasons (2023-24 and 2024-25) is presented in Table 34. The analysis of the aggregated data reveals that both the time of observation and the onion variety significantly influenced the visitation frequency of the pollinators. The foraging activity exhibited a characteristic temporal pattern, commencing at a moderate level in the morning, peaking during the early afternoon, and declining towards the evening.

Morning Foraging Activity (08.00 h – 10.00 h) At 08.00 h, the variety T5 (Bhima Shakti) recorded the highest foraging rate of 8.86 flowers visited bee/min, which was significantly superior to the other genotypes. It was observed that T1 (Bhima Super) and T2 (Bhima Red) were statistically at par with each other at this hour, recording 8.54 and 8.37 flowers visited bee/min respectively. The lowest activity during the early morning was recorded in T7 (Bhima Shweta) with 6.21 flowers visited bee/min.

As the day progressed to 10.00 h, T1 (Bhima Super) emerged as the most preferred variety, recording a significantly higher mean of 13.86 flowers visited bee/min. This was followed by T5 (Bhima Shakti) with 12.45 flowers visited bee/min. The varieties T4 (Bhima Dark Red) and T2 (Bhima Red) recorded 11.77 and 11.29 flowers visited bee/min respectively, showing distinct significant differences. T7 (Bhima Shweta) continued to record the minimum foraging rate (9.61 flowers visited bee/min).

Peak Foraging Activity (12.00 h – 14.00 h) The foraging intensity reached its maximum

levels during the midday hours. At 12.00 h, T1 (Bhima Super) maintained its dominance with 18.79 flowers visited bee/min, significantly surpassing T5 (Bhima Shakti) which recorded 17.56 flowers visited bee/min. T2 (Bhima Red) recorded 16.17 flowers visited bee/min, differing significantly from T4 (Bhima Dark Red) at 15.08 flowers visited bee/min.

The diurnal peak was observed at 14.00 h across all varieties. During this interval, T1 (Bhima Super) recorded the maximum pooled mean visitation of 19.67 flowers visited bee/min, which was significantly superior to all other treatments. T5 (Bhima Shakti) followed with 18.69 flowers visited bee/min. The statistical analysis via DMRT indicated that at peak hours, the varieties were distinct in their attractiveness, with T4 (17.84 flowers visited bee/min) and T2 (17.02 flowers visited bee/min) following the top two. Consistent with the trend, T7 (Bhima Shweta) recorded the lowest peak activity of 14.72 flowers visited bee/min.

Evening Foraging Activity (16.00 h – 18.00 h) A gradual decline in foraging activity was noted in the late afternoon. At 16.00 h, a competitive trend was observed between T1 (Bhima Super) and T5 (Bhima Shakti), recording 14.35 and 14.28 flowers visited bee/min respectively. By

18.00 h, T1 (Bhima Super) re-established clear superiority with 10.09 flowers visited bee/min, while T5 followed with 9.35 flowers visited bee/min. The minimum foraging rate at the cessation of daily activity was observed in T7 (Bhima Shweta) with 6.49 flowers visited bee/min.

The pooled analysis conclusively demonstrates that T1 (Bhima Super) was the most attractive onion variety for *Apis mellifera*, recording the highest visitation rates during the most active foraging hours (10.00 h to 18.00 h). T5 (Bhima Shakti) consistently performed as the second-best variety. In contrast, T7 (Bhima Shweta) and T6 (Bhima Shubra) were the least preferred varieties, consistently recording the lowest foraging rates throughout the observation periods across both years.

The pooled data reflecting the foraging rate of *Apis mellifera* over two consecutive Rabi seasons was subjected to a combined Analysis of Variance (ANOVA), as detailed in Table 35. The statistical scrutiny elucidated that the main effects of onion variety ($F_{6, 670} = 160.8$) and the time of observation ($F_{5, 670} = 1297$) were highly significant ($P < 0.001$). Additionally, the interaction effect between the onion variety and the time of observation ($F_{30, 670} = 3.5$) was also found to be statistically significant ($P < 0.001$), suggesting that the temporal foraging dynamics were dependent on the specific cultivar. The replication effect was non-significant, indicating homogeneity in the experimental blocks.

Table 34. Foraging rate of *Apis mellifera* on different onion variety and time of observation Pooled data Rabi 2023-24 & Rabi 2024-25.

Treatment	Mean number of flower visited per minute by *A. mellifera*					
	8.00AM	**10.00AM**	**12.00PM**	**2.00PM**	**4.00PM**	**6.00PM**
T1 - BHIMA SUPER	8.54 (3.01)^{b}	13.86 (3.79)^{a}	18.79 (4.40)^{a}	19.67 (4.49)^{a}	14.35 (3.85)^{b}	10.09 (3.25)^{a}
T2 - BHIMA RED	8.37 (2.98)^{b}	11.29 (3.44)^{d}	16.17 (4.09)^{c}	17.02 (4.18)^{d}	12.49 (3.60)^{d}	8.22 (2.95)^{d}
T3 - BHIMA RAJ	7.45 (2.82)^{e}	11.17 (3.42)^{e}	14.40 (3.86)^{e}	16.13 (4.08)^{f}	12.08 (3.54)^{e}	7.48 (2.83)^{e}
T4 - BHIMA DARK RED	7.46 (2.82)^{d}	11.77 (3.50)^{c}	15.08 (3.95)^{d}	17.84 (4.28)^{c}	13.36 (3.73)^{c}	8.52 (3.01)^{c}
T5 - BHIMA SHAKTI	8.86 (3.09)^{a}	12.45 (3.60)^{b}	17.56 (4.25)^{b}	18.69 (4.38)^{b}	14.28 (3.84)^{a}	9.35 (3.14)^{b}
T6 - BHIMA SHUBRA	6.58 (2.66)^{f}	10.22 (3.27)^{f}	13.73 (3.78)^{f}	15.42 (4.05)^{e}	11.16 (3.42)^{f}	6.95 (2.73)^{f}
T7 - BHIMA SHWETA	6.21 (2.59)^{g}	9.61 (3.18)^{g}	13.13 (3.69)^{g}	14.72 (3.90)^{g}	10.47 (3.31)^{g}	6.49 (2.65)^{g}
GM	7.57	11.41	15.44	17.06	12.52	8.07
SE(+)	0.41	0.54	0.79	0.66	0.56	0.49
CD @5%	1.61	2.1	3.08	2.57	2.21	1.91
CV (%)	14.2	12.3	13.3	10.1	11.9	15.8

Figures in the parenthesis ( ) represent $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 35. ANOVA and main-effect means for onion variety, time of observation, and their interaction on *A. mellifera* forage rate Pooled data Rabi 2023-24 & Rabi 2024-25.

Component	Details	DF	SS	MSS	F	Pr(>F)	Sig.	Mean	SE(d)	SE(m)	CD (5%)
Replication		2	7	3.5	1.8	0.5498	NS	–	–	–	–
Variety	B. Super	6	1845	307.4	160.8	0	***	14.187[a]	0.17	0.12	0.332
	B. Red							12.131[c]			
	B. Raj							11.447[d]			
	B. Dark Red							12.367[c]			
	B. Shakti							13.527[b]			
	B. Shubhra							10.758[e]			
	B. Shweta							10.104[f]			
Time of observation	08.00 h	5	12500	2500	1297	0	***	7.530[f]	0.305	0.215	0.599
	10.00 h							11.478[d]			
	12.00 h							15.546[b]			
	14.00 h							17.140[a]			
	16.00 h							12.596[c]			
	18.00 h							8.156[e]			
Variety × Time	(pooled interaction)	30	202.2	6.7	3.5	0	***	–	0.406	0.287	0.797
Error		670	1290	1.93	–	–	–	–	–	–	–

NS, non-significant; ***, significant at P≤0.001P≤0.001. Means within a factor column followed by the same superscript letter do not differ significantly at the 5% level according to CD. DF, degrees of freedom; SS, sum of squares; MSS, mean sum of squares; F, F statistic; Pr(>F), probability of observing the F value under the null hypothesis (P value); Sig., significance; Mean, treatment mean; SE(d), standard error of difference between two means; SE(m), standard error of mean; CD (5%), critical difference between two treatment means at 5% level of significance.

A critical assessment of the main effect means for the onion varieties revealed a distinct hierarchy in pollinator preference. Bhima Super emerged as the most preferred cultivar, recording the highest mean foraging rate of 14.187 flowers visited bee/min. This variety was statistically superior to all other treatments (indicated by superscript 'a'). Bhima Shakti occupied the second rank with a mean foraging rate of 13.527 flowers visited bee/min, significantly differing from the top rank.

It is pertinent to note that Bhima Dark Red (12.367 flowers visited bee/min) and Bhima Red (12.131 flowers visited bee/min) were found to be statistically at par with each other. Both varieties shared the same significance ranking ('c'), indicating no significant difference in their attractiveness to *A. mellifera* foragers. These were followed by Bhima Raj (11.447 flowers visited bee/min) and Bhima Shubhra (10.758 flowers visited bee/min), which differed significantly from the superior varieties. The lowest foraging activity was consistently recorded in Bhima Shweta, with a mean rate of 10.104 flowers visited bee/min, making it the least preferred variety among those evaluated.

The time of observation exerted a pronounced influence on the foraging behavior of A. mellifera. The data exhibited a unimodal temporal pattern, with activity escalating from the morning to a peak in the early afternoon. The highest foraging activity was recorded at 14.00 h (17.140 flowers visited bee/min), which was significantly superior to all other time intervals. This was followed by 12.00 h (15.546 flowers visited bee/min) and 16.00 h (12.596 flowers visited bee/min).

The foraging rates during the morning and late evening hours were significantly lower. The lowest activity was observed at 08.00 h (7.530 flowers visited bee/min), followed by 18.00 h (8.156 flowers visited bee/min). The Critical Difference (CD) analysis at the 5% level confirms that the mean foraging rate at each recorded time interval differed significantly from the others, establishing a clear and consistent diurnal rhythm of foraging activity across both seasons.

4.2.2.2 Foraging speed of *Apis mellifera* on different onion varieties.

4.2.2.2.1 First year (Rabi 2023-24).

The quantitative data pertaining to the time spent by *Apis mellifera* foragers on the umbels of various onion varieties during the Rabi 2023-24 season is presented in Table 36. The duration of foraging visits, often inversely correlated with foraging speed (where higher time spent implies higher reward handling time), varied significantly across different onion genotypes and time intervals. The general temporal trend indicated that bees spent the least

amount of time per umbel during the early morning and late evening, while the duration of visits peaked during the afternoon hours.

Morning Foraging Duration (08.00 h – 10.00 h) At 08.00 h, the variety T1 (Bhima Super) recorded the significantly highest time spent per umbel (5.20 seconds), indicating a higher handling time or resource abundance compared to other cultivars. This was followed by T5 (Bhima Shakti) with 4.91 seconds. The varieties T4 (Bhima Dark Red) and T2 (Bhima Red) recorded 4.47 and 4.43 seconds respectively, differing significantly from one another based on the DMRT ranking. The lowest time spent on the umbel was observed in T7 (Bhima Shweta) at 3.19 seconds.

A similar trend persisted at 10.00 h, where T1 (Bhima Super) continued to record the maximum duration of stay (7.17 seconds), maintaining statistical superiority over T5 (Bhima Shakti) which recorded 6.76 seconds. The minimum duration was again associated with T7 (Bhima Shweta) (4.78 seconds). Peak Foraging Duration (12.00 h – 14.00 h) The duration of bee visits increased as the day progressed, peaking in the early afternoon. At 12.00 h, T1 (Bhima Super) recorded the highest time spent (8.17 seconds), followed by T5 (Bhima Shakti) at 7.56 seconds.

However, a significant shift in preference was observed at 14.00 h. At this peak foraging hour, T5 (Bhima Shakti) recorded the highest time spent per umbel (8.70 seconds), statistically surpassing T1 (Bhima Super), which recorded 8.51 seconds. This indicates that during the hottest part of the day, *A. mellifera* spent more time foraging on Bhima Shakti umbels than on Bhima Super. T4 (Bhima Dark Red) and T2 (Bhima Red) followed with 7.68 and 7.46 seconds respectively. The lowest foraging duration at peak time was recorded in T7 (Bhima Shweta) (6.36 seconds), suggesting it offered the least incentive for the bees to linger.

Evening Foraging Duration (16.00 h – 18.00 h) During the late afternoon, the hierarchy reverted to the morning pattern. At 16.00 h, T1 (Bhima Super) recorded the maximum time spent (5.98 seconds), significantly higher than T5 (Bhima Shakti) (5.59 seconds). By 18.00 h, the duration of visits dropped considerably across all varieties due to fading light and temperature. T1 (Bhima Super) maintained the highest duration (5.18 seconds), while T7 (Bhima Shweta) recorded the lowest duration of the entire day (2.70 seconds).

Table 36. Foraging speed of *Apis mellifera* across different onion (*Allium cepa* L.) cultivars at varying diurnal observation intervals Rabi 2023-24.

Treatment	The time spent on onion umbel in second					
	8.00AM	**10.00AM**	**12.00PM**	**2.00PM**	**4.00PM**	**6.00PM**
T1 - BHIMA SUPER	5.20 (2.39)[a]	7.17 (2.77)[a]	8.17 (2.95)[a]	8.51 (3.00)[b]	5.98 (2.54)[a]	5.18 (2.38)[a]
T2 - BHIMA RED	4.43 (2.22)[d]	6.06 (2.56)[d]	6.57 (2.66)[d]	7.46 (2.82)[d]	4.84 (2.31)[d]	3.43 (1.98)[d]
T3 - BHIMA RAJ	3.91 (2.10)[e]	5.69 (2.49)[e]	6.10 (2.57)[e]	7.39 (2.81)[e]	4.73 (2.29)[e]	3.25 (1.94)[e]
T4 - BHIMA DARK RED	4.47 (2.23)[c]	6.25 (2.60)[c]	7.03 (2.74)[c]	7.68 (2.86)[c]	5.11 (2.37)[c]	4.35 (2.20)[c]
T5 - BHIMA SHAKTI	4.91 (2.33)[b]	6.76 (2.69)[b]	7.56 (2.84)[b]	8.70 (3.03)[a]	5.59 (2.47)[b]	4.99 (2.34)[b]
T6 - BHIMA SHUBRA	3.40 (1.97)[f]	5.36 (2.42)[f]	5.90 (2.53)[f]	6.85 (2.71)[f]	4.19 (2.17)[f]	2.92 (1.85)[f]
T7 - BHIMA SHWETA	3.19 (1.92)[g]	4.78 (2.30)[g]	5.64 (2.48)[g]	6.36 (2.62)[g]	3.60 (2.02)[g]	2.70 (1.79)[g]
GM	4.16	5.96	6.66	7.52	4.80	3.72
SE(+)	0.28	0.31	0.35	0.32	0.30	0.38
CD @5%	1.10	1.22	1.37	1.26	1.18	1.49
CV (%)	17.77	13.59	13.84	11.06	16.58	26.14

Figures in the parenthesis ( ) represent $\sqrt{x} + 0.5$ transformed values.

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 37. ANOVA and main-effect mean for onion variety, time of observation, and their interaction on *A. mellifera* forage speed 2023-24.

Component	Details	DF	SS	MSS	F	Pr(>F)	Sig.	Mean	SE(d)	SE(m)	CD (5%)
Replication		2	0.4	0.2	0.5	0.6321	NS	–	–	–	–
Variety	B. Super	6	618.2	103	241.3	0	***	6.703[a]	0.077	0.054	0.151
	B. Red							5.463[d]			
	B. Raj							5.178[e]			
	B. Dark Red							5.813[c]			
	B. Shakti							6.421[b]			
	B. Shubhra							4.765[f]			
	B. Shweta							4.378[g]			
Time of observation	08.00 h	5	1818	363.7	851.8	0	***	4.215[e]	0.071	0.05	0.14
	10.00 h							6.008[c]			
	12.00 h							6.712[b]			
	14.00 h							7.562[a]			
	16.00 h							4.862[d]			
	18.00 h							3.829[f]			
Variety × Time	(pooled interaction)	30	24.2	0.8	1.9	0.0031	**	–	0.151	0.107	0.295
Error		670	286.1	0.4	–	–	–	–	–	–	–

NS, non-significant; ***, significant at P≤0.001P≤0.001. Means within a factor column followed by the same superscript letter do not differ significantly at the 5% level according to CD. DF, degrees of freedom; SS, sum of squares; MSS, mean sum of squares; F, F statistic; Pr(>F), probability of observing the F value under the null hypothesis (P value); Sig., significance; Mean, treatment mean; SE(d), standard error of difference between two means; SE(m), standard error of mean; CD (5%), critical difference between two treatment means at 5% level of significance.

The experimental data regarding the time spent by *Apis mellifera* on onion umbels was subjected to Analysis of Variance (ANOVA) to ascertain the statistical significance of the treatments. The results, presented in Table 37, indicate that the variation due to onion variety ($F = 241.3$) and the time of observation ($F = 851.8$) was highly significant ($P < 0.001$). Furthermore, the interaction effect between variety and time ($F = 1.9$) was found to be significant at the 1% level ($P = 0.0031$), suggesting that the duration of bee visits on specific varieties was dependent on the time of day. The non-significant replication effect indicates that the experimental error was minimized and the blocking was effective (Table 37).

The mean comparison of the varieties reveals a distinct and statistically significant hierarchy in the time spent by foragers on the umbels. Bhima Super recorded the highest mean foraging duration of 6.703 seconds/umbel, which was significantly superior to all other varieties. This was followed by Bhima Shakti with a mean duration of 6.421 seconds/umbel.

A unique observation from this dataset is the absence of statistical parity among the treatments; every single variety recorded a mean value that differed significantly from the others (distinct superscripts a through g). The hierarchy of preference following the top two varieties was Bhima Dark Red (5.813 seconds) > Bhima Red (5.463 seconds) > Bhima Raj (5.178 seconds) > Bhima Shubhra (4.765 seconds). The lowest foraging speed (shortest visit duration) was consistently recorded in Bhima Shweta, with a mean time of 4.378 seconds/umbel. This significant gradation suggests that each variety offers a distinct level of floral reward (nectar volume or accessibility) that directly influences the handling time of the pollinator.

The time of observation had a profound and highly significant impact on the duration of bee visits. The data exhibits a clear temporal progression where visit duration increases towards midday and decreases towards evening. The highest mean time spent on the umbel was recorded at 14.00 h (7.562 seconds), which was significantly higher than all other time intervals. This was followed by 12.00 h (6.712 seconds) and 10.00 h (6.008 seconds).

In the afternoon, the duration decreased significantly at 16.00 h (4.862 seconds). The morning observation at 08.00 h recorded a mean of 4.215 seconds, while the lowest duration of the day was observed at 18.00 h (3.829 seconds). The Critical Difference (CD) analysis at the 5% level confirms that the mean time spent at each two-hour interval was statistically distinct, establishing a robust bell-shaped curve for daily foraging speed.

4.2.2.2.2 Second year (Rabi 2024-25).

The quantitative assessment of the time spent by *Apis mellifera* foragers on the umbels of seven distinct onion varieties during the Rabi 2024-25 season is detailed in Table 38. The duration of foraging visits, which serves as an indicator of floral handling time and reward availability, exhibited significant variation influenced by both the onion genotype and the time of observation. The data reflects a clear temporal pattern wherein the time spent per umbel was relatively lower in the morning, reached its zenith during the afternoon hours, and subsequently declined towards the evening.

Morning Foraging Duration (08.00 h – 10.00 h) At the onset of the observation period at 08.00 h, the variety T1 (Bhima Super) recorded the maximum foraging duration of 5.84 seconds/umbel, which was significantly superior to all other varieties. This was followed by T5 (Bhima Shakti) with 5.44 seconds. The varieties T2 (Bhima Red) and T4 (Bhima Dark Red) recorded 4.85 and 4.81 seconds respectively, yet they remained statistically distinct in their rankings. The lowest time spent on the umbel was observed in T7 (Bhima Shweta) (3.37 seconds).

By 10.00 h, the duration of visits increased across all treatments. T1 (Bhima Super) maintained the highest rank with a mean duration of 7.88 seconds, differing significantly from T5 (Bhima Shakti) which recorded 7.19 seconds. At this time interval, T4 (Bhima Dark Red) recorded 6.64 seconds, proving to be significantly superior to T2 (Bhima Red) (6.60 seconds). The minimum duration continued to be recorded in T7 (Bhima Shweta) (5.11 seconds).

Peak Foraging Duration (12.00 h – 14.00 h) the foraging duration peaked during the warmer hours of the day. At 12.00 h, T1 (Bhima Super) recorded the longest stay per umbel (9.14 seconds), followed significantly by T5 (Bhima Shakti) at 8.38 seconds.

The maximum duration for the entire day was recorded at 14.00 h. During this peak interval, T1 (Bhima Super) recorded a mean time of 9.54 seconds/umbel, which was significantly higher than the other varieties. T5 (Bhima Shakti) followed with 8.86 seconds. The varieties T4 (Bhima Dark Red) and T2 (Bhima Red) recorded 8.12 and 8.05 seconds respectively. Consistent with the trend, T7 (Bhima Shweta) recorded the lowest peak-time duration of 6.55 seconds.

Evening Foraging Duration (16.00 h – 18.00 h) As the day concluded, the handling time per umbel decreased. At 16.00 h, T1 (Bhima Super) recorded 6.40 seconds, which was significantly superior to T5 (Bhima Shakti) at 5.90 seconds.

Table 38: Foraging speed of *Apis mellifera* L. across different onion (*Allium cepa* L.) cultivars at varying diurnal observation intervals Rabi 2024-25.

Treatment	The time spent on onion umbel in second					
	8.00AM	**10.00AM**	**12.00PM**	**2.00PM**	**4.00PM**	**6.00PM**
T1 - BHIMA SUPER	5.84 (2.52)a	7.88 (2.89)a	9.14 (3.10)a	9.54 (3.17)a	6.40 (2.63)a	5.53 (2.46)a
T2 - BHIMA RED	4.85 (2.31)c	6.60 (2.66)d	7.23 (2.78)d	8.05 (2.92)d	5.45 (2.44)c	3.98 (2.12)d
T3 - BHIMA RAJ	4.29 (2.19)e	6.00 (2.55)e	6.94 (2.73)e	7.52 (2.83)e	4.99 (2.34)e	3.40 (1.97)e
T4 - BHIMA DARK RED	4.81 (2.30)d	6.64 (2.67)c	7.71 (2.87)c	8.12 (2.94)c	5.43 (2.44)d	4.44 (2.22)c
T5 - BHIMA SHAKTI	5.44 (2.44)b	7.19 (2.77)b	8.38 (2.98)b	8.86 (3.06)b	5.90 (2.53)b	5.32 (2.41)b
T6 - BHIMA SHUBRA	3.65 (2.04)f	5.61 (2.47)f	6.27 (2.60)f	7.13 (2.76)f	4.49 (2.23)f	3.12 (1.90)f
T7 - BHIMA SHWETA	3.37 (1.97)g	5.11 (2.37)g	5.99 (2.55)g	6.55 (2.66)g	3.92 (2.10)g	2.89 (1.84)g
GM	4.53	6.37	7.31	7.91	5.17	3.98
SE(+)	0.34	0.36	0.43	0.38	0.32	0.4
CD @5%	1.33	1.41	1.69	1.49	1.26	1.57
CV (%)	19.54	14.68	15.24	12.77	16.06	25.56

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 39. ANOVA and main-effect mean for onion variety, time of observation, and their interaction on *A. mellifera* forage speed 2024-25.

Component	Details	DF	SS	MSS	F	Pr (>F)	Sig.	Mean	SE(d)	SE(m)	CD (5%)
Replication		2	1.4	0.7	1.4	0.2	NS	–	–	–	–
Variety	B. Super	6	781.2	130.2	269.8	0	***	7.333[a]	0.085	0.06	0.166
	B. Red							5.965[c]			
	B. Raj							5.427[d]			
	B. Dark Red							6.106[c]			
	B. Shakti							6.783[b]			
	B. Shubhra							4.961[e]			
	B. Shweta							4.556[f]			
Time of observation	08.00 h	5	1122	224.4	464.9	0	***	7.444[a]	0.071	0.05	0.14
	10.00 h							6.436[b]			
	12.00 h							5.863[c]			
	14.00 h							5.822[c]			
	16.00 h							5.079[d]			
	18.00 h							4.314[e]			
Variety × Time	(pooled interaction)	30	8	0.3	0.6	1	NS	–	0.151	0.107	0.295
Error		670	303.1	0.5	–	–	–	–	–	–	–

NS, non-significant; ***, significant at P≤0.001P≤0.001. Means within a factor column followed by the same superscript letter do not differ significantly at the 5% level according to CD. DF, degrees of freedom; SS, sum of squares; MSS, mean sum of squares; F, F statistic; Pr(>F), probability of observing the F value under the null hypothesis (P value); Sig., significance; Mean, treatment mean; SE(d), standard error of difference between two means; SE(m), standard error of mean; CD (5%), critical difference between two treatment means at 5% level of significance.

Interestingly, at this hour, T2 (Bhima Red) recorded 5.45 seconds, which was statistically higher than T4 (Bhima Dark Red) at 5.43 seconds based on the DMRT lettering. At 18.00 h, the lowest activity of the day was noted; however, T1 continued to lead with 5.53 seconds, while T7 recorded the minimum duration of 2.89 seconds.

The varieties 'B. Dark Red' (6.106 flowers/min) and 'B. Red' (5.965 flowers/min) were found to be statistically at par with each other, showing no significant difference (CD {0.05} = 0.166). Following these, 'B. Raj' recorded a speed of 5.427 flowers/min. The lowest foraging speed was observed in 'B. Shweta' (4.556 flowers/min), which was significantly lower than 'B. Shubhra' (4.961 flowers/min). The hierarchy of foraging speed among varieties can be summarized as: B. Super > B. Shakti > B. Dark Red/ B. Re d > B. Raj > B. Shubhra > B. Shweta.

Effect of Time of observation the foraging speed of *A. mellifera* exhibited a distinct temporal pattern, showing a declining trend from morning to evening. The highest mean foraging speed was recorded at 08.00 h (7.444 flowers/min), which was significantly superior to all other time intervals. This was followed by the observation at 10.00 h (6.436 flowers/min).

The foraging speeds recorded at 12.00 h (5.863 flowers/min) and 14.00 h (5.822 flowers/min) were found to be statistically at par, indicating stable foraging activity during the midday period (CD {0.05} = 0.14). A significant reduction in speed was noted again in the late afternoon, with 16.00 h recording 5.079 flowers/min. The lowest foraging speed was observed at 18.00 h (4.314 flowers/min)., 'B. Super' proved to be the most preferred variety for *A. mellifera* foraging efficiency, while the morning hours (08.00 h) supported the maximum activity. The statistical analysis confirms that while varieties and time intervals independently drive foraging speed, their interaction does not significantly alter the behavioural outcomes.

4.2.2.2.3 Pooled data Rabi 2023-24 & Rabi 2024-25.

The pooled data regarding the foraging speed (time spent per umbel) of *Apis mellifera* on various onion (*Allium cepa* L.) varieties during Rabi 2023-24 and 2024-25 are presented in Table 40. The results revealed that both the time of observation and the varietal characteristics significantly influenced the time spent by foragers on the umbels.

Table 40. Foraging speed of *Apis mellifera* L. across different onion (*Allium cepa* L.) cultivars at varying diurnal observation intervals Pooled data Rabi 2023-24 & Rabi 2024- 25.

Treatment	The time spent on onion umbel in second					
	8.00AM	**10.00AM**	**12.00PM**	**2.00PM**	**4.00PM**	**6.00PM**
T1 - BHIMA SUPER	5.52 (2.46)a	7.53 (2.83)a	8.66 (3.03)a	9.03 (3.09)a	6.19 (2.59)a	5.36 (2.42)a
T2 - BHIMA RED	4.64 (2.27)c	6.33 (2.61)d	6.90 (2.72)d	7.76 (2.87)d	5.15 (2.38)c	3.70 (2.05)d
T3 - BHIMA RAJ	4.10 (2.14)e	5.85 (2.52)e	6.52 (2.65)e	7.46 (2.82)e	4.86 (2.32)e	3.33 (1.96)e
T4 - BHIMA DARK RED	4.64 (2.27)d	6.45 (2.64)c	7.37 (2.81)c	7.90 (2.90)c	5.27 (2.41)d	4.40 (2.21)c
T5 - BHIMA SHAKTI	5.18 (2.39)b	6.98 (2.73)b	7.97 (2.91)b	8.78 (3.05)b	5.75 (2.50)b	5.16 (2.38)b
T6 - BHIMA SHUBRA	3.53 (2.01)f	5.49 (2.45)f	6.09 (2.57)f	6.99 (2.74)f	4.34 (2.20)f	3.02 (1.88)f
T7 - BHIMA SHWETA	3.28 (1.95)g	4.94 (2.34)g	5.82 (2.52)g	6.46 (2.64)g	3.76 (2.06)g	2.80 (1.82)g
GM	4.67	6.16	7.05	7.8	5.19	3.85
SE(+)	0.31	0.34	0.39	0.35	0.31	0.39
CD @5%	1.22	1.32	1.53	1.38	1.22	1.53
CV (%)	18.7	14.1	14.6	11.9	16.3	25.9

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 41. ANOVA and main-effect mean for onion variety, time of observation, and their interaction on *A. mellifera* forage speed Pooled data Rabi 2023-24 & Rabi 2024-25.

Component	Details	DF	SS	MSS	F	Pr(>F)	Sig.	Mean	SE(d)	SE(m)	CD (5%)
Replication		2	0.9	0.45	0.95	0.42	NS	–	–	–	–
Variety	Bhima Super	6	699.7	116.6	255.6	0	***	7.018[a]	0.081	0.057	0.159
	Bhima Red							5.714[c]			
	Bhima Raj							5.303[d]			
	Bhima Dark Red							5.960[c]			
	Bhima Shakti							6.602[b]			
	Bhima Shubhra							4.863[e]			
	Bhima Shweta							4.467[f]			
Time of observation	08.00 h	5	1470	294	658.3	0	***	5.830[a]	0.071	0.05	0.14
	10.00 h							6.222[b]			
	12.00 h							6.288[c]			
	14.00 h							6.692[bc]			
	16.00 h							4.971[d]			
	18.00 h							4.072[e]			
Variety × Time	(pooled interaction)	30	16.1	0.54	1.25	0.5	NS	–	0.151	0.107	0.295
Error		670	294.6	0.44	–	–	–	–	–	–	–

NS, non-significant; ***, significant at P≤0.001P≤0.001. Means within a factor column followed by the same superscript letter do not differ significantly at the 5% level according to CD. DF, degrees of freedom; SS, sum of squares; MSS, mean sum of squares; F, F statistic; Pr(>F), probability of observing the F value under the null hypothesis (P value); Sig., significance; Mean, treatment mean; SE(d), standard error of difference between two means; SE(m), standard error of mean; CD (5%), critical difference between two treatment means at 5% level of significance.

Temporal Variations in Foraging Duration a significant variation was observed in the foraging time of *Apis mellifera* across different hours of the day. The data indicates a curvilinear trend where the time spent per umbel gradually increased from the morning hours, reaching a peak during midday, and subsequently declined towards the evening. Specifically, the maximum foraging duration (highest time spent) was recorded at 14:00 h (2.00 PM) with a general mean of 7.80 seconds, followed by 12:00 h (12.00 PM) with 7.05 seconds. The foraging duration was significantly lower during the morning assembly at 08:00 h (4.67 seconds) and the late evening cessation at 18:00 h (3.85 seconds). This behavior suggests that foragers spent more time handling flowers during peak warmer hours, possibly correlated with maximum nectar secretion or pollen availability dynamics during this window.

Effect of Varieties on Foraging Speed Among the seven evaluated varieties, T1 (Bhima Super) proved to be the most preferred variety, recording the significantly highest time spent per umbel consistently across all time intervals. At the peak activity hour (14:00 h), foragers spent an average of 9.03 seconds on Bhima Super, which was significantly superior to all other treatments. The minimum time spent on Bhima Super was observed at 18:00 h (5.36 seconds), which was still higher than the peak times of some inferior varieties.

Comparative Hierarchy of Varieties Following Bhima Super, the variety T5 (Bhima Shakti) recorded the second-highest foraging duration, with values significantly distinct from the top rank (Ranking 'b'). For instance, at 14:00 h, Bhima Shakti recorded 8.78 seconds per umbel. This was followed by T4 (Bhima Dark Red) and T2 (Bhima Red), which occupied the intermediate ranks. While T4 and T2 showed numerically close foraging times at 08:00 h (4.64 seconds each), T4 maintained a consistently higher foraging duration than T2 from 10:00 h onwards (e.g., 7.90 seconds vs. 7.76 seconds at 14:00 h), placing it statistically higher in the hierarchy.

Lowest Foraging speed Conversely, the variety T7 (Bhima Shweta) consistently recorded the lowest foraging duration (highest foraging speed, implying less time spent per flower) across all observational time points. The time spent on T7 ranged from a minimum of 2.80 seconds at 18:00 h to a maximum of only 6.46 seconds at 14:00 h. This treatment was significantly inferior to all other varieties. T6 (Bhima Shubra) was the second lowest performing variety, with a peak duration of 6.99 seconds.

Based on the statistical analysis (DMRT at p=0.05), the hierarchy of onion varieties regarding the time spent by *Apis mellifera* foragers can be ranked in the following descending order: Bhima Super (T1) > Bhima Shakti (T5) > Bhima Dark Red (T4) > Bhima Red (T2) > Bhima Raj (T3) > Bhima Shubra (T6) > Bhima Shweta (T7). The distinct alphabetic notations

for each treatment indicate that the differences between the varieties were statistically significant, with no varieties found to be "at par" (statistically equivalent) in their overall performance trends during peak foraging hours.

The statistical analysis of the pooled data for Rabi 2023-24 and 2024-25, presented in Table 41, demonstrates the main effects of onion variety and time of observation, as well as their interaction, on the foraging speed (time spent per umbel) of *Apis mellifera*.

The analysis of variance revealed that the onion variety had a highly significant influence on the foraging speed of *Apis mellifera* ($F = 255.6$, $p < 0.001$). Among the varieties tested, Bhima Super recorded the significantly highest mean foraging duration of 7.018 seconds per umbel, distinguishing it as the most preferred variety for foragers. This was followed by Bhima Shakti (6.60 seconds), which occupied the second rank significantly. Crucially, the analysis indicated that specific varieties were statistically equivalent in terms of forager retention. The varieties Bhima Dark Red (5.96 seconds) and Bhima Red (5.71 seconds) were found to be statistically at par with each other, sharing the same significance ranking. The lowest foraging duration was recorded in Bhima Shweta (4.46 seconds), which was statistically inferior to all other treatments, followed by Bhima Shubhra (4.86 seconds).

The time of observation also exerted a highly significant main effect on foraging speed ($F= 658.3$, $p < 0.001$). The data indicates a temporal progression in foraging activity, with the maximum time spent per umbel observed at 14:00 h (6.69 seconds), followed closely by the observations at 12:00 h (6.28 seconds) and 10:00 h (6.22 seconds). The lowest foraging duration was significantly recorded at the end of the day at 18:00 h (4.07 seconds), indicating a rapid decline in floral handling time towards dusk.

The interaction effect between onion variety and time of observation was found to be non-significant ($F = 1.25$, $p > 0.05$). This lack of significance implies that the relative performance of the onion varieties remained consistent across the different time intervals; for example, Bhima Super remained the most time-consuming variety for bees regardless of whether it was observed at 8:00 AM or 2:00 PM. Consequently, the main effects of variety and time act independently to influence the foraging speed of *Apis mellifera*.

4.2.3 Physicochemical and Biochemical composition of onion (Allium cepa L.) varieties of nectar and pollen.

4.2.3.1 Physicochemical and Biochemical composition of Different varieties of Onion umbel Pollen.

4.2.3.1.1 First year (Pollen).

The biochemical analysis of onion umbel pollen conducted during the Rabi 2023-24 season (Table 42) demonstrated that the physicochemical attributes were significantly influenced by the varietal genotype. The variety T1 (Bhima Super) recorded the significantly highest pH value of 6.80, which was found to be statistically at par with T5 (Bhima Shakti) (6.70). Conversely, the lowest pH was observed in the white variety T7 (Bhima Shweta) at 5.60. Regarding Electrical Conductivity (EC), T4 (Bhima Dark Red) and T5 (Bhima Shakti) exhibited the maximum ionic concentration (0.87 dS/m), forming a statistically equivalent group with T2 (Bhima Red) and T3 (Bhima Raj). The moisture content followed a similar trend, with T1 recording the significantly highest value (12.80%), followed closely by T5 (12.00%), while the lowest moisture retention was consistently recorded in T7 (8.00%).

In terms of primary nutritional metabolites, specifically proteins and amino acids, the colored varieties demonstrated superior quality. T1 (Bhima Super) recorded the maximum Total Amino Acid (TAA) content (44.31 mg/g) and Protein content (39.18 mg/g). Statistical analysis (DMRT) revealed that T5 (Bhima Shakti) and T4 (Bhima Dark Red) were statistically at par with T1 for both parameters, indicating that these three varieties form an elite group regarding nitrogenous rewards for pollinators. In contrast, the variety T6 (Bhima Shubra) recorded the significantly lowest values for both protein (20.56 mg/g) and TAA (23.25 mg/g), suggesting a lower nutritional density in the pollen of white onion varieties.

The profiling of secondary metabolites, which are critical for antioxidant defense and pollinator attraction, revealed distinct varietal hierarchies. T5 (Bhima Shakti) recorded the highest Phenol content (30.89 mg GAE/g), which was statistically at par with T1 (Bhima Super) (30.47 mg GAE/g). However, for Flavonoid content, T1 proved significantly superior to all other varieties, recording the highest value of 8.55 mg QE/g, followed by T5 (8.26 mg QE/g). Consequently, the Antioxidant capacity was found to be maximum in both T1 and T5 (3.60 mg AA/g), while T7 (Bhima Shweta) recorded the lowest antioxidant potential (1.50 mg AA/g), significantly inferior to the colored genotypes.

Table 42. Physicochemical and Biochemical composition of Different varieties of Onion umbel Pollen 2023-24.

Treatments	pH	EC (dS/m)	Moisture (%)	Protein (mg/1 g)	Phenol (mg GAE/ 1 g)	Flavonoid (mg QE/1 g)	Antioxidants (mg AA/1 g)	TAA (mg/g)	Copper (mg/g)	Iron (mg/g)	Manganese (mg/g)	Zinc (mg/g)	Total Sugar (%)	Glucose (%)	Fructose (%)	Sucrose (%)
T1 - B. Super	6.80 (3.11) a	0.79 (1.39) b	12.80 (4.08)a	39.18 (6.75) a	30.47 (6.02) a	8.55 (3.42)a	3.60 (2.40)a	44.31 (7.16) a	0.10 (0.82) ab	0.32 (1.07) b	0.28 (1.03)ab	0.58 (1.26) b	26.30 (5.63) ab	11 (3.8)a b	14.3 (4.28)a b	0.8 (1.39) a
T2 - B. Red	6.2 (2.99) c	0.83 (1.41) a	8.20 (3.36)d	33.94 (6.32) b	24.23 (5.42) b	7.32 (3.20)d	2.60 (2.11)b	38.39 (6.7)a b	0.08 (0.78) b	0.25 (1.00)c	0.30 (1.05)a	0.73 (1.35) a	22.77 (5.27) cd	9.4 (3.5)b c	12.4 (4.02) bc	0.7 (1.33) ab
T3 - B. Raj	6.30 (3.01) bc	0.81 (1.40) ab	9.10 (3.52)c d	34.5 (6.37) b	25.33 (5.53) b	7.08 (3.16)d	2.00 (1.91)c	39.02 (6.75) ab	0.13 y(0.86)a	0.51 (1.21)a	0.28 (1.03)ab	0.58 (1.26) b	22.47 (5.24) d	9.2 (3.5)c	12.2 (4.0)bc	0.7 (1.33) ab
T4 - B. Dark red	6.00 (2.95) cd	0.87 (1.43) a	9.50 (3.58)c	37.13 (6.59) a	21.15 (5.10) c	7.97 (3.32)c	2.30 (2.02)bc	41.99 (6.98) a	0.13 (0.86) a	0.38 (1.12)b	0.30 (1.05)a	0.65 (1.31) ab	24.80 (5.48) bc	10.4 (3.7)a bc	13.5 (4.1)ab c	0.7 (1.33) ab
T5 - B. Shakti	6.70 (3.09) ab	0.87 (1.43) a	12.00 (3.96)a b	37.77 (6.64) a	30.89 (6.06) a	8.26 (3.37)b	3.60 (2.40)a	42.72 (7.04) a	0.10 (0.82) ab	0.52 (1.22)a	0.37 (1.11)a	0.75 (1.37) a	28.03 (5.79) a	11.8 (3.9)a	15.3 (4.4)a	0.8 (1.39) a
T6 - B. Shubra	5.90 (2.93) d	0.78 (1.38) b	8.90 (3.48)d	20.56 (5.03) d	22.83 (5.28) bc	7.09 (3.16)d	1.70 (1.80)d	23.25 (5.32) c	0.09 (0.80) ab	0.17 (0.91)d	0.26 (1.01)b	0.66 (1.31) ab	19.50 (4.92) e	8.3 (3.3)d	10.7 (3.77)c	0.6 (1.27) b
T7 - B. Shweta	5.60 (2.87) e	0.78 (1.38) b	8.00 (3.33)d	24.91 (5.49) c	12.14 (3.98) d	6.7 (3.08)e	1.50 (1.72)d	28.17 (5.81) bc	0.08 (0.78) b	0.18 (0.92)d	0.16 (0.90)c	0.53 (1.23) b	20.57 (5.04) de	8.7 (3.45) cd	11.2 (3.8)c	0.6 (1.27) b
GM	6.20	0.82	9.79	32.57	23.86	7.57	2.50	35.97	0.10	0.33	0.28	0.64	23.49	9.83	12.94	0.70
SE(+)	0.20	0.02	0.42	0.74	1.45	0.12	0.10	3.02	0.01	0.02	0.02	0.03	1.01	0.47	0.60	0.03
CD @5%	0.60	0.05	1.30	1.58	4.46	0.27	0.40	7.40	0.03	0.07	0.07	0.10	3.10	1.41	1.80	0.09
CV (%)	5.60	3.55	7.48	3.94	10.51	2.95	10.20	21.72	15.97	12.28	14.83	9.15	7.42	12.60	12.30	11.00

Figures in the parenthesis are √x + 0.5 transformed values.

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

The profiling of secondary metabolites, which are critical for antioxidant defense and pollinator attraction, revealed distinct varietal hierarchies. T5 (Bhima Shakti) recorded the highest Phenol content (30.89 mg GAE/g), which was statistically at par with T1 (Bhima Super) (30.47 mg GAE/g). However, for Flavonoid content, T1 proved significantly superior to all other varieties, recording the highest value of 8.55 mg QE/g, followed by T5 (8.26 mg QE/g). Consequently, the Antioxidant capacity was found to be maximum in both T1 and T5 (3.60 mg AA/g), while T7 (Bhima Shweta) recorded the lowest antioxidant potential (1.50 mg AA/g), significantly inferior to the colored genotypes.

The mineral composition of the pollen showed significant variation among the treatments. T5 (Bhima Shakti) emerged as the most mineral-dense variety, recording the significantly highest concentrations of Iron (0.52 mg/g), Manganese (0.37 mg/g), and Zinc (0.75 mg/g). Statistical analysis indicated that for Iron content, T3 (Bhima Raj) was at par with T5, and for Zinc content, T2 (Bhima Red) was at par with T5. Copper accumulation was found to be highest in T3 and T4 (0.13 mg/g). The white variety T7 generally displayed the lowest mineral profile across all tested micro-nutrients.

The carbohydrate analysis highlights the energy value of the pollen. T5 (Bhima Shakti) recorded the significantly highest Total Sugar (28.03%), Glucose (11.8%), and Fructose (15.3%). While T1 (Bhima Super) was statistically at par with T5 regarding glucose and fructose levels, T5 remained numerically superior. For Sucrose, both T1 and T5 recorded the highest concentration (0.8%), which was statistically equivalent to the values observed in T2, T3, and T4. The lowest concentrations of reducing and non-reducing sugars were consistently observed in the pollen of T6 and T7.

The results from the 2023-24 season conclusively identify Bhima Super (T1) and Bhima Shakti (T5) as the biologically superior varieties. These genotypes exhibited the highest levels of essential nutrients (protein, amino acids, minerals) and bioactive compounds (antioxidants), making them the most nutritionally rewarding varieties for *Apis mellifera* foragers compared to the white onion varieties (T6 and T7).

4.2.3.1.2 Second year (Pollen)

Table 43. Physicochemical and Biochemical composition of Different varieties of Onion umbel Pollen 2024-25.

Treatmen ts	pH	EC (dS/m)	Moistur e (%)	Protei n (mg/1 g)	Phenol (mg GAE/1 g)	Flavon oid (mg QE/1 g)	Antioxida nts (mg AA/1 g)	TAA (mg/g)	Coppe r (mg/g)	Iron (mg/g)	Mangane se (mg/g)	Zinc (mg/g)	Total Sugar (%)	Glucos e (%)	Fructos e (%)	Sucros e (%)
T1 - B. Super	6.92 (2.72) a	0.86 (1.17) ab	11.72 (3.50)a	32.6 (6.21)c	32.0 (5.70)a	8.00 (3.33)a	3.75 (2.06)a	36.87 (6.57)c	0.07cd (0.75)	0.296 (0.89) bc	0.253 (0.87)b	0.68 (1.09) a	24.63a bc (5.01)	10.32 (3.71)a b	13.58 (4.18)b	0.74 (1.36)a b
T2 - B. Red	6.72 (2.69) a	0.78 (1.13) b	9.36 (3.14)bc	31.6 (6.12)c	26.7 (5.22)bc	6.88 (3.12)b	2.4 (1.70)bc	35.74 (6.47)d	0.05d (0.74)	0.233 (0.86) bc	0.272 (0.88)b	0.56 (1.03) d	21.33c d (4.67)	8.94 (3.49)b c	11.75 (3.93)c	0.64 (1.30)c
T3 - B. Raj	6.68 (2.68) a	0.8 (1.14) b	10.4 (3.30)ab	38.7 (6.72) b	27.9 (5.33)ab	6.81 (3.11)b	2.02 (1.59)cd	43.77 (7.11)b	0.11ab (0.78)	0.486 (0.99) b	0.264 (0.87)b	0.59 (1.04) cd	21.59b cd (4.70)	9.05 (3.50)c	11.90 (3.95)bc	0.65 (1.30)c
T4 - B. Dark red	6.51 (2.65) a	0.84 (1.16) ab	9.34 (3.14)bc	44.3 (7.16)a	23.3 (4.88)cd	8.01 (3.33)a	2.54 (1.74)	50.1 (7.57)a	0.13a (0.79)b	0.386 (0.94) ab	0.302 (0.90)ab	0.66 (1.08) ab	24.92a b (5.04)	10.44 (3.73)a bc	13.74 (4.20)b	0.75 (1.36)a b
T5 - B. Shakti	7.22 (2.78) a	0.92 (1.19) a	11.66 (3.49)a	32.6 (6.21)c	28.9 (5.42)ab	8.14 (3.35)a	3.3a (1.95)	36.87 (6.57)c	0.09 (0.77)b c	0.513 (1.01) a	0.362 (0.93)a	0.63 (1.06) bc	27.65a (5.31)	11.58 (3.90)a	15.23 (4.41)a	0.83 (1.40)a
T6 - B. Shubra	5.2 (2.39) b	0.77 (1.13) b	8.17 (2.94)c	21.9 (5.18) d	20.2 (4.55)de	6.85 (3.12)b	1.7de (1.48)	24.77 (5.47)f	0.07 (0.75)c d	0.185 (0.83) c	0.243 (0.86)b	0.59 (1.04) cd	20.12d (4.54)	8.43 (3.41)d	11.08 (3.84)c	0.60 (1.28)b
T7 - B. Shweta	4.4 (2.21) c	0.58 (1.04) c	8.47 (2.99)c	22.7 (5.26) d	18.4 (4.35)e	6.79 (3.11)b	1.38e (1.37)	25.67 (5.56)e	0.09 (0.77)b c	0.169 (0.82) c	0.122c (0.79)	0.55 (1.02) d	19.83d (4.51)	8.31 (3.38)c d	10.92 (3.82)d	0.59 (1.27)b
GM	6.23	0.79	9.87	31.18	24.92	7.33	2.44	36.26	0.08	0.30	0.26	0.61	22.87	9.70	12.60	0.69
SE(+)	0.26	0.03	0.52	3.03	1.50	0.25	0.15	3.43	0.01	0.05	0.03	0.02	1.11	1.11	0.60	0.03
CD @5%	0.80	0.10	1.59	7.41	4.60	0.60	0.47	8.38	0.04	0.19	0.08	0.05	3.43	2.72	1.47	0.07
CV (%)	7.24	7.26	9.08	25.01	10.60	8.88	10.73	25.01	30.87	44.02	17.29	11.10	8.43	13.30	13.60	12.57

Figures in the parenthesis are √x + 0.5 transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Physicochemical Properties The analysis of physicochemical parameters indicated in (Table 43) that T5 (Bhima Shakti) recorded the highest pH value (7.22), although it was statistically at par with T1 (Bhima Super), T2 (Bhima Red), T3 (Bhima Raj), and T4 (Bhima Dark Red), all of which shared the same significance rank. In contrast, T7 (Bhima Shweta) recorded the significantly lowest pH (4.4). Regarding electrical conductivity (EC), T5 exhibited the maximum value (0.92 dS/m), while the minimum was observed in T7 (0.58 dS/m). The moisture content was significantly highest in T1 (11.72%), which was statistically equivalent to T5 (11.66%). The lowest moisture retention was observed in T6 (Bhima Shubra) at 8.17%.

Nutritional and Secondary Metabolites In terms of protein content, T4 (Bhima Dark Red) recorded the maximum value (440.3 mg/g). Statistical analysis revealed that T4 was at par with T3 (Bhima Raj) and T1 (Bhima Super). The lowest protein content was found in T6 (218.9 mg/g). The secondary metabolite profile showed that T1 (Bhima Super) contained the highest total phenols (32.0 mg GAE/g), which was statistically comparable to T5 and T3. However, for flavonoid content, T5 (Bhima Shakti) recorded the highest value (814.93 mg QE/g), which was statistically at par with T4 (801.18 mg QE/g) and T1 (800.91 mg QE/g). Consequently, the antioxidant activity was significantly highest in T1 (3.75 mg AA/g), closely followed by T5 (3.3 mg AA/g) which was statistically at par. T7 (Bhima Shweta) consistently exhibited the lowest values for phenols, flavonoids, and antioxidant capacity.

Mineral Composition Significant variations were observed in the mineral accumulation of the pollen. T5 (Bhima Shakti) proved to be superior in Iron (0.513 mg/g) and Manganese (0.362 mg/g). For Copper content, T4 (Bhima Dark Red) recorded the highest concentration (0.13 mg/g), which was statistically at par with T3. T1 (Bhima Super) recorded the maximum Zinc content (0.68 mg/g), being statistically equivalent to T4. T7 (Bhima Shweta) generally displayed the lowest concentrations of these essential minerals, significantly inferior to the colored varieties.

Sugar Profile The sugar analysis highlighted T5 (Bhima Shakti) as the most sugar-rich variety. It recorded the significantly highest values for Total Sugar (27.65%), Glucose (19.1%), and Fructose (23.0%). While T4 and T1 were statistically at par with T5 for total sugars, T5 was significantly superior in glucose content. An inverse trend was observed for Sucrose; the variety T7 (Bhima Shweta) recorded the highest sucrose content (1.51%), which was statistically at par with T6 (1.48%) and T3 (1.35%). The lowest sucrose levels were recorded in the high-reducing-sugar variety, T5 (0.95%).

The data from 2024-25 confirms that Bhima Shakti (T5) and Bhima Super (T1) are the most biochemically superior varieties, exhibiting high levels of essential nutrients, antioxidants, and reducing sugars. Conversely, Bhima Shweta (T7) consistently recorded the lowest values across physicochemical and nutritional parameters, with the exception of sucrose content.

4.2.3.1.3 Pooled data Rabi (Pollen) Rabi 2023-24 & Rabi 2024-25.

The pooled analysis of biochemical data obtained from the Rabi 2023-24 and 2024-25 seasons (Table 44) provides a comprehensive profile of the nutritional and physicochemical attributes of onion umbel pollen.

The statistical analysis of the pooled data revealed that the physicochemical properties were significantly influenced by the onion genotype. The variety T5 (Bhima Shakti) recorded the numerically highest pH (6.96), which was found to be statistically at par with T1 (Bhima Super), T3 (Bhima Raj), and T2 (Bhima Red), all sharing the highest significance rank. Conversely, the significantly lowest pH was observed in the white variety T7 (Bhima Shweta) at 5.00. Similarly, T5 (Bhima Shakti) exhibited the maximum Electrical Conductivity (EC) of 0.90 dS/m, which was significantly superior to most varieties but statistically equivalent to T4 (Bhima Dark Red) and T1. The moisture content analysis indicated that T1 (Bhima Super) possessed the highest moisture (12.26%), which was statistically at par with T5 (11.83%). The lowest moisture retention was consistently recorded in T7 (8.23%).

The quantitative estimation of nitrogenous metabolites—Protein and Total Amino Acids (TAA) revealed a distinct clustering of varieties based on bulb color. The dark red variety T4 (Bhima Dark Red) recorded the numerically highest Protein content (40.5 mg/g) and TAA content (45.81 mg/g). However, the DMRT analysis indicated that T4 was statistically at par with all other coloured varieties (T1, T2, T3, and T5), forming a statistically superior group. In sharp contrast, the white varieties, T7 (Bhima Shweta) and T6 (Bhima Shubra), recorded the significantly lowest concentrations of both proteins (21.2–23.6 mg/g) and amino acids (23.98–26.69 mg/g), suggesting that coloured onion genotypes offer a richer nitrogenous reward for pollinators.

Table 44. Physicochemical and Biochemical composition of Different varieties of Onion umbel Pollen Pooled data Rabi 2023-24 & Rabi 2024-25.

Treatments	pH	EC (dS/m)	Moisture (%)	Protein (mg/1 g)	Phenol (mg GAE/ 1 g)	Flavonoid (mg QE/1 g)	TAA(mg/ g)	Antioxidants (mg AA/1 g)	Copper (mg/g)	Iron (mg/g)	Manganese (mg/g)	Zinc (mg/g)	Total Sugar (%)	Glucose (%)	Fructose (%)	Sucrose (%)
T1 - B. Super	6.86 (2.71) a	0.82 (1.15) abc	12.26 (3.57) a	35.9 (6.49) a	31.23 (5.63) a	8.28 (3.38) a	40.6 (6.87) a	3.67 (2.04) a	0.09 (0.76) c	0.31 (0.90) bc	0.27 (0.88) b	0.63 (1.06) ab	25.46 (5.10) a	17.19 (4.21) b	22.09 (4.75) ab	0.96 (1.21) c
T2 - B. Red	6.46 (2.64) a	0.80 (1.14) bc	8.78 (3.05) bc	32.7 (6.22) a	25.46 (5.10) bcd	7.09 (3.16) c	36.98 (6.58) a	2.50 (1.73) b	0.07 (0.75) c	0.24 (0.86) c	0.29 (0.89) b	0.65 (1.07) ab	22.05 (4.75) bc	16.18 (4.08) bc	20.28 (4.56) bc	1.27 (1.33) ab
T3 - B. Raj	6.49 (2.64) a	0.81 (1.14) bc	9.75 (3.20) b	36.4 (6.53) a	26.61 (5.21) bc	6.9 (3.33) cd	41.17 (6.92) a	2.01 (1.58) cd	0.12 (0.79) ab	0.50 (1.00) a	0.27 (0.88) b	0.58 (1.04) bc	22.03 (4.75) bc	15.93 (4.05) bc	18.82 (4.40) c	1.37 (1.37) a
T4 - B. Dark red	6.25 (2.60) ab	0.85 (1.16) ab	9.42 (3.15) bc	40.5 (6.41) a	22.23 (4.77) cd	7.99 (3.36) b	45.81 (7.27) a	2.42 (1.71) bc	0.13 (0.79) a	0.38 (0.94) ab	0.30 (0.89) ab	0.66 (1.07) ab	24.86 (5.04) ab	16.96 (4.18) b	20.23 (4.55) bc	1.24 (1.32) abc
T5 - B. Shakti	6.96 (2.73) a	0.90 (1.18) a	11.83 (3.51) a	34.9 (6.41) a	29.89 (5.51) ab	8.20 (3.33) ab	39.47 (6.78) a	3.45 (1.99) a	0.10 (0.77)bc	0.52 (1.01) a	0.37 (0.93)a	0.69 (1.09)a	27.84 (5.32) a	19.25 (4.44)a	23.19 (4.87)a	0.98 (1.22)bc
T6 - B. Shubra	5.55 (2.46)bc	0.78 (1.13) c	8.54 (3.01)bc	21.2 (5.10)b	21.52 (4.69) d	6.97 (3.14)cd	23.98 (5.40)b	1.70 (1.48)de	0.08 (0.76)c	0.18 (0.82) c	0.25 (0.87)b	0.62 (1.06)ab	19.81 (4.51) c	15.09 (3.95)c	18.12 (4.32)cd	1.50 (1.41)a
T7 - B. Shweta	5.00 (2.35)c	0.68 (1.09) d	8.23 (2.96)c	23.6 (5.36)b	15.27 (3.97) e	6.75 (3.10)d	26.69 (5.67)b	1.44 (1.39)e	0.08 (0.76)c	0.17 (0.82) c	0.14 (0.80)c	0.54 (1.02)c	20.20 (4.55) c	13.27 (3.71)d	16.15 (4.08)d	1.54 (1.43)a
GM	6.23	0.81	9.83	31.42	24.60	7.43	35.53	2.46	0.09	0.33	0.27	0.62	23.18	16.27	19.84	1.27
SE(+)	0.23	0.03	0.47	2.68	1.47	0.25	3.04	0.13	0.01	0.04	0.02	0.03	1.06	0.53	0.83	0.10
CD @5%	0.71	0.08	1.45	6.57	4.53	0.62	7.43	0.44	0.03	0.14	0.08	0.08	3.27	1.65	2.57	0.31
CV (%)	6.42	5.41	8.28	22.08	10.56	8.99	22.08	10.47	23.42	28.15	16.06	10.13	7.93	5.75	7.29	13.70

Figures in the parenthesis are √x + 0.5 transformed values

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

In the evaluation of secondary metabolites, which contribute to the antioxidant defense system, T1 (Bhima Super) demonstrated superior biochemical quality. T1 recorded the significantly highest Phenol content (31.23 mg GAE/g) and Flavonoid content (8.28 mg QE/g). For flavonoid accumulation, T5 (Bhima Shakti) was found to be statistically at par with T1. Consequently, the Total Antioxidant Capacity was significantly highest in T1 (3.67 mg AA/g), which was statistically equivalent to T5 (3.45 mg AA/g). The variety T7 (Bhima Shweta) consistently exhibited the lowest bioactivity, recording the minimum values for phenols, flavonoids, and antioxidants.

The mineral profile of the pollen highlighted T5 (Bhima Shakti) as the most mineral-dense genotype. T5 recorded the significantly highest concentrations of Iron (0.52 mg/g), Manganese (0.37 mg/g), and Zinc (0.69 mg/g). Statistical analysis revealed that for Iron content, T3 (Bhima Raj) was at par with T5. For Zinc content, the varieties T1, T2, T4, and T6 were statistically comparable to T5. Copper accumulation was found to be highest in T4 (0.13 mg/g), which was statistically at par with T3. Similar to other parameters, T7 generally displayed the lowest mineral concentrations across the spectrum.

The carbohydrate profile, a critical determinant of pollinator energy, indicated that T5 (Bhima Shakti) was the superior source of reducing sugars. T5 recorded the significantly highest Total Sugar (27.84%), Glucose (19.25%), and Fructose (23.19%).

While T1 (Bhima Super) was statistically at par with T5 for total sugar and fructose, T5 remained significantly superior in glucose content. Interestingly, an inverse trend was observed for the non-reducing sugar, Sucrose; the white variety T7 (Bhima Shweta) recorded the highest sucrose content (1.54%), which was statistically at par with T6 (1.50%) and T3 (1.37%). The lowest sucrose levels were recorded in the reducing-sugar-rich varieties T1 and T5.

The pooled results conclusively identify Bhima Shakti (T5) and Bhima Super (T1) as the elite varieties. They offer the highest nutritional value to pollinators, characterized by superior levels of proteins, amino acids, antioxidants, minerals, and essential reducing sugars. In contrast, the white variety Bhima Shweta (T7) generally recorded the lowest biochemical quality across the evaluated parameters.

4.2.3.2 Physicochemical and Biochemical composition of onion (*Allium cepa* L.) varieties of Nectar.

4.2.3.2.1 First year (Nectar Rabi 2023-24).

The biochemical analysis of onion umbel nectar conducted during the Rabi 2023-24 season revealed significant quantitative variations among the seven evaluated varieties. The results, presented in Table 45, indicate that the physicochemical properties, nutritional metabolites, and sugar profiles are strongly influenced by the onion genotype.

Physicochemical Properties The analysis of physicochemical traits revealed distinct differences in the quality of the nectar. The variety T7 (Bhima Shweta) recorded the significantly highest Electrical Conductivity (EC) of 0.60 dS/m, which was statistically at par with T5 (Bhima Shakti) (0.59 dS/m). Regarding pH, the varieties T1 (Bhima Super), T2 (Bhima Red), T5, T7, and T4 recorded the highest values (ranging from 5.3 to 5.7), forming a statistically equivalent group. In contrast, T3 (Bhima Raj) and T6 (Bhima Shubra) recorded the significantly lowest pH (4.2). A distinct trend was observed in moisture content; T7 (Bhima Shweta) recorded the significantly highest moisture (67.67%), followed by T1 (65.67%). Conversely, T2 (Bhima Red) recorded the lowest moisture content (49.67%), suggesting a higher sugar concentration and viscosity in its nectar.

Nitrogenous Metabolites (Protein and Amino Acids) the quantitative estimation of nitrogenous compounds highlighted T5 (Bhima Shakti) as the superior variety. It recorded the significantly highest Protein content (0.87 mg/L) and Total Amino Acid (TAA) content (0.98 mg/g). Statistical analysis (DMRT) revealed that for protein content, T1 (Bhima Super) (0.83 mg/L) and T3 (Bhima Raj) (0.79 mg/L) were statistically at par with T5. Similarly, for TAA content, T1 (0.93 mg/g) and T3 (0.89 mg/g) were comparable to T5. The lowest values for both protein (0.30 mg/L) and amino acids (0.33 mg/g) were consistently observed in the white variety T7 (Bhima Shweta).

Secondary Metabolites and Antioxidants The analysis of secondary metabolites, which often serve as attractants or defense compounds, indicated that T1 (Bhima Super) possessed the highest biochemical quality. T1 recorded the significantly highest Phenol content (4.55 mg GAE/g) and Flavonoid content (0.97 mg QE/g). For flavonoid accumulation, T5 (0.95 mg QE/g) and T4 (0.90 mg QE/g) were found to be statistically at par with T1. Consequently, the Total Antioxidant Capacity was significantly highest in T5 (0.50 mg AA/g), closely followed by T1 (0.40 mg AA/g), which was statistically equivalent. The white varieties, particularly T7, generally recorded the lowest concentrations of these bioactive compounds.

Table 45. Physicochemical and Biochemical composition of Different varieties of Onion umbel Nectar Rabi 2023-24.

Treatments	pH	EC (dS/m)	Moisture (%)	Protein (mg/1 L)	Phenol (mg GAE/ 1 g)	Flavonoid (mg QE/1 g)	Antioxidants (mg AA/1 g)	TAA (mg/g)	Copper (mg/g)	Iron (mg/g)	Manganese (mg/g)	Zinc (mg/g)	Total Sugar (%)	Glucose (%)	Fructose (%)	Sucrose (%)
T1 – B. Super	5.7 (2.49)^{a}	0.46 (0.98)^{d}	65.67 (8.13)^{b}	0.83 (1.41)^{ab}	4.55 (2.25)^{a}	0.97 (1.48)^{a}	0.4 (0.95)^{a}	0.93 (1.47)^{ab}	0.09 (0.77)^{a}	0.10 (0.77)^{b}	0.03 (0.73)^{c}	0.04 (0.73)^{a}	43.50 (6.63)^{a}	15.40 (3.99)^{a}	25.37 (5.09)^{a}	4.08 (2.14)^{a}
T2 – B. Red	5.7 (2.49)^{a}	0.52 (1.01)^{bcd}	49.67 (7.08)^{f}	0.41 (1.14)^{c}	3.96 (2.11)^{b}	0.82 (1.41)^{bcd}	0.3 (0.89)^{b}	0.46 (1.18)^{c}	0.08 (0.76)^{ab}	0.08 (0.76)^{b}	0.04 (0.73)^{b}	0.03 (0.73)^{b}	35.71 (6.02)^{c}	11.23 (3.42)^{c}	19.93 (4.52)^{bc}	3.15 (1.91)^{c}
T3 – B. Raj	4.2 (2.17)^{b}	0.51 (1.00)^{cd}	54.67 (7.43)^{e}	0.79 (1.39)^{ab}	3.43 (1.98)^{bc}	0.81 (1.40)^{cd}	0.3 (0.89)^{b}	0.89 (1.44)^{ab}	0.07 (0.75)^{b}	0.13 (0.79)^{a}	0.04 (0.73)^{b}	0.02 (0.72)^{b}	45.62 (6.79)^{a}	12.08 (3.55)^{bc}	20.46 (4.58)^{bc}	3.29 (1.95)^{bc}
T4 – B. Dark red	5.3 (2.41)^{a}	0.56 (1.03)^{abc}	56.00 (7.52)^{e}	0.74 (1.36)^{b}	3.43 (1.98)^{bc}	0.90 (1.45)^{abc}	0.3 (0.89)^{b}	0.83 (1.41)^{b}	0.06 (0.75)^{c}	0.13 (0.79)^{a}	0.05 (0.74)^{a}	0.03 (0.73)^{b}	34.47 (5.91)^{c}	12.96 (3.67)^{abc}	23.02 (4.85)^{ab}	3.43 (1.98)^{abc}
T5 – B. Shakti	5.5 (2.45)^{a}	0.59 (1.04)^{ab}	60.00 (7.78)^{d}	0.87 (1.43)^{a}	2.97 (1.86)^{cd}	0.95 (1.47)^{ab}	0.5 (1.00)^{a}	0.98 (1.49)^{a}	0.07 (0.75)^{b}	0.10 (0.77)^{b}	0.06 (0.75)^{a}	0.04 (0.73)^{a}	39.96 (6.36)^{b}	14.89 (3.92)^{ab}	24.53 (5.00)^{a}	3.94 (2.11)^{ab}
T6 – B. Shubra	4.2 (2.17)^{b}	0.58 (1.04)^{abc}	61.67 (7.88)^{c}	0.45 (1.43)^{c}	2.91 (1.85)^{cd}	0.69 (1.33)^{d}	0.2 (0.84)^{b}	0.50 (1.21)^{c}	0.06 (0.75)^{c}	0.09 (0.77)^{b}	0.03 (0.73)^{c}	0.02 (0.72)^{b}	32.88 (5.78)^{cd}	10.64 (3.34)^{c}	17.53 (4.25)^{c}	2.82 (1.82)^{c}
T7 – B. Shweta	5.4 (2.43)^{a}	0.60 (1.05)^{a}	67.67 (8.26)^{a}	0.30 (1.05)^{d}	2.73 (1.80)^{d}	0.68 (1.32)^{d}	0.3 (0.89)^{b}	0.33 (1.08)^{d}	0.07 (0.75)^{b}	0.08 (0.76)^{b}	0.03 (0.73)^{c}	0.02 (0.72)^{b}	30.87 (5.60)^{d}	10.50 (3.32)^{c}	17.29 (4.22)^{c}	2.78 (1.81)^{c}
GM	5.14	0.55	59.34	0.59	3.43	0.82	0.33	0.66	0.07	0.10	0.04	0.03	37.57	12.53	21.16	3.36
SE(+)	0.30	0.02	0.52	0.09	0.18	0.04	0.00	0.10	0.00	0.01	0.00	0.00	0.96	1.05	1.17	0.21
CD @5%	0.80	0.07	1.60	0.22	0.54	0.11	0.10	0.24	0.01	0.03	0.01	0.01	2.97	3.24	3.59	0.66
CV (%)	8.70	6.85	1.52	37.02	8.94	14.02	18.00	37.11	10.97	15.97	13.49	22.80	4.48	14.53	9.54	11.08

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Mineral Composition The mineral profile of the nectar showed specific varietal dominance. T1 (Bhima Super) recorded the highest Copper content (0.09 mg/g), while T3 (Bhima Raj) and T4 (Bhima Dark Red) recorded the significantly highest Iron content (0.13 mg/g). T5 (Bhima Shakti) exhibited the highest accumulation of Manganese (0.06 mg/g) at par with T4 and Zinc (0.04 mg/g), which was at par with T1. Generally, the white varieties (T6 and T7) showed lower mineral concentrations across the spectrum.

Sugar Profile The carbohydrate analysis, a critical factor for pollinator energy, revealed that T3 (Bhima Raj) recorded the numerically highest Total Sugar (45.62%), which was statistically at par with T1 (Bhima Super) (43.5%). T5 occupied the second statistical rank ('b'). However, regarding specific sugars, T1 (Bhima Super) displayed the most balanced profile; it recorded the highest Glucose (15.4%), Fructose (25.37%), and Sucrose (4.08%). In all three specific sugar categories, T5 and T4 were found to be statistically at par with T1. The variety T7 (Bhima Shweta) consistently recorded the lowest values for total sugars (30.87%) and individual sugar components.

The 2023-24 nectar analysis identifies Bhima Super (T1) and Bhima Shakti (T5) as the elite varieties. They offer superior nutritional rewards to foraging insects, characterized by high concentrations of proteins, amino acids, antioxidants, and essential sugars. In contrast, the white variety Bhima Shweta (T7), despite having high moisture content, provided significantly lower nutritional value.

4.2.3.2.2 Second year (Nectar Rabi 2024-25).

The biochemical constituents of onion umbel nectar were analyzed during the Rabi 2024-25 season. The data, presented in Table 46, reveals that the genotype of the onion varieties significantly influenced the physicochemical properties, nutritional metabolites, mineral composition, and sugar profiles of the nectar.

Physicochemical Properties The analysis of physicochemical parameters indicated that T1 (Bhima Super) recorded the numerically highest pH (5.8). However, statistical analysis (DMRT) revealed that T1 was at par with T2 (Bhima Red), T7 (Bhima Shweta), T4 (Bhima Dark Red), and T5 (Bhima Shakti), which all shared the significance ranking 'a'. The significantly lowest pH was observed in T6 (Bhima Shubra) at 4.1. Regarding electrical conductivity (EC), T7 (Bhima Shweta) recorded the maximum value (0.62 dS/m), which was statistically at par with T5 (0.61 dS/m). The moisture content was significantly highest in T1 (67.1%) and T7 (66.5%), whereas T2 (Bhima Red) recorded the lowest moisture content (51.2%), suggesting a higher viscosity in the nectar of Bhima Red.

The evaluation of nitrogenous metabolites, crucial for pollinator nutrition, identified T5 (Bhima Shakti) as the superior variety. It recorded the significantly highest Protein content (0.859 mg/mL) and Total Amino Acid (TAA) content (0.97 mg/mL). Statistical analysis revealed that for protein content, T1 (Bhima Super) (0.815 mg/mL) and T3 (Bhima Raj) (0.778 mg/mL) were statistically at par with T5. Similarly, for TAA content, T1 (0.92 mg/mL) and T3 (0.88 mg/mL) formed a statistically comparable group with T5. The lowest concentrations of both protein (0.312 mg/mL) and amino acids (0.35 mg/mL) were consistently observed in the white variety T7 (Bhima Shweta).

In terms of secondary metabolites, which function as antioxidants and potential attractants, T1 (Bhima Super) demonstrated the highest biochemical quality. T1 recorded the significantly highest Phenol content (4.62 mg GAE/mL) and Flavonoid content (0.99 mg QE/mL). For flavonoid accumulation, T5 (0.93 mg QE/mL) and T4 (0.92 mg QE/mL) were found to be statistically at par with T1. Consequently, the Total Antioxidant Capacity was significantly highest in T5 (0.48 mg AA/mL), which was statistically equivalent to T1 (0.42 mg AA/mL). The white variety T6 (Bhima Shubra) consistently recorded the lowest antioxidant potential (0.22 mg AA/mL).

Mineral Composition The mineral profile showed specific varietal dominance. T1 (Bhima Super) recorded the significantly highest copper content (0.09 mg/g), which was at par with T2, T3, and T5. For Iron, T4 (Bhima Dark Red) recorded the maximum concentration (0.14 mg/g), significantly superior to the white varieties (T6 and T7). T5 (Bhima Shakti) recorded the highest levels of Manganese (0.06 mg/g) and Zinc (0.04 mg/g), with T1 being statistically at par for Zinc content.

Sugar Profile The sugar composition analysis highlighted T3 (Bhima Raj) and T1 (Bhima Super) as the superior varieties. T3 recorded the numerically highest Total Sugar (46.1%), which was statistically at par, with T1 (44.1%). T5 occupied the second rank ('b'). However, regarding specific sugars, T1 (Bhima Super) appeared most balanced. It recorded the highest Glucose (15.8%) and Sucrose (4.15%). For Fructose, T5 recorded the highest value (25.1%), which was statistically at par with T1 (24.9%). The variety T7 (Bhima Shweta) consistently recorded the lowest values for total sugars (31.5%) and individual sugar components.

Table 46. Physicochemical and Biochemical composition of Different varieties of Onion umbel Nectar Rabi 2024-25.

Treatments	pH	EC (dS/m)	Moisture (%)	Protein (mg/mL)	Phenol (mg GAE/mL)	Flavonoid (mg QE/mL)	Antioxidants (mg AA/mL)	TAA (mg/mL)	Copper (mg/mL)	Iron (mg/mL)	Manganese (mg/mL)	Zinc (mg/mL)	Total Sugar (%)	Glucose (%)	Fructose (%)	Sucrose (%)
T1 - B. Super	5.8 (2.51)a	0.44 (0.97)c	67.1 (8.22)a	0.815 (1.40)ab	4.62 (2.26)a	0.99 (1.49)a	0.42 (0.96)ab	0.92 (1.46)ab	0.09 (0.77)a	0.11 (0.78)bc	0.03 (0.73)b	0.04 (0.73)a	44.1 (6.68)a	15.8 (4.04)a	24.9 (5.04)a	4.1 (2.16)a
T2 - B. Red	5.6 (2.47)a	0.54 (1.02)ab	51.2 (7.19)f	0.423 (1.15)c	4.05 (2.13)ab	0.80 (1.39)bcd	0.31 (0.90)cd	0.47 (1.190c	0.08 (0.76)a	0.07 (0.75)d	0.04 (0.73)ab	0.03 (0.73)ab	34.9 (5.95)cd	11.1 (3.46)c	19.5 (4.47)bcd	3.2 (1.92)bcd
T3 - B. Raj	4.3 (2.19)b	0.5 (1.00)bc	53.8 (7.37)e	0.778 (1.38)ab	3.55 (2.01)bc	0.83 (1.41)bc	0.33 (0.91)bc	0.88 (1.44)ab	0.07 (0.75)ab	0.12 (0.79)ab	0.04 (0.73)ab	0.02 (0.72)b	46.1 (6.83)a	12.35 (3.58)bc	20.9 (4.63)b c	3.35 (1.96)bcd
T4 - B. Dark red	5.4 (2.43) a	0.58 (1.04)ab	57.5 (7.62)d	0.725 (1.38)b	3.5 (2.00)bc	0.92 (1.46)ab	0.32 (0.91)bc	0.82 (1.41)b	0.06 (0.75)bc	0.14 (0.80)a	0.05 (0.74)a	0.03 (0.73)ab	35.1 (5.97)c	13.1 (3.69)abc	22.5 (4.80)ab	3.5 (2.00)abc
T5 - B. Shakti	5.4 (2.43)a	0.61 (1.05)a	59.2 (7.73)c	0.859 (1.430a	3.05 (1.88)cd	0.93 (1.46)ab	0.48 (0.99)a	0.97 (1.49)a	0.08 (0.76)a	0.11 (0.78)bc	0.06 (0.75)a	0.04 (0.73)a	40.5 (6.40)b	15.2 (3.96)ab	25.1 (5.06)a	3.85 (2.09)ab
T6 - B. Shubra	4.1 (2.14)b	0.56 (1.03)ab	62.9 (7.96)b	0.468 (1.180c	2.85 (1.83)d	0.71 (1.34)cd	0.22 (0.85)d	0.52 (1.23)c	0.05 (0.74)c	0.09 (0.77)cd	0.03 (0.73)b	0.02 (0.72)b	31.9 (5.69)de	10.9 (3.38)c	17.1 (4.20)d	2.9 (1.84)cd
T7 - B. Shweta	5.5 (2.45)a	0.62 (1.06)a	66.5 (8.19)a	0.312 (1.06)d	2.65 (1.77)d	0.66 (1.31)d	0.31 (0.90)cd	0.35 (1.09)c	0.07 (0.75)ab	0.07 (0.75)d	0.03 (0.73)b	0.02 (0.72)b	31.5 (5.66)e	10.8 (3.36)c	17.6 (4.25)cd	2.7 (1.79)d
GM	5.16	0.55	59.74	0.59	3.47	0.83	0.34	0.67	0.07	0.10	0.04	0.03	37.73	12.81	21.09	3.38
SE(+)	0.29	0.03	0.61	0.08	0.21	0.05	0.04	0.09	0.01	0.01	0.01	0.01	1.09	1.18	1.30	0.24
CD @5%	0.82	0.08	1.70	0.20	0.58	0.11	0.10	0.23	0.02	0.03	0.02	0.02	3.05	3.30	3.65	0.68
CV (%)	12.04	10.69	9.46	34.99	18.56	14.50	22.87	35.02	17.44	23.82	26.73	29.15	14.38	14.56	14.26	13.95

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

The 2024-25 nectar analysis confirms that Bhima Super (T1) and Bhima Shakti (T5) are the most biochemically rich varieties, offering high concentrations of proteins, antioxidants, and essential sugars. In contrast, the white varieties (T6 and T7) exhibited significantly lower nutritional quality in their nectar, characterized by lower sugar and protein content despite having high moisture levels.

4.2.3.2.3 Pooled data Rabi (Nectar) Rabi 2023-24 & Rabi 2024-25.

The pooled biochemical data from the Rabi 2023-24 and 2024-25 seasons (Table 47) provides a robust assessment of the nectar quality across seven onion varieties. The statistical analysis reveals that while certain parameters like mineral composition remained stable across genotypes, significant variations were observed in physicochemical properties, nutritional metabolites, and sugar profiles.

Physicochemical Properties the analysis of physicochemical traits revealed that T1 (Bhima Super) recorded the numerically highest pH (5.75), which was statistically at par with T2, T4, T5, and T7. The significantly lowest pH was observed in T6 (Bhima Shubra) at 4.15. Regarding Electrical Conductivity (EC), T7 (Bhima Shweta) exhibited the highest ionic concentration (0.61 dS/m), which was statistically equivalent to T5 (Bhima Shakti) at 0.60 dS/m. A distinct inverse relationship was observed between moisture and nectar concentration; T7 recorded the significantly highest moisture content (67.09%), whereas T2 (Bhima Red) recorded the lowest (50.44%), suggesting that Bhima Red produces a more viscous and concentrated nectar.

Nitrogenous Metabolites The protein content, a vital nutritional factor for foraging insects, was highest in T5 (Bhima Shakti) with 0.86 mg/g. Statistical analysis (DMRT) indicated that T5 was at par with T1 (Bhima Super) (0.82 mg/g), T3 (Bhima Raj) (0.78 mg/g), and T4 (Bhima Dark Red) (0.73 mg/g).Similarly, for Total Amino Acids (TAA), T5 (0.97 mg/mL) and T1 (0.92 mg/mL) formed a statistically superior group. The white variety T7 recorded the significantly lowest protein content (0.30 mg/g) and TAA content (0.33 mg/mL), indicating poor nitrogenous rewards. Secondary Metabolites and Antioxidants In the context of secondary metabolites, T1 (Bhima Super) consistently demonstrated superior quality. It recorded the significantly highest Phenol content (4.58 mg GAE/g) and Flavonoid content (0.98 mg QE/g). For flavonoids, T5 and T4 were found to be statistically at par with T1. Consequently, the Total Antioxidant Capacity was highest in T5 (0.49 mg AA/g), closely followed by T1 (0.41 mg AA/g), while T6 recorded the lowest antioxidant activity (0.21 mg AA/g).

Mineral composition contrasting with other biochemical parameters, the pooled analysis for mineral composition (Copper, Iron, Manganese, and Zinc) revealed non-significant differences among the varieties. As indicated by the uniform ranking letter ('a') across all columns, no single variety proved statistically superior in mineral accumulation. However, numerically, T4 (Bhima Dark Red) recorded the highest Iron (0.14 mg/g) and T5 (Bhima Shakti) recorded the highest Manganese (0.06 mg/g). The extremely high Coefficient of Variation (CV) observed for Zinc (198.78%) and Manganese (149.44%) suggests a high degree of environmental influence or experimental variability for these micro-nutrients in nectar.

Sugar Profile The carbohydrate analysis indicates that T3 (Bhima Raj) possessed the highest Total Sugar content (45.86%), which was statistically at par with T1 (43.80%) and T5 (40.23%). However, regarding the specific sugar composition, T1 (Bhima Super) displayed the most nutritionally balanced profile. T1 recorded the significantly highest levels of Glucose (15.60%) and Sucrose (4.12%). For Fructose content, T1 (25.13%) was statistically at par with T5 (24.82%). The variety T7 (Bhima Shweta) consistently recorded the lowest concentrations for total sugar, glucose, and sucrose, reinforcing its status as a lower-energy reward source for pollinators.

The pooled data conclusively identifies Bhima Super (T1) and Bhima Shakti (T5) as the elite varieties regarding nectar quality. They offer the highest combination of proteins, antioxidants, and essential sugars (glucose/fructose/sucrose). Conversely, the white variety Bhima Shweta (T7), despite having high moisture, provided the lowest nutritional value per unit volume, characterized by significantly lower protein and sugar levels.

Table 47. Physicochemical and Biochemical composition of Different varieties of Onion umbel Nectar Pooled data Rabi 2023-24 & Rabi 2024-25.

Treatments	pH	EC (dS/m)	Moisture (%)	Protein (mg/ mL)	Phenol (mg GAE/ mL)	Flavonoid (mg QE/ mL)	Antioxidants (mg AA/ mL)	TAA (mg/mL)	Copper (mg/ mL)	Iron (mg/ mL)	Manganese (mg/ mL)	Zinc (mg/ mL)	Total Sugar (%)	Glucose (%)	Fructose (%)	Sucrose (%)
T1 - B. Super	5.75 (2.5)a	0.45 (0.97)a	66.38 (8.18)a	0.82 (1.41)a	4.58 (2.25)a	0.98 (1.49)a	0.41 (0.95)ab	0.92 (1.46)a	0.09 (0.77)a	0.11 (0.78)a	0.03 (0.73)a	0.04 (0.73)a	43.80 (6.66)ab	15.60 (4.01)a	25.13 (5.06)a	4.12 (2.15)a
T2 - B. Red	5.65 (2.48)a	0.53 (1.01)a	50.44 (7.14)b	0.41 (1.14)bc	4.0 (2.12)a	0.81 (1.40)ab	0.3 (0.9) ab	0.46 (1.18)c	0.08 (0.76)a	0.08 (0.76)a	0.04 (0.73)a	0.03 (0.73)a	35.30 (5.98)ab	11.37 (3.44)c	19.71 (4.50)abc	3.17 (1.92)ab
T3 - B. Raj	4.25 (2.18)ab	0.51 (1.0)a	54.23 (7.4)ab	0.78 (1.38)a	3.49 (2.0)ab	0.82 (1.41)b	0.32 (0.9)ab	0.88 (1.44)ab	0.07 (0.75)a	0.12 (0.79)a	0.04 (0.73)a	0.02 (0.72)a	45.86 (6.81)a	12.21 (3.57)bc	20.68 (4.60)abc	3.32 (1.95)ab
T4 - B. Dark red	5.35 (2.42)ab	0.57 (1.03)a	56.75 (7.57)b	0.73 (1.35)a	3.46 (1.99)ab	0.91 (1.45)ab	0.31 (0.9)ab	0.82 (1.41)b	0.06 (0.75)a	0.14 (0.80)a	0.05 (0.74)a	0.03 (0.73)a	34.78 (5.94)ab	13.03 (3.68)bc	22.76 (4.82)ab	3.46 (1.99)ab
T5 - B. Shakti	5.45 (2.44)ab	0.6 (1.05)a	59.6 (7.75)ab	0.86 (1.43)a	3.01 (1.87)bc	0.94 (1.47)ab	0.49 (0.99)a	0.97 (1.49)a	0.08 (0.76)a	0.11 (0.78)a	0.06 (0.75)a	0.04 (0.73)a	40.23 (6.38)ab	15.04 (3.94)ab	24.82 (5.03)ab	3.90 (2.10)ab
T6 - B. Shubra	4.15 (2.16)b	0.57 (1.03)a	62.28 (7.92)ab	0.46 (1.18)b	2.88 (1.84)bc	0.70 (1.34)b	0.21 (0.84)b	0.52 (1.22)c	0.06 (0.74)a	0.09 (0.77)a	0.03 (0.73)a	0.02 (0.72)a	32.39 (5.73)b	10.77 (3.36)c	17.32 (4.22)c	2.86 (1.83)b
T7 - B. Shweta	5.45 (2.44)ab	0.61 (1.05)a	67.09 (8.22)a	0.30 (1.05)c	2.69 (1.79)c	0.67 (1.32)b	0.3 (0.9)ab	0.33 (1.08)d	0.07 (0.75)a	0.08 (0.76)a	0.03 (0.73)a	0.02 (0.72)a	31.19 (5.63)ab	10.65 (3.34)c	17.45 (4.24)bc	2.74 (1.80)b
GM	5.15	0.55	59.54	0.58	3.44	0.83	0.33	0.66	0.07	0.1	0.04	0.03	37.65	12.67	21.12	3.37
SE(+)	0.325	0.053	2.877	0.09	0.148	0.045	0.049	0.1	0.032	0.029	0.035	0.033	2.539	1.061	1.27	0.153
CD @5%	0.985	0.162	8.726	0.21	0.448	0.11	0.148	0.24	0.098	0.087	0.105	0.099	7.701	3.219	3.853	0.464
CV (%)	10.92	16.89	8.37	36.34	7.42	14.2	25.33	36.35	77.01	47.83	149.44	198.78	11.68	14.51	10.41	7.88

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

4.2.4 Amino acid Analysis.

4.2.4.1 Analysis of Amino acid by LCMS/MS.

The amino acid composition of pollen exhibited significant variability among onion varieties across both experimental years (Table 48). In the pooled data analysis, total amino acid (TAA) content ranged from 23.98 mg/g in T6 (Bhima Shubra) to 45.81 mg/g in T4 (Bhima Dark Red), representing nearly a two-fold difference.

The amino acid composition of pollen exhibited significant variability among onion varieties across both experimental years. In the pooled data analysis, total amino acid (TAA) content ranged from 23.98 mg/g in T6 (Bhima Shubra) to 45.81 mg/g in T4 (Bhima Dark Red), representing nearly a two-fold difference. Bhima Dark Red demonstrated consistently superior amino acid accumulation, recording the highest TAA content of 41.99 mg/g and 50.10 mg/g during Rabi 2023-24 and 2024-25, respectively, followed by Bhima Shakti (42.72 mg/g and 36.87 mg/g) and Bhima Raj (39.02 mg/g and 43.77 mg/g). The white-bulb varieties, Bhima Shubra and Bhima Shweta, consistently exhibited the lowest pollen amino acid concentrations, with pooled TAA values of 23.98 mg/g and 26.69 mg/g, respectively.

Essential amino acids (EAA) constituted approximately 51% of total amino acids across all varieties, ranging from 12.25 mg/g (Bhima Shubra) to 23.41 mg/g (Bhima Dark Red) in pooled data. This proportion remained relatively consistent across varieties, suggesting a conserved biosynthetic regulation of amino acid pathways in onion pollen. Non-essential amino acids (NEAA) showed parallel trends, with Bhima Dark Red accumulating 33.09 mg/g and white varieties showing significantly lower values (17.32-19.28 mg/g).

Table 48. Total amino acid, essential amino acid & non- essential amino acid of pollen.

Variety	Pollen 2023-24			Pollen 2024-25			Pooled Data		
	TAA (mg/g)	EAA (mg/g)	NEAA (mg/g)	TAA (mg/g)	EAA (mg/g)	NEAA (mg/g)	TAA (mg/g)	EAA (mg/g)	NEAA (mg/g)
T1 - B. Super	44.31^{a}	22.65^{a}	32.0^{a}	36.87^{c}	18.84^{c}	26.64^{c}	40.60^{a}	20.75^{ab}	29.33^{ab}
T2 - B. Red	38.39^{b}	19.62^{b}	27.73^{ab}	35.74^{c}	18.27^{c}	25.82^{c}	36.98^{ab}	18.90^{bc}	26.72^{bc}
T3 - B. Raj	39.02^{ab}	19.94^{b}	28.19^{ab}	43.77^{b}	22.37^{b}	31.62^{b}	41.17^{a}	21.04^{ab}	29.74^{ab}
T4 - B. Dark Red	41.99^{a}	21.46^{ab}	30.34^{a}	50.10^{a}	25.61^{a}	36.19^{a}	45.81^{a}	23.41^{a}	33.09^{a}
T5 - B. Shakti	42.72^{a}	21.83^{ab}	30.86^{a}	36.87^{c}	18.84^{c}	26.64^{c}	39.47^{ab}	20.17^{ab}	28.51^{ab}
T6 - B. Shubra	23.25^{c}	11.88^{d}	16.8^{d}	24.77^{d}	12.66^{d}	17.89^{d}	23.98^{b}	12.25^{c}	17.32^{c}
T7 - B. Shweta	28.17^{c}	14.40^{c}	20.35^{c}	25.67^{d}	13.12^{d}	18.55^{d}	26.69^{b}	13.64^{c}	19.28^{c}

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

Table 49. Total amino acid, essential amino acid & non- essential amino acid of nectar.

Variety	Nectar 2023-24			Nectar 2024-25			Pooled Data		
	TAA (mg/g)	EAA (mg/g)	NEAA (mg/g)	TAA (mg/g)	EAA (mg/g)	NEAA (mg/g)	TAA (mg/g)	EAA (mg/g)	NEAA (mg/g)
T1 - B. Super	0.939^{ab}	0.480^{ab}	0.678^{ab}	0.922^{ab}	0.471^{ab}	0.666^{ab}	0.927^{ab}	0.474^{ab}	0.670^{ab}
T2 - B. Red	0.464^{e}	0.237^{e}	0.335^{e}	0.478^{e}	0.245^{e}	0.346^{e}	0.464^{e}	0.237^{e}	0.335^{e}
T3 - B. Raj	0.893^{b}	0.457^{b}	0.645^{b}	0.880^{b}	0.450^{b}	0.636^{b}	0.882^{b}	0.451^{b}	0.637^{b}
T4 - B. Dark Red	0.837^{c}	0.428^{c}	0.605^{c}	0.820^{c}	0.419^{c}	0.592^{c}	0.826^{c}	0.422^{c}	0.596^{c}
T5 - B. Shakti	0.984^{a}	0.503^{a}	0.711^{a}	0.972^{a}	0.497^{a}	0.702^{a}	0.973^{a}	0.497^{a}	0.703^{a}
T6 - B. Shubra	0.509^{d}	0.260^{d}	0.368^{d}	0.529^{d}	0.271^{d}	0.382^{d}	0.520^{d}	0.266^{d}	0.376^{d}
T7 - B. Shweta	0.339^{f}	0.173^{f}	0.245^{f}	0.353^{f}	0.180^{f}	0.255^{f}	0.339^{f}	0.173^{f}	0.245^{f}

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Temporal variation between years was evident, particularly in Bhima Dark Red, which showed an increase from 41.99 mg/g to 50.10 mg/g TAA between 2023-24 and 2024-25, indicating potential influence of seasonal abiotic factors such as temperature, humidity, and soil nutrient availability on pollen amino acid biosynthesis.

Nectar amino acid concentrations were approximately 40-50 times lower than pollen values, reflecting nectar's primary role as a carbohydrate source rather than a protein reservoir (Table 48). Total amino acids in nectar ranged from 0.339 mg/g (Bhima Shweta) to 0.973 mg/g (Bhima Shakti) in pooled data. Notably, Bhima Shakti exhibited the highest nectar TAA content (0.984 mg/g and 0.972 mg/g in both years), followed by Bhima Super (0.939 mg/g and

0.922 mg/g) and Bhima Raj (0.893 mg/g and 0.880 mg/g). The white-bulb varieties again demonstrated the lowest amino acid content, with Bhima Shweta recording merely 0.339 mg/g TAA.

Essential amino acids in nectar maintained approximately 51% of total composition, similar to pollen, with values ranging from 0.173 mg/g (Bhima Shweta) to 0.497 mg/g (Bhima Shakti) in pooled data. This proportional consistency suggests coordinated metabolic regulation between pollen and nectar amino acid synthesis pathways.

Remarkably, nectar amino acid concentrations exhibited exceptional year-to-year stability compared to pollen, with minimal variation between 2023-24 and 2024-25 seasons across all varieties. This temporal consistency indicates that nectar amino acid composition is under stricter genetic control and less susceptible to environmental fluctuations.

The substantial differences in amino acid content among varieties have direct implications for *Apis mellifera* foraging preferences. Red-bulb varieties (Bhima Dark Red, Bhima Raj, Bhima Super, and Bhima Shakti) consistently produced pollen and nectar with elevated amino acid concentrations, which correlates with enhanced honeybee attraction as demonstrated in the correlation analysis ($r = 0.949^{**}$ for pollen TAA; $r = 0.781^{*}$ for nectar TAA). The higher essential amino acid content in these varieties provides superior nutritional resources for colony brood rearing and worker bee development, as EAAs serve as fundamental building blocks for vitellogenin synthesis and physiological maturation. Conversely, white-bulb varieties (Bhima Shubra and Bhima Shweta) exhibited significantly depleted amino acid profiles in both pollen and nectar matrices. This nutritional deficiency likely contributes to reduced pollinator visitation rates, as honeybees demonstrate sophisticated chemosensory capabilities to discriminate between floral resources based on protein quality and amino acid composition. Previous research has established that amino acids such as proline, glutamic acid, leucine, and lysine are among the most abundant in bee-preferred pollens, and varieties rich in these compounds receive preferential visitation.

Pollen Amino Acid Profile During Rabi 2023-24.

Analysis of amino acid composition in onion pollen during Rabi 2023-24 revealed significant varietal differences across all 18 amino acids quantified (Table 50). Glutamic acid emerged as the most abundant amino acid across all varieties, ranging from 3.83 mg/g in Bhima Shubra (T6) to 7.30 mg/g in Bhima Super (T1). The next most abundant amino acids followed a similar pattern: glycine (3.71-7.07 mg/g), aspartic acid (3.68-7.01 mg/g), and alanine (2.86-5.45 mg/g).

Among the red-bulb varieties, Bhima Super (T1) recorded the significantly highest concentrations for most amino acids, including glutamic acid (7.30 mg/g), glycine (7.07 mg/g), aspartic acid (7.01 mg/g), alanine (5.45 mg/g), leucine (5.07 mg/g), and valine (4.04 mg/g). Bhima Shakti (T5) and Bhima Dark Red (T4) demonstrated statistically similar or slightly lower values. Bhima Dark Red showed particularly high levels of isoleucine (0.39 mg/g) and cysteine (0.66 mg/g), which were significantly greater than other varieties. In contrast, the white-bulb varieties exhibited markedly lower amino acid concentrations. Bhima Shubra (T6) recorded the lowest values across all amino acids, with glutamic acid at 3.83 mg/g, glycine at 3.71 mg/g, and leucine at 2.66 mg/g—representing approximately 50% of the levels found in Bhima Super. Bhima Shweta (T7) occupied an intermediate but still significantly lower position, with glutamic acid at 4.64 mg/g and glycine at 4.50 mg/g.

Essential amino acids such as leucine, valine, lysine, isoleucine, and threonine followed the same varietal ranking pattern. Leucine ranged from 2.66 mg/g (T6) to 5.07 mg/g (T1), while valine ranged from 2.12 mg/g (T6) to 4.04 mg/g (T1). Among the aromatic amino acids, phenylalanine concentrations ranged from 0.59 mg/g (T6) to 1.13 mg/g (T1), and tyrosine from 0.45 mg/g (T6) to 0.86 mg/g (T1). Proline, an important non-essential amino acid, was present in relatively small quantities (0.13-0.24 mg/g) across varieties, with Bhima Super, Bhima Shakti, and Bhima Dark Red showing significantly higher levels (0.23-0.24 mg/g) than Bhima Shubra (0.13 mg/g).

Pollen Amino Acid Profile During Rabi 2024-25.

The amino acid composition analysis during Rabi 2024-25 revealed a shift in varietal performance compared to the previous year, though the overall pattern remained consistent. (Table 51). Bhima Dark Red (T4) emerged as the variety with the highest amino acid concentrations, recording glutamic acid at 8.25 mg/g, glycine at 8.00 mg/g, aspartic acid at 7.93 mg/g, and alanine at 6.17 mg/g. This represented a notable increase from the 2023-24 season, where Bhima Dark Red had ranked second or third for most amino acids.

Bhima Raj (T3) also showed substantial increases, with glutamic acid rising to 7.21 mg/g, glycine to 6.99 mg/g, and aspartic acid to 6.93 mg/g, positioning it as the second-highest performing variety in 2024-25. Bhima Super (T1) and Bhima Red (T2) showed relatively similar amino acid profiles, with glutamic acid concentrations of 6.07 mg/g and 5.89 mg/g, respectively. Bhima Shakti (T5) displayed identical values to Bhima Super across all amino acids except isoleucine (0.43 mg/g vs. 0.33 mg/g).

The white-bulb varieties continued to exhibit significantly lower amino acid

accumulation. Bhima Shubra (T6) recorded glutamic acid at 4.08 mg/g, glycine at 3.95 mg/g, and leucine at 2.84 mg/g, maintaining its position as the variety with the lowest amino acid content. Bhima Shweta (T7) showed marginally higher values (glutamic acid: 4.23 mg/g, glycine: 4.10 mg/g) but remained significantly inferior to red-bulb varieties.

Essential amino acid concentrations in 2024-25 showed the same varietal ranking. Leucine ranged from 2.84 mg/g (T6) to 5.74 mg/g (T4), valine from 2.26 mg/g (T6) to 4.56 mg/g (T4), and lysine from 1.89 mg/g (T6) to 3.83 mg/g (T4). Threonine, another essential amino acid, ranged from 1.15 mg/g (T6) to 2.32 mg/g (T4). The sulfur-containing amino acids cysteine and methionine were present in lower concentrations, with cysteine ranging from 0.39 mg/g (T6) to 0.78 mg/g (T4) and methionine from 0.12 mg/g (T6-T7) to 0.24 mg/g (T4). Isoleucine showed particularly interesting varietal differences, with Bhima Shakti recording the highest value (0.43 mg/g), followed by Bhima Red and Bhima Super (0.35 mg/g and 0.33 mg/g), while Bhima Raj exhibited the lowest among red varieties (0.15 mg/g). This suggests potential metabolic or biosynthetic pathway differences among varieties in the production or accumulation of specific branched-chain amino acids.

Pooled Amino Acid Composition (2023-24 to 2024-25).

The pooled data analysis across both years provided a consolidated and statistically robust picture of amino acid composition differences among onion varieties (Table 52). Bhima Dark Red (T4) emerged as the superior variety, recording significantly highest concentrations for 16 out of 18 amino acids analyzed. Glutamic acid in Bhima Dark Red averaged 7.54 mg/g, followed by glycine (7.31 mg/g), aspartic acid (7.25 mg/g), alanine (5.64 mg/g), leucine (5.24 mg/g), and valine (4.17 mg/g).

Bhima Raj (T3) and Bhima Super (T1) formed the second tier of performance, with statistically similar values for most amino acids. Both varieties recorded glutamic acid levels of approximately 6.69-6.78 mg/g, glycine at 6.48-6.57 mg/g, and aspartic acid at 6.43-6.52 mg/g. Bhima Shakti (T5) and Bhima Red (T2) occupied the third tier, with glutamic acid concentrations of 6.50 mg/g and 6.09 mg/g, respectively. The white-bulb varieties Bhima Shubra (T6) and Bhima Shweta (T7) consistently ranked lowest across all amino acids in the pooled analysis. Bhima Shubra recorded glutamic acid at 3.95 mg/g, glycine at 3.83 mg/g, leucine at 2.75 mg/g, and valine at 2.18 mg/g—values that were 47-52% lower than those of Bhima Dark Red. Bhima Shweta showed marginally higher but still significantly lower concentrations (glutamic acid: 4.40 mg/g, glycine: 4.26 mg/g).

Essential amino acids in the pooled data demonstrated clear varietal stratification.

Leucine, the most abundant essential amino acid, ranged from 2.75 mg/g (T6) to 5.24 mg/g (T4). Valine ranged from 2.18 mg/g (T6) to 4.17 mg/g (T4), lysine from 1.83 mg/g (T6) to 3.50 mg/g (T4), isoleucine from 1.45 mg/g (T6) to 2.77 mg/g (T4), and threonine from 1.11 mg/g (T6) to 2.12 mg/g (T4). These differences translate to approximately 50-60% higher essential amino acid content in Bhima Dark Red compared to Bhima Shubra.

Among the aromatic amino acids, phenylalanine and tyrosine showed similar patterns, with Bhima Dark Red recording 1.17 mg/g and 0.88 mg/g, respectively, compared to 0.61 mg/g and 0.46 mg/g in Bhima Shubra. Tryptophan, though present in smaller quantities, ranged from 0.24 mg/g (T6) to 0.47 mg/g (T4).

The sulfur-containing amino acids cysteine and methionine were least abundant, with cysteine ranging from 0.37 mg/g (T6) to 0.71 mg/g (T4) and methionine from 0.11 mg/g (T6) to 0.22 mg/g (T4). Proline, an important amino acid for insect flight metabolism, showed relatively low concentrations across all varieties (0.13-0.25 mg/g) but maintained the same varietal hierarchy, with Bhima Dark Red (0.25 mg/g) significantly higher than Bhima Shubra (0.13 mg/g). Isoleucine exhibited unique varietal differences, with Bhima Shakti recording the highest pooled value (0.40 mg/g), significantly greater than other red varieties (0.30-0.34 mg/g), while Bhima Raj showed the lowest among red varieties (0.17 mg/g) (Table.52).

Overall, the pooled data confirmed that red-bulb onion varieties, particularly Bhima Dark Red, Bhima Raj, and Bhima Super, consistently produced pollen with substantially higher concentrations of both essential and non-essential amino acids compared to white-bulb varieties. This stable varietal ranking across two consecutive growing seasons demonstrates strong genetic control over amino acid biosynthesis and accumulation in onion pollen.

Table 50. Amino acids composition (mg/g) of pollen 2023-24.

Variety	Glu	Gly	Asp	Ala	Leu	Val	Lys	Ser	Ile	Thr	His	Arg	Phe	Tyr	Cys	Trp	Pro	Met	Iso
T1 - B. Super	7.30^{a}	7.07^{a}	7.01^{a}	5.45^{a}	5.07^{a}	4.04^{a}	3.39^{a}	3.39^{a}	2.68^{a}	2.05^{a}	2.04^{a}	1.60^{a}	1.13^{a}	0.86^{a}	0.69^{a}	0.45^{a}	0.24^{a}	0.21^{a}	0.30^{b}
T2 - B. Red	6.32^{c}	6.13^{c}	6.08^{c}	4.73^{c}	4.40^{c}	3.50^{c}	2.93^{c}	2.93^{c}	2.32^{c}	1.78^{c}	1.77^{c}	1.38^{c}	0.98^{c}	0.74^{c}	0.60^{c}	0.39^{c}	0.21^{ab}	0.18^{ab}	0.26^{bc}
T3 - B. Raj	6.43^{c}	6.23^{c}	6.18^{c}	4.80^{c}	4.47^{c}	3.55^{c}	2.98^{c}	2.98^{c}	2.36^{c}	1.81^{c}	1.79^{c}	1.40^{c}	0.99^{c}	0.75^{c}	0.61^{c}	0.40^{c}	0.21^{ab}	0.18^{ab}	0.18^{c}
T4 - B. Dark red	6.92^{b}	6.70^{b}	6.65^{b}	5.17^{b}	4.81^{b}	3.83^{b}	3.21^{b}	3.21^{b}	2.54^{b}	1.94^{b}	1.93^{b}	1.51^{b}	1.07^{b}	0.81^{b}	0.66^{ab}	0.43^{ab}	0.23^{a}	0.20^{a}	0.39^{a}
T5 - B. Shakti	7.04^{ab}	6.82^{ab}	6.76^{ab}	5.26^{ab}	4.89^{ab}	3.89^{ab}	3.26^{ab}	3.26^{ab}	2.58^{ab}	1.98^{ab}	1.97^{ab}	1.54^{ab}	1.09^{ab}	0.82^{ab}	0.67^{a}	0.44^{a}	0.23^{a}	0.20^{a}	0.43^{a}
T6 - B. Shubra	3.83^{e}	3.71^{e}	3.68^{e}	2.86^{e}	2.66^{e}	2.12^{e}	1.78^{e}	1.78^{e}	1.40^{e}	1.08^{e}	1.07^{e}	0.84^{e}	0.59^{e}	0.45^{e}	0.36^{e}	0.24^{e}	0.13^{c}	0.11^{c}	0.25^{bc}
T7 - B. Shweta	4.64^{d}	4.50^{d}	4.46^{d}	3.47^{d}	3.23^{d}	2.57^{d}	2.15^{d}	2.15^{d}	1.70^{d}	1.30^{d}	1.30^{d}	1.01^{d}	0.72^{d}	0.54^{d}	0.44^{d}	0.29^{d}	0.15^{bc}	0.13^{bc}	0.11^{d}

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 51. Amino acids composition (mg/g) of pollen 2024-25.

Variety	Glu	Gly	Asp	Ala	Leu	Val	Lys	Ser	Ile	Thr	His	Arg	Phe	Tyr	Cys	Trp	Pro	Met	Iso
T1 - B. Super	6.07^{c}	5.88^{c}	5.84^{c}	4.54^{c}	4.22^{c}	3.36^{c}	2.82^{c}	2.82^{c}	2.23^{c}	1.71^{c}	1.70^{c}	1.33^{c}	0.94^{c}	0.71^{c}	0.58^{c}	0.38^{c}	0.20^{c}	0.17^{c}	0.33^{c}
T2 - B. Red	5.89^{c}	5.70^{c}	5.66^{c}	4.40^{c}	4.09^{c}	3.26^{c}	2.73^{c}	2.73^{c}	2.16^{c}	1.65^{c}	1.64^{c}	1.29^{c}	0.91^{c}	0.69^{c}	0.56^{c}	0.36^{c}	0.19^{c}	0.17^{c}	0.35^{c}
T3 - B. Raj	7.21^{b}	6.99^{b}	6.93^{b}	5.39^{b}	5.01^{b}	3.99^{b}	3.34^{b}	3.34^{b}	2.64^{b}	2.03^{b}	2.01^{b}	1.58^{b}	1.12^{b}	0.84^{b}	0.68^{b}	0.45^{b}	0.24^{b}	0.21^{b}	0.15^{d}
T4 - B. Dark red	8.25^{a}	8.00^{a}	7.93^{a}	6.17^{a}	5.74^{a}	4.56^{a}	3.83^{a}	3.83^{a}	3.03^{a}	2.32^{a}	2.30^{a}	1.80^{a}	1.28^{a}	0.97^{a}	0.78^{a}	0.51^{a}	0.27^{a}	0.24^{a}	0.34^{c}
T5 - B. Shakti	6.07^{c}	5.88^{c}	5.84^{c}	4.54^{c}	4.22^{c}	3.36^{c}	2.82^{c}	2.82^{c}	2.23^{c}	1.71^{c}	1.70^{c}	1.33^{c}	0.94^{c}	0.71^{c}	0.58^{c}	0.38^{c}	0.20^{c}	0.17^{c}	0.43^{a}
T6 - B. Shubra	4.08^{e}	3.95^{e}	3.92^{e}	3.05^{e}	2.84^{e}	2.26^{e}	1.89^{e}	1.89^{e}	1.50^{e}	1.15^{e}	1.14^{e}	0.89^{e}	0.63^{e}	0.48^{e}	0.39^{e}	0.25^{e}	0.13^{e}	0.12^{d}	0.28^{b}
T7 - B. Shweta	4.23^{d}	4.10^{d}	4.06^{d}	3.16^{d}	2.94^{d}	2.34^{d}	1.96^{d}	1.96^{d}	1.55^{d}	1.19^{d}	1.18^{d}	0.92^{d}	0.65^{d}	0.50^{d}	0.40^{d}	0.26^{d}	0.14^{d}	0.12^{d}	0.16^{d}

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 52. Amino acids composition (mg/g) of pollen pooled data 2023-24 to 2024-25.

Variety	Glu	Gly	Asp	Ala	Leu	Val	Lys	Ser	Ile	Thr	His	Arg	Phe	Tyr	Cys	Trp	Pro	Met	Iso
T1 - B. Super	6.69^{b}	6.48^{b}	6.43^{b}	5.00^{b}	4.65^{b}	3.70^{b}	3.10^{b}	3.10^{b}	2.45^{b}	1.88^{b}	1.87^{b}	1.46^{b}	1.04^{b}	0.78^{b}	0.63^{b}	0.41^{b}	0.22^{b}	0.19^{b}	0.33^{b}
T2 - B. Red	6.09^{c}	5.90^{c}	5.85^{c}	4.55^{c}	4.23^{c}	3.37^{c}	2.83^{c}	2.83^{c}	2.23^{c}	1.71^{c}	1.70^{c}	1.33^{c}	0.94^{c}	0.71^{c}	0.58^{c}	0.38^{c}	0.20^{c}	0.17^{c}	0.30^{b}
T3 - B. Raj	6.78^{b}	6.57^{b}	6.52^{b}	5.07^{b}	4.71^{b}	3.75^{b}	3.15^{b}	3.15^{b}	2.49^{b}	1.91^{b}	1.89^{b}	1.48^{b}	1.05^{b}	0.79^{b}	0.64^{b}	0.42^{b}	0.22^{b}	0.19^{b}	0.17^{d}
T4 - B. Dark red	7.54^{a}	7.31^{a}	7.25^{a}	5.64^{a}	5.24^{a}	4.17^{a}	3.50^{a}	3.50^{a}	2.77^{a}	2.12^{a}	2.11^{a}	1.65^{a}	1.17^{a}	0.88^{a}	0.71^{a}	0.47^{a}	0.25^{a}	0.22^{a}	0.34^{b}
T5 - B. Shakti	6.50^{c}	6.30^{c}	6.25^{c}	4.86^{c}	4.52^{c}	3.60^{c}	3.02^{c}	3.02^{c}	2.38^{c}	1.83^{c}	1.82^{c}	1.42^{c}	1.01^{c}	0.76^{c}	0.62^{c}	0.40^{c}	0.21^{c}	0.19^{b}	0.40^{a}
T6 - B. Shubra	3.95^{e}	3.83^{e}	3.80^{e}	2.95^{e}	2.75^{e}	2.18^{e}	1.83^{e}	1.83^{e}	1.45^{e}	1.11^{e}	1.10^{e}	0.86^{e}	0.61^{e}	0.46^{e}	0.37^{e}	0.24^{e}	0.13^{e}	0.11^{d}	0.22^{c}
T7 - B. Shweta	4.40^{d}	4.26^{d}	4.23^{d}	3.29^{d}	3.06^{d}	2.43^{d}	2.04^{d}	2.04^{d}	1.61^{d}	1.24^{d}	1.23^{d}	0.96^{d}	0.68^{d}	0.52^{d}	0.42^{d}	0.27^{d}	0.14^{d}	0.13^{c}	0.14^{d}

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

Table 53. Amino acids composition (mg/g) of nectar 2023-24.

Variety	Glu	Gly	Asp	Ala	Leu	Val	Lys	Ser	Ile	Thr	His	Arg	Phe	Tyr	Cys	Trp	Pro	Met
T1 - B. Super	0.155 ab	0.150 ab	0.149 ab	0.116 ab	0.107 ab	0.086 ab	0.072 ab	0.072 ab	0.057 ab	0.043 ab	0.043 ab	0.034 ab	0.024 ab	0.018 ab	0.015 ab	0.010 ab	0.005 a	0.004 a
T2 - B. Red	0.076 d	0.074 d	0.073 d	0.057 d	0.053 d	0.042 d	0.035 d	0.035 d	0.028 d	0.021 d	0.021 d	0.017 d	0.012 d	0.009 d	0.007 d	0.005 d	0.003 b	0.002 b
T3 - B. Raj	0.147 b	0.143 b	0.141 b	0.110 b	0.102 b	0.081 b	0.068 b	0.068 b	0.054 b	0.041 b	0.041 b	0.032 b	0.023 b	0.017 b	0.014 b	0.009 b	0.005 a	0.004 a
T4 - B. Dark red	0.138^{c}	0.134^{c}	0.132^{c}	0.103^{c}	0.096^{c}	0.076^{c}	0.064^{c}	0.064^{c}	0.051^{c}	0.039^{c}	0.038^{c}	0.030^{c}	0.021^{c}	0.016^{c}	0.013^{c}	0.009^{c}	0.005 a	0.004 a
T5 - B. Shakti	0.162 a	0.157 a	0.156 a	0.121 a	0.113 a	0.090 a	0.075 a	0.075 a	0.059 a	0.046 a	0.045 a	0.035 a	0.025 a	0.019 a	0.015 a	0.010 a	0.005 a	0.005 a
T6 - B. Shubra	0.084 d	0.081 d	0.081 d	0.063 d	0.058 d	0.046 d	0.039 d	0.039 d	0.031 d	0.024 d	0.023 d	0.018 d	0.013 d	0.010 d	0.008 d	0.005 d	0.003 b	0.002 b
T7 - B. Shweta	0.056^{e}	0.054^{e}	0.054^{e}	0.042^{e}	0.039^{e}	0.031^{e}	0.026^{e}	0.026^{e}	0.020^{e}	0.016^{e}	0.016^{e}	0.012^{e}	0.009^{e}	0.007^{e}	0.005^{e}	0.003^{e}	0.002 b	0.002 b

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 54. Amino acids composition (mg/g) of nectar 2024-25

Variety	Glu	Gly	Asp	Ala	Leu	Val	Lys	Ser	Ile	Thr	His	Arg	Phe	Tyr	Cys	Trp	Pro	Met
T1 - B. Super	0.152[a b]	0.147[a b]	0.146[a b]	0.113[a b]	0.106[a b]	0.084[a b]	0.070[a b]	0.070[a b]	0.056[a b]	0.043[a b]	0.042[a b]	0.033[a b]	0.024[a b]	0.018[a b]	0.014[a b]	0.009[a b]	0.005[a]	0.004[a]
T2 - B. Red	0.079[d]	0.076[d]	0.076[d]	0.059[d]	0.055[d]	0.044[d]	0.037[d]	0.037[d]	0.029[d]	0.022[d]	0.022[d]	0.017[d]	0.012[d]	0.009[d]	0.007[d]	0.005[d]	0.003[b]	0.002[b]
T3 - B. Raj	0.145[b]	0.140[b]	0.139[b]	0.108[b]	0.101[b]	0.080[b]	0.067[b]	0.067[b]	0.053[b]	0.041[b]	0.040[b]	0.032[b]	0.022[b]	0.017[b]	0.014[b]	0.009[b]	0.005[a]	0.004[a]
T4 - B. Dark red	0.135[c]	0.131[c]	0.130[c]	0.101[c]	0.094[c]	0.075[c]	0.063[c]	0.063[c]	0.050[c]	0.038[c]	0.038[c]	0.030[c]	0.021[c]	0.016[c]	0.013[c]	0.008[c]	0.004[a]	0.004[a]
T5 - B. Shakti	0.160[a]	0.155[a]	0.154[a]	0.120[a]	0.111[a]	0.089[a]	0.074[a]	0.074[a]	0.059[a]	0.045[a]	0.045[a]	0.035[a]	0.025[a]	0.019[a]	0.015[a]	0.010[a]	0.005[a]	0.005[a]
T6 - B. Shubra	0.087[d]	0.084[d]	0.084[d]	0.065[d]	0.061[d]	0.048[d]	0.040[d]	0.040[d]	0.032[d]	0.025[d]	0.024[d]	0.019[d]	0.013[d]	0.010[d]	0.008[d]	0.005[d]	0.003[b]	0.002[b]
T7 - B. Shweta	0.058[e]	0.056[e]	0.056[e]	0.043[e]	0.040[e]	0.032[e]	0.027[e]	0.027[e]	0.021[e]	0.016[e]	0.016[e]	0.013[e]	0.009[e]	0.007[e]	0.006[e]	0.004[e]	0.002[b]	0.002[b]

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Table 55. Amino acids composition (mg/g) of nectar pooled data 2023-24 to 2024-25.

Variety	Glu	Gly	Asp	Ala	Leu	Val	Lys	Ser	Ile	Thr	His	Arg	Phe	Tyr	Cys	Trp	Pro	Met
T1 - B. Super	0.153[a b]	0.148[a b]	0.147[a b]	0.114[a b]	0.106[a b]	0.084[a b]	0.071[a b]	0.071[a b]	0.056[a b]	0.043[a b]	0.043[a b]	0.033[a b]	0.024[a b]	0.018[a b]	0.014[a b]	0.009[a b]	0.005[a]	0.004[a]
T2 - B. Red	0.076[e]	0.074[e]	0.073[e]	0.057[e]	0.053[e]	0.042[e]	0.035[e]	0.035[e]	0.028[e]	0.021[e]	0.021[e]	0.017[e]	0.012[e]	0.009[e]	0.007[e]	0.005[e]	0.003[b]	0.002[b]
T3 - B. Raj	0.145[b]	0.141[b]	0.140[b]	0.109[b]	0.101[b]	0.080[b]	0.067[b]	0.067[b]	0.053[b]	0.041[b]	0.041[b]	0.032[b]	0.022[b]	0.017[b]	0.014[b]	0.009[b]	0.005[a]	0.004[a]
T4 - B. Dark red	0.136[c]	0.132[c]	0.131[c]	0.102[c]	0.095[c]	0.075[c]	0.063[c]	0.063[c]	0.050[c]	0.038[c]	0.038[c]	0.030[c]	0.021[c]	0.016[c]	0.013[c]	0.008[c]	0.004[a]	0.004[a]
T5 - B. Shakti	0.160[a]	0.155[a]	0.154[a]	0.120[a]	0.111[a]	0.089[a]	0.074[a]	0.074[a]	0.059[a]	0.045[a]	0.045[a]	0.035[a]	0.025[a]	0.019[a]	0.015[a]	0.010[a]	0.005[a]	0.005[a]
T6 - B. Shubra	0.086[d]	0.083[d]	0.082[d]	0.064[d]	0.060[d]	0.047[d]	0.040[d]	0.040[d]	0.031[d]	0.024[d]	0.024[d]	0.019[d]	0.013[d]	0.010[d]	0.008[d]	0.005[d]	0.003[b]	0.002[b]
T7 - B. Shweta	0.056[f]	0.054[f]	0.054[f]	0.042[f]	0.039[f]	0.031[f]	0.026[f]	0.026[f]	0.020[f]	0.016[f]	0.016[f]	0.012[f]	0.009[f]	0.007[f]	0.005[f]	0.003[f]	0.002[b]	0.002[b]

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Nectar Amino Acid Profile During Rabi 2023-24

Analysis of nectar amino acid composition during Rabi 2023-24 revealed significant varietal differences across all 18 amino acids quantified, though concentrations were substantially lower than those observed in pollen (Table 53). Glutamic acid was the most abundant amino acid in nectar across all varieties, ranging from 0.056 mg/g in Bhima Shweta (T7) to 0.162 mg/g in Bhima Shakti (T5), representing approximately 1.5-2.2% of the corresponding pollen concentrations. The next most abundant amino acids followed similar patterns: glycine (0.054-0.157 mg/g), aspartic acid (0.054-0.156 mg/g), and alanine (0.042-0.121 mg/g).

Bhima Shakti (T5) recorded significantly highest concentrations for most amino acids, including glutamic acid (0.162 mg/g), glycine (0.157 mg/g), aspartic acid (0.156 mg/g), alanine (0.121 mg/g), leucine (0.113 mg/g), and valine (0.090 mg/g). Bhima Super (T1) demonstrated statistically similar values for most parameters, with glutamic acid at 0.155 mg/g and glycine at 0.150 mg/g. Bhima Raj (T3) occupied the third position with glutamic acid at 0.147 mg/g, followed by Bhima Dark Red (T4) at 0.138 mg/g. Among the lower-performing varieties, Bhima Shweta (T7) recorded the significantly lowest concentrations across all amino acids, with glutamic acid at 0.056 mg/g, glycine at 0.054 mg/g, leucine at 0.039 mg/g, and valine at 0.031 mg/g—representing only 34-35% of the values found in Bhima Shakti. Bhima Red (T2) and Bhima Shubra (T6) showed intermediately low values, with glutamic acid at 0.076 mg/g and 0.084 mg/g, respectively, though both remained significantly lower than the red-bulb varieties Bhima Shakti, Bhima Super, and Bhima Raj.

Essential amino acids in nectar followed the same varietal ranking observed in pollen. Leucine ranged from 0.039 mg/g (T7) to 0.113 mg/g (T5), valine from 0.031 mg/g (T7) to 0.090 mg/g (T5), lysine from 0.026 mg/g (T7) to 0.075 mg/g (T5), isoleucine from 0.020 mg/g (T7) to 0.059 mg/g (T5), and threonine from 0.016 mg/g (T7) to 0.046 mg/g (T5). These essential amino acids constituted approximately 50-52% of the total amino acid content, maintaining proportional consistency with pollen composition. Aromatic amino acids phenylalanine and tyrosine were present in very low concentrations, ranging from 0.009 mg/g (T7) to 0.025 mg/g (T5) for phenylalanine and 0.007 mg/g (T7) to 0.019 mg/g (T5) for tyrosine. Tryptophan exhibited the narrower range among aromatic amino acids, from 0.003 mg/g (T7) to 0.010 mg/g (T5). The sulfur-containing amino acids cysteine and methionine were present in trace amounts, with cysteine ranging from 0.005 mg/g (T7) to 0.015 mg/g (T5) and methionine from 0.002 mg/g (T2, T6, T7) to 0.005 mg/g (T5).

Proline, a critical amino acid for honey bee flight metabolism, was present in minimal concentrations in nectar compared to pollen, ranging from 0.002 mg/g (T7) to 0.005 mg/g in several red-bulb varieties (T1, T3, T4, T5). Despite these low absolute values, the varietal differences remained statistically significant, with Bhima Shweta showing 60% lower proline content than the top-performing varieties.

Nectar Amino Acid Profile During Rabi 2024-25

The nectar amino acid composition during Rabi 2024-25 exhibited remarkable consistency with the previous year's pattern, with only minor quantitative variations (Table 54). Bhima Shakti (T5) again demonstrated significantly highest amino acid concentrations, recording glutamic acid at 0.160 mg/g, glycine at 0.155 mg/g, aspartic acid at 0.154 mg/g, and alanine at 0.120 mg/g. These values were virtually identical to those observed in 2023-24, indicating exceptional temporal stability in nectar amino acid biosynthesis.

Bhima Super (T1) maintained its second-tier position with glutamic acid at 0.152 mg/g, glycine at 0.147 mg/g, and aspartic acid at 0.146 mg/g. Bhima Raj (T3) recorded glutamic acid at 0.145 mg/g and glycine at 0.140 mg/g, while Bhima Dark Red (T4) showed slightly lower values (glutamic acid: 0.135 mg/g, glycine: 0.131 mg/g). The ranking of these top four varieties remained unchanged from 2023-24, demonstrating stable genetic control over nectar quality parameters. The lower-performing varieties also maintained their relative positions. Bhima Shweta (T7) continued to exhibit the lowest amino acid content, with glutamic acid at 0.058 mg/g, glycine at 0.056 mg/g, and leucine at 0.040 mg/g. Bhima Red (T2) recorded marginally higher values (glutamic acid: 0.079 mg/g, glycine: 0.076 mg/g), while Bhima Shubra (T6) showed intermediate-low concentrations (glutamic acid: 0.087 mg/g, glycine: 0.084 mg/g).

Essential amino acid concentrations in 2024-25 maintained nearly identical patterns to 2023-24. Leucine ranged from 0.040 mg/g (T7) to 0.111 mg/g (T5), valine from 0.032 mg/g (T7) to 0.089 mg/g (T5), and lysine from 0.027 mg/g (T7) to 0.074 mg/g (T5). Threonine, histidine, and arginine showed similar consistency, with threonine ranging from 0.016 mg/g (T7) to 0.045 mg/g (T5), histidine from 0.016 mg/g (T7) to 0.045 mg/g (T5), and arginine from 0.013 mg/g (T7) to 0.035 mg/g (T5).

The sulfur-containing amino acids cysteine and methionine remained in trace concentrations, with cysteine ranging from 0.006 mg/g (T7) to 0.015 mg/g (T5) and methionine from 0.002 mg/g (T2, T6, T7) to 0.005 mg/g (T5). Proline concentrations were similarly low and stable, ranging from 0.002 mg/g (T7) to 0.005 mg/g (T1, T3, T5), showing minimal year-to-year variation across all varieties.

The year-to-year consistency was remarkable, with most varieties showing less than 2-3%

variation in individual amino acid concentrations between 2023-24 and 2024-25. This stability contrasted sharply with pollen amino acids, which exhibited more pronounced temporal fluctuations, suggesting that nectar amino acid composition is under tighter homeostatic control and less responsive to environmental variations.

Pooled Nectar Amino Acid Composition (2023-24 to 2024-25)

The pooled nectar amino acid data across both years provided a statistically robust characterization of varietal differences (Table 55). Bhima Shakti (T5) emerged as the variety with significantly highest nectar amino acid content, recording glutamic acid at 0.160 mg/g, glycine at 0.155 mg/g, aspartic acid at 0.154 mg/g, alanine at 0.120 mg/g, leucine at 0.111 mg/g, and valine at 0.089 mg/g. This variety consistently ranked first for 17 out of 18 amino acids analyzed. Bhima Super (T1) and Bhima Raj (T3) formed the second performance tier, with Bhima Super recording glutamic acid at 0.153 mg/g and Bhima Raj at 0.145 mg/g. These varieties showed statistically similar values for most amino acids, though Bhima Super generally exhibited marginally higher concentrations. Bhima Dark Red (T4), despite being the top performer in pollen amino acids, occupied the fourth position in nectar composition, with glutamic acid at 0.136 mg/g, glycine at 0.132 mg/g, and aspartic acid at 0.131 mg/g.

The white-bulb variety Bhima Shweta (T7) demonstrated the significantly lowest amino acid content across all parameters in the pooled analysis. Glutamic acid averaged only 0.056 mg/g, glycine 0.054 mg/g, aspartic acid 0.054 mg/g, and leucine 0.039 mg/g—representing merely 35% of the corresponding values in Bhima Shakti. Bhima Red (T2) and Bhima Shubra (T6) also exhibited significantly reduced amino acid profiles, with glutamic acid at 0.076 mg/g and 0.086 mg/g, respectively, both remaining in the lower tier of performance.

Essential amino acids in the pooled nectar data showed clear stratification among varieties. Leucine, the most abundant essential amino acid, ranged from 0.039 mg/g (T7) to 0.111 mg/g (T5), representing a 2.85-fold difference. Valine ranged from 0.031 mg/g (T7) to 0.089 mg/g (T5), lysine from 0.026 mg/g (T7) to 0.074 mg/g (T5), isoleucine from 0.020 mg/g (T7) to 0.059 mg/g (T5), and threonine from 0.016 mg/g (T7) to 0.045 mg/g (T5). The magnitude of these differences (approximately 2.5-3.0-fold) was proportionally similar to those observed in pollen, maintaining consistent varietal ranking across both floral reward types.

Among aromatic amino acids, phenylalanine ranged from 0.009 mg/g (T7) to 0.025 mg/g (T5), tyrosine from 0.007 mg/g (T7) to 0.019 mg/g (T5), and tryptophan from 0.003 mg/g (T7) to 0.010 mg/g (T5). The sulfur-containing amino acids remained at trace levels, with cysteine ranging from 0.005 mg/g (T7) to 0.015 mg/g (T5) and methionine from 0.002 mg/g (T2, T6, T7) to 0.005 mg/g (T5). Histidine and arginine, important for protein synthesis and

metabolic regulation, ranged from 0.016 mg/g and 0.012 mg/g (T7) to 0.045 mg/g and 0.035 mg/g (T5), respectively.

Proline, despite its low absolute concentration (0.002-0.005 mg/g), maintained significant varietal differences in the pooled data. The red-bulb varieties Bhima Shakti, Bhima Super, Bhima Raj, and Bhima Dark Red all recorded 0.004-0.005 mg/g, while Bhima Shweta, Bhima Red, and Bhima Shubra showed significantly lower values (0.002-0.003 mg/g). This 40-60% reduction in proline content in lower-performing varieties may contribute to their reduced attractiveness to foraging honey bees, as proline serves as a critical flight fuel and gustatory cue in nectar.

The exceptionally low coefficient of variation between years for nectar amino acids (typically <5% across varieties) compared to pollen (10-20% variation) underscores the temporal reliability of nectar composition as a varietal trait. This consistency suggests that nectar amino acid profiles are primarily under genetic control with minimal environmental modulation, making them stable biochemical markers for varietal identification and pollinator attraction potential in onion seed production systems.

4.2.4.2 Analysis of Amino acid by paper chromatography.

Table 56. Identification of amino acids in pollen and nectar extract of *Allium cepa* L.

Identified AA	Colour observed	Spot distance (cm)	Cal. Rf	Std. Rf	AA type
Pollen					
Serine	Dirty pink	3	0.3	0.3	Non-essential
Glycine	Reddish brown	2.5	0.25	0.26	Non-essential
Threonine	Reddish pink	4.5	0.45	0.44	Essential
Alanine	Reddish pink	5.8	0.58	0.6	Non-essential
Valine	Pinkish violet	6.8	0.68	0.71	Essential
Glutamic acid	Deep pink	1.7	0.17	0.18	Non-essential
Aspartic acid	Greyish violet	5.2	0.52	0.52	Non-essential
Leucine	Dirty pink	8.2	0.82	0.84	Essential
Isoleucine	Pinkish violet	7.5	0.75	0.76	Essential
Nectar					
Glutamic acid	Deep pink	1.8	0.18	0.18	Non-essential
Glycine	Saffron	2.6	0.26	0.26	Non-essential
Serine	Pink	3.3	0.33	0.32	Non-essential
Threonine	Reddish pink	4.4	0.44	0.44	Essential
Alanine	Pinkish violet	5.7	0.57	0.6	Non-essential
Proline	Brownish yellow	6.6	0.66	0.66	Non-essential
Valine	Pinkish violet	7.3	0.73	0.71	Essential
Leucine	Pinkish violet	8.3	0.83	0.84	Essential
Phenyl alanine	Saffron	8.9	0.89	0.88	Essential

Paper chromatography coupled with ninhydrin staining was employed for the qualitative identification and confirmation of amino acids present in pollen and nectar extracts of *Allium cepa* L. (Table 56). The technique utilized ascending chromatography with a standard solvent system, and amino acids were visualized based on their characteristic color reactions with ninhydrin reagent. Retardation factor (Rf) values were calculated for each identified amino acid and compared with standard Rf values for confirmation.

Amino Acids Identified in Pollen Extract revealed the presence of eight distinct amino acids, comprising five non-essential and three essential amino acids. Among the non-essential amino acids, glutamic acid exhibited the lowest Rf value of 0.17 (spot distance: 1.7 cm), appearing as a deep pink spot that closely matched the standard Rf of 0.18. This low Rf value indicates high polarity and strong interaction with the stationary phase, consistent with glutamic acid's dicarboxylic acid structure containing two carboxyl groups.

Glycine, the simplest amino acid, was identified at an Rf value of 0.25 (spot distance: 2.5 cm) with a characteristic reddish-brown coloration, matching the standard Rf of 0.26. Serine appeared as a dirty pink spot at Rf 0.3 (spot distance: 3.0 cm), corresponding to the standard value of 0.3. Alanine was detected at Rf 0.58 (spot distance: 5.8 cm) as a reddish-pink spot, closely matching the standard Rf of 0.6. Aspartic acid, another dicarboxylic amino acid, showed a greyish-violet coloration at Rf 0.52 (spot distance: 5.2 cm), matching the standard Rf of 0.52.

Among the essential amino acids identified in pollen, threonine appeared as a reddish-pink spot at Rf 0.45 (spot distance: 4.5 cm), matching the standard value of 0.44. Valine, a branched-chain amino acid, exhibited a pinkish-violet coloration at Rf 0.68 (spot distance: 6.8 cm), closely corresponding to the standard Rf of 0.71. Leucine showed the highest Rf value among pollen amino acids at 0.82 (spot distance: 8.2 cm), appearing as a dirty pink spot and matching the standard Rf of 0.84. Isoleucine, another branched-chain amino acid, was detected at Rf 0.75 (spot distance: 7.5 cm) with pinkish-violet coloration, corresponding to the standard Rf of 0.76.

The calculated Rf values for all pollen amino acids showed excellent agreement with standard Rf values (deviation <0.03 units), confirming accurate identification. The higher Rf values observed for branched-chain amino acids (leucine, isoleucine, valine) reflect their hydrophobic nature and reduced polarity, resulting in weaker interaction with the polar stationary phase and faster migration with the mobile phase.

Amino Acids Identified in Nectar Extract

Chromatographic analysis of onion nectar extract identified nine amino acids, including six non-essential and three essential amino acids. Notably, nectar contained proline and phenylalanine, which were not detected in the pollen analysis, while isoleucine was absent from nectar but present in pollen (Table 56).

Among non-essential amino acids in nectar, glutamic acid again showed the lowest Rf value of 0.18 (spot distance: 1.8 cm), appearing as a deep pink spot matching the standard Rf of 0.18. Glycine was identified at Rf 0.26 (spot distance: 2.6 cm) with a distinctive saffron coloration, matching the standard value of 0.26. Serine appeared as a pink spot at Rf 0.33 (spot distance: 3.3 cm), closely corresponding to the standard Rf of 0.32. Alanine exhibited pinkish-violet coloration at Rf 0.57 (spot distance: 5.7 cm), matching the standard Rf of 0.6. Proline, detected exclusively in nectar, showed a characteristic brownish-yellow color at Rf 0.66 (spot distance: 6.6 cm), perfectly matching the standard Rf of 0.66.

The essential amino acids identified in nectar included threonine at Rf 0.44 (spot distance: 4.4 cm) with reddish-pink coloration, matching the standard value of 0.44. Valine appeared at Rf 0.73 (spot distance: 7.3 cm) with pinkish-violet color, corresponding to the standard Rf of 0.71. Leucine was detected at Rf 0.83 (spot distance: 8.3 cm) as a pinkish-violet spot, matching the standard Rf of 0.84. Phenylalanine, an aromatic amino acid found only in nectar extract, exhibited the highest Rf value of 0.89 (spot distance: 8.9 cm) with saffron coloration, closely matching the standard Rf of 0.88.

The presence of phenylalanine exclusively in nectar and its absence in pollen extract suggests differential biosynthetic or accumulation patterns between these two floral reward tissues. Phenylalanine's high Rf value (0.89) reflects its aromatic, hydrophobic nature and minimal interaction with the polar stationary phase. Similarly, the detection of proline specifically in nectar (Rf 0.66) aligns with its established role as a primary energy substrate for honeybee flight metabolism, making it a valuable nectar component for pollinator attraction.

Comparison of Amino Acid Profiles Between Pollen and Nectar

The chromatographic analysis revealed both similarities and distinct differences between pollen and nectar amino acid profiles. Six amino acids were common to both matrices: glutamic acid, glycine, serine, threonine, alanine, valine, and leucine. These shared amino acids likely represent core metabolites essential for basic cellular functions in both reproductive tissues. The consistent Rf values for these common amino acids across pollen and nectar extracts (differences <0.03 units) validate the reproducibility and accuracy of the chromatographic method. However, three amino acids showed tissue-specific distribution. Isoleucine (Rf 0.75) and aspartic acid (Rf 0.52) were detected only in pollen extract, while proline (Rf 0.66) and phenylalanine (Rf 0.89) were found exclusively in nectar. This differential amino acid composition reflects the distinct physiological roles of these tissues: pollen serves primarily as a protein-rich food source containing higher concentrations of essential amino acids and protein-building blocks like aspartic acid, whereas nectar functions as an energy-rich reward supplemented with flight-supporting amino acids like proline and sensory-active compounds like phenylalanine. The ninhydrin color reactions varied among amino acids, producing characteristic hues ranging from deep pink (glutamic acid) to reddish-brown (glycine in pollen), pinkish-violet (branched-chain amino acids), greyish-violet (aspartic acid), and brownish yellow (proline). These color variations reflect differences in amino acid structure and the specific chemical interactions between ninhydrin and different R-groups, providing additional qualitative confirmation beyond Rf values.

4.2.5 Correlation between Physicochemical and Biochemical composition of onion (*Allium cepa* L.) of Pollen, Nectar and *A. mellifera* forage rate.

4.2.5.1 First year (Rabi 2023-24).

The Pearson correlation analysis conducted during Rabi 2023-24 revealed significant positive associations between the foraging rate (FR) of *Apis mellifera* measured as the mean number of bee visitors per m² during peak time (14:00 h) over 5 minutes and various physicochemical and biochemical properties of onion umbel pollen and nectar (Table 57).

The forage rate of *A. mellifera* exhibited highly significant positive correlations with nectar antioxidant content ($r = 0.969$, $p < 0.001$), sucrose concentration ($r = 0.971$, $p < 0.001$), and total sugar content ($r = 0.951$, $p < 0.001$). These strong associations indicate that honeybees preferentially forage on umbels producing nectar with higher energy-rich carbohydrate content and elevated antioxidant levels. The preference for sucrose-rich nectar aligns with honeybee nutritional requirements, as sucrose provides immediate energy for flight metabolism and colony maintenance. Additionally, significant correlations were observed with fructose ($r = 0.944$, $p < 0.01$), phenol ($r = 0.789$, $p < 0.05$), copper ($r = 0.789$, $p < 0.05$), and total amino acids ($r = 0.781$, $p < 0.05$), suggesting that bees are attracted to nutritionally complete nectar containing balanced proportions of sugars, antioxidants, and essential amino acids. Conversely, nectar moisture content showed a moderate negative correlation with bee visitation ($r = -0.54$), though not statistically significant. For onion flower nectar (*Allium cepa* L.), *Apis mellifera* shows peak visitation within a preferred sugar concentration range of 30% to 65% Total Soluble Solids (TSS / Brix), which corresponds to an optimal nectar moisture content range of 35% to 70%$ water content (Silva and Dean, 2000; Waller, 1970).

The negative correlations with moisture also indicate that environmental conditions promoting nectar concentration (lower humidity, optimal temperature) may enhance bee attractiveness. Protein content in nectar showed negligible correlation ($r = -0.091$), indicating that while protein is essential in pollen, its presence in nectar plays a minimal role in foraging decisions for this species on onion flowers. For pollen properties, the forage rate demonstrated highly significant positive correlations with total amino acids ($r = 0.949$, $p < 0.01$), antioxidants ($r = 0.93$, $p < 0.01$), sucrose content ($r = 0.95$, $p < 0.01$), and moisture ($r = 0.878$, $p < 0.01$). The strong association with amino acid content underscores the importance of protein-rich pollen for honeybee nutrition, particularly for brood rearing and worker bee development. Amino acids serve as building blocks for bee body proteins and are essential for colony growth and health. The significant correlation with pollen antioxidants ($r = 0.93$, $p < 0.01$) reflects the protective role

these compounds play in bee immunity and longevity, as dietary antioxidants help bees combat oxidative stress from pesticide exposure and environmental challenges.

Pollen moisture content showed a strong positive correlation ($r = 0.878$, $p < 0.01$), suggesting that fresher, more hydrated pollen may be more palatable and easier for bees to collect and pack into corbiculae. The correlation with flavonoids ($r = 0.911$, $p < 0.01$) and phenolic compounds ($r = 0.845$, $p < 0.05$) further indicates bee preference for pollen with higher secondary metabolite content, which may provide health benefits including antimicrobial and immune-stimulating properties.

Among micronutrients, zinc showed the strongest correlation with pollen amino acids ($r = 0.802$, $p < 0.05$), while iron demonstrated positive associations with flavonoid content ($r = 0.795$, $p < 0.05$). However, copper and manganese exhibited relatively weaker correlations with forage rate ($r = 0.217$ and $r = 0.735$, respectively), suggesting these micronutrients may not be primary foraging cues for honeybees, though they remain essential for bee nutrition and colony health.

The analysis revealed that all sugar components—total sugars, glucose, fructose, and sucrose in both nectar and pollen showed strong positive correlations with bee visitation rates.

In nectar, sucrose exhibited the highest correlation ($r = 0.971$, $p < 0.001$), followed by total sugars ($r = 0.951$, $p < 0.001$) and fructose ($r = 0.944$, $p < 0.01$). Similarly, in pollen, sucrose ($r = 0.95$, $p < 0.01$) and total sugars ($r = 0.828$, $p < 0.05$) were significantly correlated with forage rates. This pattern indicates that *A. mellifera* workers possess sophisticated chemosensory mechanisms to detect and select floral resources with optimal sugar composition, prioritizing high-energy food sources that maximize foraging efficiency and colony energy balance.

Table 57. Pearson correlation analysis between *A. mellifera* foraging rate (No. of flower visited bee mean of peak time/ m2/ 5 min) and physicochemical, biochemical, micronutrient properties of pollen of onion umbel (Upper diagonal) and nectar of onion umbel (Lower diagonal) 2023-24.

Parameters	FR	pH	EC	Moisture	Protein	TAA	Phenol	Flavonoid	Antioxidant	Copper	Iron	Manganese	Zinc	Total sugar	Glucose	Fructose	Sucrose
pH	1	0.717	0.878**	0.77*	0.949**	0.822*	0.93**	0.77*	0.217	0.629	0.735	0.337	0.828*	0.804*	0.828*	0.95**	0.95**
EC (dS/m)	0.527	1	0.235	0.642	0.345	0.498	0.446	0.642	0.443	0.648	0.761*	0.669	0.675	0.665	0.677	0.519	0.519
Moisture (%)	-0.54	-0.14	1	0.642	0.794*	0.909**	0.887**	0.641	0.198	0.486	0.558	0.149	0.836*	0.852*	0.839*	0.861*	0.861*
Protein (mg/1g)	-0.091	0.087	0.199	1	0.645	0.783*	0.789*	1***	0.491	0.726	0.655	0.24	0.889**	0.846*	0.88**	0.909**	0.909**
Phenol (mg GAE/1g)	0.789*	0.028	-0.409	-0.082	1	0.763*	0.845*	0.645	0.249	0.598	0.842*	0.503	0.717	0.696	0.721	0.85*	0.85*
Flavonoid (mg QE/1g)	0.657	0.416	-0.94**	-0.219	0.356	1	0.911**	0.783*	0.279	0.466	0.685	0.336	0.906**	0.916**	0.909**	0.889**	0.889**
Antioxidants (mg AA/1g)	0.969***	0.517	-0.496	-0.147	0.849*	0.607	1	0.789*	0.049	0.499	0.725	0.446	0.919**	0.914**	0.921**	0.958***	0.958***
TAA (mg/g)	0.781*	0.587	-0.108	0.147	0.652	0.197	0.778*	1	0.491	0.726	0.655	0.24	0.889**	0.846*	0.88**	0.909**	0.909**
Copper (mg/g)	0.789*	0.028	-0.409	-0.09	1***	0.356	0.85*	0.653	1	0.712	0.353	-0.125	0.312	0.276	0.304	0.289	0.289
Iron (mg/g)	0.565	0.58	-0.752	0.098	0.169	0.795*	0.453	0.445	0.169	1	0.692	0.244	0.696	0.656	0.692	0.691	0.691
Manganese (mg/g)	0.232	-0.36	-0.241	-0.294	0.708	0.105	0.411	0.059	0.709	-0.305	1	0.802*	0.737	0.72	0.744	0.747	0.747
Zinc (mg/g)	0.462	0.219	0.283	-0.432	0.558	-0.183	0.57	0.607	0.563	-0.27	0.409	1	0.388	0.392	0.402	0.35	0.35
Total Sugar (%)	0.951***	0.713	-0.343	0.029	0.627	0.538	0.908**	0.835*	0.626	0.545	0.013	0.481	1	0.995***	1***	0.951**	0.951**
Glucose (%)	0.625	-0.1	-0.712	-0.174	0.795*	0.542	0.622	0.485	0.797*	0.499	0.519	0.185	0.388	1	0.997***	0.928**	0.928**
Fructose (%)	0.944**	0.442	-0.43	0.154	0.871*	0.5	0.942**	0.838*	0.87*	0.464	0.337	0.451	0.897**	0.644	1	0.948**	0.948**
Sucrose (%)	0.961***	0.487	-0.469	-0.023	0.874*	0.567	0.991***	0.79*	0.873*	0.432	0.422	0.531	0.904**	0.62	0.974***	1	1***
Sucrose (%)	0.971***	0.463	-0.499	0.051	0.87*	0.568	0.965***	0.841*	0.869*	0.525	0.331	0.465	0.91**	0.692	0.991***	0.981***	1

*. Correlation is significant at the 0.05 level (2-tailed), **. Correlation is significant at the 0.01 level (2-tailed).
Potential of Hydrogen – Ph, Electrical Conductivity – EC, TAA – Total Amino Acid.

The inter-correlations between sugar fractions (glucose-fructose: $r = 0.997$, $p < 0.001$; fructose-sucrose: $r = 0.974$, $p < 0.001$) in pollen indicate synchronized biosynthetic pathways for carbohydrate production in onion umbels, where environmental and physiological factors affecting one sugar component similarly influence others. This coordinated sugar metabolism ensures consistent nectar and pollen quality that attracts and sustains pollinator populations throughout the flowering period.

The observed correlation patterns reflect evolved mutualistic relationships between onion flowers and honeybee pollinators. Onion plants producing nectar and pollen with higher nutritional value—particularly elevated sugar, amino acid, and antioxidant concentrations receive more frequent bee visits, thereby increasing cross-pollination rates and subsequent seed set. Conversely, honeybees benefit by selectively foraging on umbels offering superior nutritional rewards, optimizing their energy intake and colony provisioning efficiency. These findings emphasize the critical role of floral biochemistry in mediating plant-pollinator interactions and suggest that agricultural practices enhancing nectar and pollen quality could significantly improve pollination success in onion seed production systems.

4.2.5.2 Second year (Rabi 2024-25).

The Pearson correlation analysis (Table 58) illustrates the relationship between A. mellifera foraging activity (mean number of bee visitors at peak time/m^2/5 min) and the various physicochemical, biochemical, and micronutrient constituents of onion umbel pollen (represented by the upper diagonal) and onion umbel nectar (represented by the lower diagonal) during the 2024-25 season.

Forage rate showed the strongest positive correlations with nectar antioxidants ($r = 0.969^{***}$), sucrose ($r = 0.971^{***}$ and $r = 0.961^{***}$), and total sugars ($r = 0.951^{***}$), indicating bees prioritize energy-dense, protective nectar for efficient colony provisioning. These highest correlations reflect honeybee sensory detection of high-energy carbohydrates via gustatory receptors and antioxidants that mitigate oxidative stress during foraging flights. Phenol ($r = 0.789^{*}$), total amino acids ($r = 0.781^{*}$), copper ($r = 0.789^{*}$), and fructose ($r = 0.944^{**}$) followed, suggesting secondary attraction to antimicrobial and nutrient-balanced nectar that supports larval development and immunity.

Table 58. Pearson correlation analysis between *A. mellifera* foraging rate (No. of flower visited bee mean of peak time / m^2/ 5 min) and physicochemical, biochemical, micronutrient properties of pollen of onion umbel (Upper diagonal) and nectar of onion umbel (Lower diagonal) 2024-25.

Parameters	FR	pH	EC	Moisture	Protein	TAA	Phenol	Flavonoid	Antioxidant	Copper	Iron	Manganese	Zinc	Total sugar	Glucose	Fructose	Sucrose
pH	1	0.831*	0.824*	0.859*	0.464	0.86*	0.849*	0.997***	0.464	-0.086	0.463	0.666	0.821*	0.837*	0.838*	0.838*	0.841*
EC (dS/m)	0.538	1	0.897**	0.813*	0.699	0.902**	0.614	0.815*	0.699	0.045	0.737	0.857*	0.585	0.753	0.754	0.754	0.766*
Moisture (%)	-0.475	0.012	1	0.732	0.574	0.761*	0.733	0.811*	0.574	0.096	0.704	0.944**	0.733	0.823*	0.824*	0.824*	0.831*
Protein (mg/1g)	0.034	0.177	-0.009	1	0.43	0.924**	0.687	0.885**	0.43	0.03	0.696	0.585	0.639	0.789*	0.79*	0.79*	0.794*
Phenol (mg GAE/1g)	0.762*	0.047	-0.395	-0.093	1	0.484	0.503	0.418	1***	0.644	0.715	0.587	0.553	0.551	0.552	0.553	0.57
Flavonoid (mg QE/1g)	0.712	0.432	-0.846*	-0.169	0.408	1	0.533	0.867*	0.484	-0.146	0.591	0.609	0.574	0.635	0.636	0.636	0.646
Antioxidants (mg AA/1g)	0.948**	0.42	-0.471	-0.079	0.887**	0.676	1	0.845*	0.503	0.299	0.516	0.638	0.889**	0.943**	0.943**	0.943**	0.941**
TAA (mg/g)	0.778*	0.567	-0.109	0.094	0.71	0.322	0.741	1	0.418	-0.104	0.469	0.647	0.805*	0.841*	0.842*	0.842*	0.844*
Copper (mg/g)	0.759*	0.05	-0.392	-0.091	1***	0.405	0.886**	0.712	1	0.644	0.715	0.587	0.553	0.551	0.552	0.553	0.57
Iron (mg/g)	0.676	0.71	-0.429	0.032	0.354	0.655	0.549	0.776*	0.354	1	0.56	0.149	0.322	0.293	0.293	0.294	0.3
Manganese (mg/g)	0.462	-0.11	-0.221	-0.124	0.826*	0.216	0.705	0.317	0.828*	-0.102	1	0.741	0.439	0.72	0.721	0.72	0.73
Zinc (mg/g)	0.4	0.172	0.409	-0.487	0.559	-0.108	0.501	0.565	0.559	0.107	0.498	1	0.537	0.79*	0.79*	0.79*	0.797*
Total Sugar (%)	0.953***	0.679	-0.233	0.086	0.627	0.556	0.849*	0.838*	0.625	0.708	0.294	0.481	1	0.764*	0.765*	0.766*	0.769*
Glucose (%)	0.586	-0.012	-0.671	-0.162	0.82*	0.566	0.683	0.62	0.821*	0.57	0.527	0.212	0.406	1	0.997***	0.928**	0.928**
Fructose (%)	0.917**	0.427	-0.377	0.235	0.871*	0.493	0.913**	0.875**	0.871*	0.616	0.58	0.42	0.871*	0.683	1	0.948**	0.948**
Sucrose (%)	0.924**	0.478	-0.319	0.01	0.894**	0.527	0.958***	0.895**	0.895**	0.634	0.636	0.582	0.884**	0.697	0.966***	1	1***
Sucrose (%)	0.97***	0.414	-0.51	0.021	0.887**	0.668	0.976***	0.815*	0.886**	0.643	0.602	0.436	0.885**	0.737	0.962***	0.969***	1

*. Correlation is significant at the 0.05 level (2-tailed), **. Correlation is significant at the 0.01 level (2-tailed).
Potential of Hydrogen – Ph, Electrical Conductivity – EC, TAA – Total amino acid.

Conversely, moisture exhibited the lowest (most negative) correlation (r = -0.54), implying bees avoid dilute nectar requiring excessive processing, while protein showed negligible association (r = -0.091), as nectar protein contributes minimally to bee diet compared to pollen. Electrical conductivity (r = 0.527) and pH (r = 1) displayed moderate to weak links, likely due to optimal nectar osmolarity enhancing palatability under varying abiotic conditions like temperature and humidity.

Pollen parameters yielded the highest correlations with total amino acids (r = 0.949**), antioxidants (r = 0.93**), sucrose (r = 0.95**), and moisture (r = 0.878**), underscoring pollen's role as a protein source critical for brood rearing. Elevated amino acid and antioxidant levels attract bees seeking essential building blocks and oxidative protection, with moisture facilitating pollen packing into corbiculae. Flavonoids (r = 0.911**) and total sugars (r = 0.828*) ranked next, promoting foraging on nutritionally superior pollen that boosts colony health and longevity.

Weakest pollen correlations appeared for copper (r = 0.217), zinc (r = 0.337), and protein with certain micronutrients (e.g., r = 0.24 with zinc), indicating these trace elements serve nutritional needs but not primary attractants. Negative extremes included flavonoids with moisture (r = -0.94**) and glucose with moisture (r = -0.712), attributable to concentration effects where drier pollen concentrates secondary metabolites, aligning with bee preferences for compact, high-value loads.

Strong inter-sugar correlations (e.g., glucose-fructose r = 0.997***, fructose-sucrose r = 0.974***) across both matrices signify coordinated carbohydrate biosynthesis in onion umbels, ensuring reliable rewards that sustain *A. mellifera* visitation. Micronutrient-amino acid links (e.g., manganese-zinc r = 0.802*) suggest synergistic pollen nutrition, while negative moisture-antioxidant trends (r = -0.496) reflect evaporative concentration under favorable weather, peaking foraging during 1000-1200 hours. These patterns demonstrate evolved plant-pollinator mutualism, where superior floral biochemistry enhances cross-pollination and seed set in onion production.

The present investigation comprehensively evaluated the foraging dynamics of *Apis mellifera* across seven onion varieties, revealing significant varietal preferences and distinct temporal patterns in pollinator activity. (Gebremedhn *et al.*, 2014) the foraging rate of *A. mellifera* exhibited a characteristic unimodal diurnal pattern, with activity commencing moderately in early morning hours (08:00 h), progressively escalating to peak levels during

early afternoon (14:00 h), and subsequently declining towards evening (18:00 h). This temporal foraging pattern aligns closely with the findings of (Abou-Shaara, 2014), who documented that honeybee foraging activity follows environmental cues, particularly temperature and solar radiation, which regulate both metabolic efficiency and flight capability. The early afternoon peak observed in the present study corresponds with maximum ambient temperature and optimal light intensity, conditions that have been demonstrated to enhance both nectar secretion rates and pollen availability in onion umbels (Divija & Kamala Jayanthi, 2022). These findings are consistent with those of (Caselles *et al.,* 2019), who reported a high visitation rate of bees on onion flowers during the afternoon. (Mazeed and Marey, 2018) and (Abrol & Sharma, 2023) observed that the peak foraging activity of *A. florea* and *A. mellifera* on onions occurred during the afternoon hrs (12:00-14:00) rather than in the morning or evening. Similarly, (Badade *et al.,* 2017) noted that the intensity of *A. florea*, *A. cerana* and *Tetragonula* spp. in onion ecosystems was dominant in the afternoon hrs (12:00-14:00), while *A. dorsata* was more intense during 14:00-16:00 hrs.

The pronounced varietal differences in attracting *A. mellifera* foragers represent a critical finding with significant implications for onion seed production programs. Across both experimental years and in pooled analysis, Bhima Super consistently recorded the highest foraging rate (14.187 flowers visited bee/min), followed significantly by Bhima Shakti (13.527 flowers visited bee/min), while Bhima Shweta exhibited the lowest visitation frequency (10.104 flowers visited bee/min). These substantial differences—representing approximately 40% variation between the most and least preferred varieties suggest that floral reward quality and accessibility differ markedly among onion genotypes. (Silva *et al.,* 2003) demonstrated that honeybees can be conditioned to associate specific floral odor components with reward quality, and that innate preferences exist for certain volatile profiles. The colored bulb varieties (Bhima Super, Bhima Shakti, Bhima Dark Red) consistently outperformed white varieties (Bhima Shweta, Bhima Shubra) in attracting pollinators, suggesting a potential correlation between bulb pigmentation pathways and the biosynthesis of floral attractants or rewards. Anthocyanin and flavonoid biosynthetic pathways, which determine bulb coloration in onion, are known to be systemically expressed and may influence the production of phenolic compounds in floral tissues, thereby affecting nectar and pollen quality (Nicolson, 2022).

The significant interaction effect between variety and time of observation ($F = 3.5$, $P < 0.001$) indicates that the temporal foraging patterns were not uniform across varieties but were modulated by genotype-specific factors. This interaction suggests that different varieties may

have distinct patterns of nectar secretion or pollen presentation throughout the day, creating temporal niches in floral reward availability by (Pandit *et al.*, 2025). For instance, while Bhima Super dominated foraging activity during most observation periods, Bhima Shakti occasionally surpassed it during specific hours (particularly at 16:00 h in the first year), suggesting differential temporal dynamics in reward presentation. Such findings are consistent with (Pan *et al.*, 2024), who reported that flowering period and time-of-day significantly affect floral traits and consequently influence pollinator visitation patterns.

The analysis of foraging speed, quantified as time spent per umbel, provides complementary insights into the quality and accessibility of floral rewards across onion varieties. The pooled data revealed that *A. mellifera* spent significantly more time on Bhima Super umbels (7.018 seconds) compared to Bhima Shweta (4.467 seconds), representing a 57% increase in handling time. In pollination ecology, increased handling time typically indicates either higher nectar volumes requiring longer uptake periods, greater nectar viscosity necessitating extended feeding bouts, or superior pollen availability demanding more intensive collection efforts. The inverse relationship between foraging rate (flowers visited per minute) and foraging speed (time spent per flower) has been well-documented in honeybee literature, where slower foraging speed paradoxically indicates higher reward quality by (Thakur *et al.*, 2024).

The temporal pattern of foraging speed mirrored that of foraging rate, with maximum handling time observed at 14:00 h (6.692 seconds) when nectar secretion and pollen dehiscence are typically at their (zenith. Nicolson, 2022) explained that nectar sugar concentration and volume exhibit diurnal fluctuations driven by temperature-dependent secretion rates and evaporation dynamics. The morning hours (08:00 h) recorded lower handling times (5.830 seconds), possibly reflecting cooler temperatures that reduce nectar fluidity and secretion rates, while the late evening decline (18:00 h: 4.072 seconds) corresponds with reduced nectar availability after intensive foraging activity throughout the day.

Notably, the interaction between variety and time was non-significant for foraging speed in the pooled analysis ($F = 1.25$, $P = 0.5$), contrasting with the significant interaction observed for foraging rate. This suggests that while the absolute number of bees visiting different varieties varied with time of day, the relative quality of floral rewards (as indicated by handling time) remained consistent across temporal windows. This stability in reward quality throughout the photoperiod indicates that the superior varieties (Bhima Super and

Bhima Shakti) maintained consistently higher nectar and pollen production regardless of environmental fluctuations during the day.

The biochemical profiling of pollen from different onion varieties provided mechanistic insights into the observed foraging preferences. The pooled analysis revealed that colored varieties, particularly Bhima Shakti and Bhima Super, exhibited significantly superior nutritional profiles compared to white varieties. Protein content, a critical nutritional parameter for honeybee brood development and colony health, ranged from 40.5 mg/g in Bhima Dark Red to only 21.2 mg/g in Bhima Shubra, representing nearly a two-fold difference. (Vaudo *et al.,* 2020 & Vaudo *et al.,* 2024) demonstrated that pollen protein content is a primary driver of honeybee foraging preferences, with bees actively seeking pollen sources containing 20-25% protein to meet colony nutritional demands. The superior protein levels observed in Bhima Super (35.9 mg/g) and Bhima Shakti (34.9 mg/g) likely contribute significantly to their heightened attractiveness to *A. mellifera* foragers (Boulfous *et al.,* 2025).

Total Amino Acid (TAA) content followed a similar pattern, with Bhima Dark Red recording the maximum value (45.81 mg/g) while white varieties exhibited significantly lower concentrations. Amino acids serve dual functions in pollen: they provide essential nitrogen sources for protein biosynthesis in developing larvae and act as phagostimulants that influence foraging decisions. (Quinlan *et al.,* 2021) emphasized that pollen protein content ranging from 20-25% is optimal for honeybee health and colony development, with protein-deficient diets leading to reduced brood rearing and compromised immune function. The protein-rich pollen of colored onion varieties thus represents a high-quality nutritional resource that would be preferentially targeted by *A. mellifera* colonies stated by (Lau *et al.,* 2022).

The secondary metabolite profile revealed even more pronounced varietal differences. Bhima Super recorded the highest phenolic content (31.23 mg GAE/g), statistically equivalent to Bhima Shakti (29.89 mg GAE/g), while Bhima Shweta exhibited the lowest concentration (15.27 mg GAE/g). Phenolic compounds in pollen serve multiple ecological functions: they provide antioxidant protection for pollen grains against oxidative stress during storage and transit, contribute to pollen color and visual attractiveness, and may influence taste perception by foraging bees. (Nicolson, 2022) noted that phenolic compounds, particularly flavonoids, can enhance pollinator memory and learning, thereby reinforcing revisitation to high-quality floral resources. The flavonoid content exhibited a similar hierarchy, with Bhima Super (8.28 mg QE/g) and Bhima Shakti (8.20 mg QE/g) significantly outperforming other varieties.

The total antioxidant capacity, which integrates the cumulative effect of multiple bioactive compounds, was highest in Bhima Super (3.67 mg AA/g) and Bhima Shakti (3.45 mg AA/g), representing more than double the antioxidant potential of Bhima Shweta (1.44 mg AA/g). These antioxidants are crucial for honeybee health, as they support immune function and detoxification of xenobiotics encountered during foraging. The preference of *A. mellifera* for varieties with elevated antioxidant profiles may reflect an evolved ability to assess and select nutritionally superior pollen sources that enhance colony fitness.

Mineral composition analysis revealed that Bhima Shakti excelled in micronutrient density, recording the highest concentrations of iron (0.52 mg/g), manganese (0.37 mg/g), and zinc (0.69 mg/g). These trace minerals are essential cofactors for numerous enzymatic processes in honeybee metabolism, including energy production, antioxidant defense systems, and neurological function. (Stephen *et al.*, 2024) emphasized that mineral composition of pollen influences its nutritional value and consequently affects pollinator preference, with bees demonstrating the capacity to balance their intake of essential micronutrients. The superior mineral profile of Bhima Shakti and Bhima Super likely contributes to their elevated attractiveness to foraging bees.

Carbohydrate analysis of pollen revealed interesting patterns in sugar composition. Bhima Shakti recorded the highest total sugar content (27.84%), glucose (19.25%), and fructose (23.19%), while sucrose content exhibited an inverse relationship, being highest in white varieties. Reducing sugars (glucose and fructose) provide immediately accessible energy for honeybee flight metabolism, whereas sucrose requires enzymatic hydrolysis before utilization. The elevated reducing sugar content in colored varieties may enhance their immediate energetic value to foragers, contributing to increased handling time and preference. (Lau *et al.*, 2022) demonstrated that the ratio of different sugar forms influences pollen attractiveness and consumption rates by honeybees.

While pollen serves as the protein and lipid source for honeybee colonies, nectar provides the carbohydrate energy essential for flight metabolism and colony maintenance. The biochemical analysis of nectar from different onion varieties revealed patterns that complement and reinforce the pollen-based findings. Bhima Super and Bhima Shakti demonstrated superior nectar quality across multiple parameters, establishing a consistent pattern of reward presentation that would strongly reinforce pollinator fidelity. The protein content of nectar, though substantially lower than in pollen, exhibited significant varietal differences, with Bhima Shakti (0.86 mg/g) and Bhima Super (0.82 mg/g) recording the highest concentrations. Nectar

proteins, including invertases and other enzymes, contribute to nectar stability and may serve as taste cues for pollinators. The amino acid profile followed similar trends, with Bhima Shakti recording maximum TAA content (0.97 mg/mL) compared to only 0.33 mg/mL in Bhima (Shweta. Nicolson, 2022 and Vandelook *et al.*, 2019) documented that amino acids in nectar function both as nutritional supplements and as gustatory stimulants that modulate sugar preference and intake rates in honeybees. The presence of specific amino acids such as proline, which is preferentially accumulated in nectar and serves as a flight fuel, may enhance the attractiveness of certain onion

The secondary metabolite composition of nectar mirrored the patterns observed in pollen, with Bhima Super exhibiting the highest phenolic (4.58 mg GAE/g) and flavonoid (0.98 mg QE/g) contents. These compounds contribute to nectar's defensive properties against microbial colonization and fermentation, thereby maintaining nectar quality over extended presentation periods. Additionally, phenolic compounds in nectar can influence foraging behavior through gustatory perception and post-ingestive effects on bee cognition. Caffeine and related alkaloids have been shown to enhance memory formation in honeybees at concentrations below their taste threshold, improving the bee's ability to relocate rewarding floral patches. The elevated polyphenol content in Bhima Super and Bhima Shakti nectar may similarly enhance pollinator learning and fidelity, contributing to their observed higher visitation rates (González-Teuber & Heil, 2009).

The sugar composition of nectar represents perhaps the most critical determinant of its energetic value and attractiveness to pollinators. Bhima Raj recorded the highest total sugar content (45.86%), followed by Bhima Super (43.80%) and Bhima Shakti (40.23%), while white varieties exhibited significantly lower sugar concentrations. The ratio of hexoses (glucose and fructose) to sucrose varies among varieties, with Bhima Super demonstrating elevated fructose levels (25.13%) relative to glucose (15.60%), creating a hexose-rich nectar profile. This composition is particularly favorable for honeybees, as hexoses provide immediately accessible energy without requiring enzymatic breakdown, and the high fructose: glucose ratio prevents crystallization in honey stores.

The moisture content of nectar exhibited an inverse relationship with sugar concentration, with Bhima Super (66.38%) and Bhima Shweta (67.09%) recording the highest moisture levels. However, despite similar moisture levels, these varieties differed markedly in sugar concentration, indicating that Bhima Super produces a higher absolute volume of nectar with favorable sugar content, whereas Bhima Shweta produces dilute nectar with low reward

value. Nectar concentration is a critical parameter affecting pollinator visitation, as excessively dilute nectar provides insufficient energy return to justify the handling time, while extremely concentrated nectar may be too viscous for efficient uptake. The optimal nectar concentration for honeybees typically ranges from 30-50% sugar content, a range encompassed by the superior onion varieties in this study.

The convergence of evidence from foraging behavior observations and biochemical analyses establishes a clear mechanistic framework explaining varietal preferences in *A. mellifera* foraging on onion. Bhima Super and Bhima Shakti emerge as elite varieties offering consistently superior floral rewards across multiple dimensions: elevated foraging rates indicating high pollinator attraction, extended handling times reflecting abundant resource availability, protein-rich pollen supporting colony nutrition, high antioxidant capacity promoting bee health, and sugar-rich nectar providing optimal energy returns. These integrated characteristics create a syndrome of floral reward quality that positions these varieties as highly attractive targets for pollinator foraging.

The statistical equivalence observed between certain colored varieties (e.g., Bhima Red and Bhima Dark Red were often statistically at par) suggests that common biochemical pathways associated with anthocyanin biosynthesis may pleiotropically influence floral reward production. The flavonoid biosynthetic pathway, responsible for red pigmentation in onion bulbs, produces intermediates and byproducts that contribute to nectar and pollen chemistry. This genetic linkage between bulb coloration and floral reward quality has significant implications for onion breeding programs, as selection for bulb color characteristics may inadvertently co-select for pollinator-attractive traits.

Conversely, white varieties (Bhima Shweta and Bhima Shubra) consistently recorded the lowest pollinator visitation, shortest handling times, and most nutrient-deficient pollen and nectar profiles. The reduced anthocyanin and flavonoid biosynthesis in white onion genotypes appears to extend to floral tissues, resulting in diminished production of phenolic compounds that serve both as antioxidants and as signaling molecules attracting pollinators. This consistent pattern across multiple reward parameters creates a synergistic deterrent effect, wherein pollinators avoid white varieties not due to any single deficiency but rather due to their overall inferior reward profile stated by (Gill & Walters, 2023).

The findings of this investigation carry substantial practical implications for commercial onion seed production strategies. The approximately 40% differential in *A.*

mellifera visitation rates between elite and inferior varieties translates directly into differences in pollination effectiveness and, consequently, seed yield and quality. Inadequate pollination in onion results in reduced seed set, deformed seeds with low germination capacity, and compromised seed vigor. Given that onion is an obligate cross-pollinating species with protandrous flowers requiring multiple pollinator visits for successful fertilization, maximizing pollinator activity through varietal selection becomes a critical determinant of production success (Padamshali & Mandal, 2018).

(Long, & Morandin, 2011) stated the for-seed production enterprises cultivating multiple onion varieties in proximity, the pronounced varietal preferences documented here suggest potential for competitive exclusion, wherein highly attractive varieties may divert pollinators from less attractive genotypes, exacerbating pollination deficits in inferior varieties. Strategic spatial arrangement of varieties and differential placement of managed honeybee colonies could mitigate these effects by (Liu *et al.,* 2024 & Prasifka *et al.,* 2018). Alternatively, the biochemical insights gained from this study could inform bee attractant development programs; supplemental application of synthetic or extracted phenolic compounds, amino acid solutions, or sugar sprays mimicking the chemical profiles of elite varieties might enhance pollinator visitation to less attractive genotypes. The striking congruence between foraging behavior metrics (rate and speed) and biochemical composition across onion varieties provides compelling evidence for a mechanistic linkage between floral reward quality and pollinator decision-making. The hierarchical ranking of foraging preference (Bhima Super > Bhima Shakti > Bhima Dark Red ≈ Bhima Red > Bhima Raj > Bhima Shubra > Bhima Shweta) parallels precisely with the ranking of biochemical quality parameters. This functional relationship can be explained through optimal foraging theory, wherein honeybees make visit decisions based on expected resource profitability—the ratio of net energy gain to energy expenditure (Bryś & Strachecka, 2024). The temporal dynamics of foraging activity establish optimal windows for critical management interventions. The peak foraging period (12:00-14:00 h) represents the timeframe of maximum pollination potential, during which pesticide applications must be strictly avoided to prevent pollinator mortality or behavioural disruption. Conversely, late evening applications (after 18:00 h) when foraging activity has largely ceased would minimize direct exposure risks while allowing time for residue weathering before morning activity resumes (Yokota *et al.,* 2024).

This comprehensive investigation integrated behavioural ecology and biochemical analysis to elucidate the mechanisms underlying *Apis mellifera* foraging preferences among

onion varieties. The consistent superiority of Bhima Super and Bhima Shakti across foraging metrics and floral reward quality parameters establishes these genotypes as model systems for understanding pollinator-plant mutualistic interactions in onion (Jeannerod *et al.*, 2022). Future research should investigate the genetic architecture underlying these quality differences, employing transcriptomic and metabolomic approaches to identify candidate genes and metabolic pathways regulating floral reward production. Additionally, controlled-environment studies manipulating individual reward parameters (protein content, sugar concentration, phenolic levels) would enable dissection of their relative contributions to pollinator preference. The development of molecular markers linked to high-reward phenotypes would facilitate marker-assisted selection in onion breeding programs, enabling simultaneous improvement of agronomic performance and pollinator attractiveness, ultimately enhancing both seed production efficiency and the sustainability of onion agriculture.

Red-bulb varieties (Bhima Dark Red, Bhima Raj, Bhima Super, Bhima Shakti) had almost double the total amino acids and significantly higher essential amino acids than white-bulb varieties, and these traits were positively correlated with A. mellifera foraging rate. Bryś et al. (2024) showed that pollen richer in total and essential amino acids supports better larval growth, higher survival, and improved physiological condition of worker bees, directly linking pollen amino acid quality with colony performance. (Ellis & Ellis, 2020) and the honey bee nutrition guide from NSW DPI emphasize that pollen is the sole natural source of amino acids for honey bees and that deficits in essential amino acids limit brood rearing and longevity even when pollen quantity is high. (Hendriksma & Shafir, 2016) and Pollen Source Affects Development and Behavioral Preferences in Honey Bees (Lan et al. 2021) reported that bees prefer and dance more intensely for high-quality pollens with better amino acid balance, thereby increasing recruitment to superior sources.

These studies stated that varieties with higher TAA/EAA (like Bhima Dark Red) inherently attract more foragers and better sustain colonies, while amino acid-poor varieties (Bhima Shubra, Bhima Shweta) are nutritionally limiting and less attractive. Glutamic acid, glycine, aspartic acid, alanine, and the branched-chain amino acids (leucine, valine, isoleucine) dominated onion pollen, and proline and glutamic acid were particularly abundant in high-performing varieties reported by (Gage *et al.*, 2020).

(Bryś *et al.*, 2024) identified glutamic acid, proline, leucine, and valine as among the most abundant amino acids in bee-preferred pollens and highlighted their importance for brain function and metabolism. (Gage *et al.*, 2020) demonstrated that dietary pollen alters glutamic

acid and other amino acid levels in the honey bee brain, affecting neural pathways related to learning and foraging. (Noor-ul-Ane *et al.,* 2022) showed that supplementation with proline and glutamic acid improved physiological condition and stress tolerance in honey bees, confirming their role as key metabolic fuels. Proline has been directly linked to flight energetics; (Teulier *et al.,* 2016) reviewed how proline acts as a rapid fuel that enhances carbohydrate oxidation in flying insects, including bees. These findings mirror observation that varieties richer in these amino acids (Bhima Dark Red, Bhima Raj, Bhima Super) are associated with greater foraging activity, because they provide not just protein but also neuroactive and energy-supporting amino acids.

White-bulb varieties with low TAA/EAA showed weaker relationships with foraging rate, suggesting bees perceive them as low-value resources. (Cook *et al.,* 2003) explicitly tested whether honeybee foraging preferences are affected by pollen amino acid composition and found that colonies preferentially collect and dance for pollens with higher essential amino acid content. (Waddington *et al.,* 1998) reported that the quality of pollen and genotype influence the intensity of waggle dances and recruitment, linking nutrient quality directly to field foraging dynamics. Extension resources on bee nutrition note that poor-quality pollen leads to reduced brood area, smaller workers, and increased susceptibility to disease, even when pollen is abundant. These studies are consistent inference that Bhima Shubra and Bhima Shweta, having depleted amino acid profiles, would support weaker recruitment and visitation than amino-acid-rich red varieties by (Micheu *et al.,* 2020).

Nectar amino acids were 40–50× lower than in pollen but varied significantly among varieties; Bhima Shakti, Bhima Super, and Bhima Raj had the highest nectar TAA, including phenylalanine and proline, and these varieties also showed higher forage rates.

Inouye & Waller and later studies summarized by (Nicolson, 2022) showed that certain amino acids in nectar (notably phenylalanine, glycine, and alanine) can increase bee visitation even when sugar concentration is constant, indicating that amino acids can act as phago-stimulants. (Roguz *et al.,* 2019) documented wide diversity in nectar amino acid profiles in Fritillaria and suggested that phenylalanine-rich nectars may be particularly attractive to bees, supporting your observation of phenylalanine in onion nectar as a potential attraction factor. LCMS/MS quantification and paper chromatography gave consistent identification of core amino acids in pollen and nectar, with tissue-specific differences (isoleucine and aspartic acid only in pollen; proline and phenylalanine only in nectar).

Classic chromatographic protocols show that Rf patterns for amino acids are highly reproducible and match standards when solvent systems and ninhydrin visualization are optimized, supporting your use of paper chromatography for qualitative confirmation. (Teper & Zajdel, 2020) similarly used chromatography to show overlapping but distinct amino acid sets in pollen and nectar of melliferous plants, with nectar often enriched in proline and certain aromatic amino acids, while pollen contained a broader set including aspartic acid and isoleucine. Floral biology and pollination ecology studies in onion have already emphasized that varieties differ in nectar and pollen rewards and that bee activity is closely tied to these traits, which in turn affects seed yield.

The strong positive correlations observed between Apis mellifera forage rate and various physicochemical, biochemical, and micronutrient properties of onion umbel nectar and pollen highlight the intricate biochemical basis underlying pollinator preferences and their ecological importance in onion seed production. The consistent finding across two consecutive years (Rabi 2023-24 and 2024-25) of a significant association between pollinator visitation and nectar sugar composition especially sucrose and total sugars—demonstrates how honeybee foraging behavior is closely tied to nectar's energy value. Sucrose's dominant role, showing the highest correlation coefficients ($r \sim 0.97$, $p < 0.001$), aligns with established knowledge that sucrose provides immediate metabolic energy crucial for sustained flight and colony maintenance in honeybees (Suarez *et al.*, 1996; Wheeler *et al.*, 2014). The coordinated rise in nectar antioxidant content further emphasizes a mutualistic adaptation where honeybees are drawn to nectar that not only fuels them energetically but also protects them through antioxidant intake. This preference likely stems from the role of dietary antioxidants in upregulating detoxification genes and combating oxidative stress accumulated during metabolically demanding foraging flights (Mao *et al.*, 2013; Yazlovytska *et al.*, 2023).

The observed moderate negative correlation between nectar moisture and forage rate suggests bees favor more concentrated nectar with lower water content. Concentrated nectar significantly reduces the energy expenditure required for evaporative processing during honey production, thereby enhancing overall foraging efficiency (Nicolson & Human, 2008). While protein content in nectar showed negligible correlations with foraging rate, this finding is consistent with the physiological understanding that nectar primarily functions as a carbohydrate source for adults, whereas the protein and amino acids necessary for larval development and physiological maturation are derived almost exclusively from pollen

(Brodschneider & Crailsheim, 2010). This distinction underscores the complementary nutritional roles of nectar and pollen in honeybee diets Ghramh & Khan, 2023).

Onion pollen properties revealed highly significant positive correlations with total amino acids, antioxidants, sucrose, and moisture, reflecting pollen's essential role as a protein source. Amino acids are vital for brood development and worker bee growth, serving as the fundamental building blocks for the synthesis of vitellogenin and other storage proteins (Bryś *et al.,* 2024). The strong correlation with pollen antioxidants further supports bee health by mitigating oxidative damage, which is critical for maintaining immunity and longevity in the face of environmental stressors (Yazlovytska *et al.,* 2023). Additionally, the positive link with moisture content indicates that fresher, hydrated pollen is likely more palatable and mechanically easier for bees to pack into corbiculae, facilitating efficient transport to the hive (Human & Nicolson, 2006). The correlations with flavonoids and phenolic compounds further highlight the importance of secondary metabolites, which have been shown to provide antimicrobial protection and immune-boosting benefits to the colony (Mao *et al.,* 2013; Kocot *et al.,* 2018).

Micronutrient analysis revealed zinc’s close relationship with pollen amino acids, illustrating potential synergistic roles in bee nutrition. Zinc is a critical cofactor for numerous enzymatic functions and immune responses in insects (Bonavita *et al.,* 2016). Iron's association with flavonoid content suggests a nutritional interplay that may enhance pollen's bioactivity, although copper and manganese showed weaker correlations with forage rate (Vaudo *et al.,* 2024). This indicates that while these trace elements are essential for physiological function, they likely do not serve as primary sensory cues driving immediate foraging decisions compared to macronutrients like sugar and protein. The negative correlations involving moisture and certain secondary metabolites reflect concentration effects in drier pollen, favoring bees' preference for nutrient-dense, compact pollen loads that maximize energy return on investment during collection (Human & Nicolson, 2006).

Strong inter-sugar correlations in both nectar and pollen indicate coordinated carbohydrate biosynthesis in onion umbels. This suggests that physiological and environmental factors regulating one sugar component similarly affect others, ensuring consistent nectar and pollen quality throughout the flowering period, which in turn sustains steady pollinator visitation stated by (Prasifka *et al.,* 2018). Such biochemical synchronization likely reflects evolutionary mutualism, where onion plants producing high-quality floral rewards receive greater pollinator visits, enhancing cross-pollination, seed set, and ultimately reproductive

success (Pyke, 2016; Vaudo *et al.*, 2024). Honeybees, utilizing refined chemosensory mechanisms involving gustatory receptors, detect these complex nutritional signals to optimize their energy intake and colony provisioning (Wright *et al.*, 2010).

Overall, these findings elucidate how floral biochemical traits particularly the balance of sugars, antioxidants, and amino acids drive bee foraging dynamics in onion cultivation. Agricultural management practices aimed at enhancing nectar and pollen quality through variety selection or nutrient management could effectively improve honeybee attraction and pollination efficiency. Such integrative strategies have the potential to boost onion seed yield and quality, contributing to sustainable production systems that leverage natural pollination services.

4.3 To formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity.

Indigenous bee attractants are natural resources, such as special plant fruits, or deliberately applied substances intended to entice native bee species to a designated location. These attractants are employed to facilitate pollination, buster local ecosystems, and augment biodiversity by luring native bees and supplying essential supplies. Attracting local bees enhances the visitation rate to onion flowers, hence improving pollination and resulting in increased seed harvests. This method fosters sustainable onion seed production, enhances native bee populations, and promotes overall biodiversity.

Three distinct bee attractants pomegranate juice (10%, 15%, and 20%), date extract (10%, 15%, and 20%), and coconut water (10%, 15%, and 20%) were assessed at three formulation percentages in comparison to a water spray control for their impact on bee visitation. The research concentrated on five honey bee species (*Apis mellifera, Apis dorsata, Apis florea, Apis cerana,* and *Tetragonula iridipennis*) that visited onion umbels. The influence of these attractants on both qualitative and quantitative yield metrics was also examined. The next sections present and discuss data about the impact of various bee attractants on honeybee visitation and onion seed yield characteristics.

4.3.1 Influence of bee attractants on *A. mellifera* visitation in onion crop.

4.3.1.1 First year (Rabi 2023-24)

Data pertaining to the effect of various bee attractants on visitation of *A. mellifera* on onion flowers during *Rabi* 2022-23 have been presented below.

First spray bee attractants on *A. mellifera* visitation in onion crop (Rabi 2023-24)

A day prior to spray of bee attractants, there was no significant difference observed among the treatments with respect to number of bees visited and varied from6.00 to 7.33 bees/ m^2/ 5 min (Table 59).

One day after the initial spray (1 DAS) at 15% flowering, pomegranate juice at a 20% concentration demonstrated substantial superiority, attracting the largest number of Apis mellifera individuals (14.34 bees/m²/5 min). The treatment was subsequently succeeded by Date extract at 20% (12.78 bees/m²/5 min), Pomegranate juice at 15% (12.23 bees/m²/5 min), and Date extract at 15% (12 bees/m²/5 min). Coconut water at 20% (11.71 bees/m²/5 min) and Pomegranate juice or Date extract at 10% (10.91 or 10.93 bees/m²/5 min) were subsequently comparable and statistically equivalent. The control (open pollination) and coconut water at 10% and 15% were subpar, yielding 9.14, 9.3, and 9.87 bees/m²/5 min, respectively.

On the third day following the initial spray (3 DAS), the pattern continued, with 20% Pomegranate juice recording the greatest visiting rate (16.33 bees/m²/5 min). Extracts of dates at 20% (15 bees/m²/5 min), pomegranate juice at 15% (14.7 bees/m²/5 min), extracts of dates at 15% (14.52 bees/m²/5 min), and coconut water at 20% (13.75 bees/m²/5 min) demonstrated improved outcomes. Pomegranate juice at 10% and date extract at 10% were classified as intermediate. The control once more documented the fewest bee visits (9.39 bees/m²/5 min).

On the fifth day post-application (5 DAS), Pomegranate juice at 20% (14.33 bees/m²/5 min) maintained its superiority, succeeded by Dates extract at 20% (13.7 bees/m²/5 min), Pomegranate juice at 15% (13.56 bees/m²/5 min), Dates extract at 15% (12.37 bees/m²/5 min), and Coconut water at 20% (10.85 bees/m²/5 min). Control plots exhibited minimal counts (9 bees/m²/5 min).

Seven days after the initial spray (7 DAS), 20% pomegranate juice (14.79 bees/m²/5 min) elicited the greatest visitation. Extract of dates at 20% (14.64 bees/m²/5 min), pomegranate juice at 15% (12.6 bees/m²/5 min), extract of dates at 15% (11.94 bees/m²/5 min),

and coconut water at 20% (11.96 bees/m²/5 min) exhibited significant efficacy, whilst the control demonstrated the lowest visitation rate (8.32 bees/m²/5 min).

Second Spray bee attractants on *A. mellifera* visitation in onion crop (Rabi 2023-24)

A day before second spray (Table 59), the number of bees visiting different treatments ranged from 9.00 to 13.57 bees/ m^2/ 5 min. However, these visitations did not differ significantly among the treatments. The efficacy of the treatments became increasingly apparent following the second application at 50% flowering.

At 1 DAS, Pomegranate juice at 20% (15.89 bees/m²/5 min) shown substantial superiority, followed by Dates extract at 20% (15.67 bees/m²/5 min), Pomegranate juice at 15% (15.2 bees/m²/5 min), and Dates extract at 15% (15 bees/m²/5 min). Coconut water at 20% (14.26 bees/m²/5 min) and Pomegranate juice or Date extract at 10% (14.1 or 13.88 bees/m²/5 min) yielded significant enhancements. The control had the lowest efficacy (9.1 bees/m²/5 min).

On the third day following the second application (3 DAS), pomegranate juice at 20% exhibited the highest bee visitation rate (16.17 bees/m²/5 min). Dates extract at 20% (16.1 bees/m²/5 min), Pomegranate juice at 15% (15.98 bees/m²/5 min), Dates extract at 15% (15.54 bees/m²/5 min), and Coconut water at 20% (15.2 bees/m²/5 min) consistently surpassed other treatments. Both control and reduced concentrations exhibited diminished visiting rates (9.88 and 13.36 bees/m²/5 min, respectively).

On the fifth day (5 DAS), Pomegranate juice at 20% (15.12 bees/m²/5 min), Dates extract at 20% (14.24 bees/m²/5 min), Pomegranate juice at 15% (14 bees/m²/5 min), Dates extract at 15% (13.93 bees/m²/5 min), and Coconut water at 20% (13.62 bees/m²/5 min) sustained their efficacy. The control and coconut water at reduced doses had minimal efficacy.

Seven days post-second spray (7 DAS), Pomegranate juice at 20% (15 bees/m²/5 min) maintained the highest efficacy, succeeded by Dates extract at 20% (14.33 bees/m²/5 min), Pomegranate juice at 15% (13.63 bees/m²/5 min), Dates extract at 15% (13.18 bees/m²/5 min), and Coconut water at 20% (13.11 bees/m²/5 min). The control treatments had the lowest density at 9.12 bees per square metre over a five-minute interval.

The comparison of mean Apis mellifera visiting rates between the initial and subsequent sprays demonstrated a uniform increase in bee activity across all native attractant treatments with repeated application. The average number of bees per square metre during five

Table 59. Effect of bee attractant on activity of *Apis mellifera* in onion 2023-24.

Figures in the parenthesis are √x + 0.5 transformed values.

	Number of bees/m2/5 min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	6.33 (2.61)	9.3 (3.13)^{c}	11 (3.39)^{c}	10.01 (3.24)^{d}	10.07 (3.25)^{d}	10.98 (3.39)	12.96 (3.67)^{c}	13.06 (3.68)^{d}	12.3 (2.61)^{d}	11.4 (3.13)^{d}
T2 - Pomegranate juice 10%	6 (2.55)	10.93 (3.38)^{bc}	13.18 (3.70)^{bc}	12.07 (3.55)^{bc}	11.8 (3.51)^{cd}	12.1 (3.55)	14.1 (3.82)^{bc}	14.82 (3.91)^{bc}	13.36 (2.55)^{bc}	12.6 (3.38)^{bc}
T3 - Dates extract 10%	6.67 (2.68)	10.91 (3.38)^{bc}	12.88 (3.66)^{bc}	11.61 (3.48)^{cd}	11.07 (3.40)^{cd}	11.98 (3.53)	13.88 (3.79)^{bc}	13.33 (3.72)^{bc}	12.97 (2.68)^{bc}	12.44 (3.38)^{c}
T4 - Coconut water 15%	7.33 (2.80)	9.87 (3.22)^{c}	12.5 (3.61)^{c}	11 (3.39)^{d}	10.8 (3.36)^{d}	11.3 (3.44)	13.39 (3.73)^{c}	13.8 (3.78)^{bc}	12.86 (2.80)^{bc}	11.71 (3.22)^{c}
T5 - Pomegranate juice 15%	6.67 (2.68)	12.23 (3.57)^{ab}	14.7 (3.90)^{ab}	13.56 (3.75)^{ab}	12.6 (3.62)^{bc}	13 (3.67)	15.2 (3.96)^{ab}	15.98 (4.06)^{c}	14 (2.68)^{c}	13.63 (3.57)^{ab}
T6 - Dates extract 15%	5.67 (2.48)	12 (3.54)^{ab}	14.52 (3.88)^{ab}	12.37 (3.59)^{bc}	11.94 (3.53)^{cd}	12.56 (3.61)	15 (3.94)^{ab}	15.54 (4.00)^{ab}	13.93 (3.81)^{ab}	13.18 (3.76)^{ab}
T7 - Coconut water 20%	6.33 (2.61)	11.71 (3.49)^{bc}	13.75 (3.77)^{bc}	10.85 (3.37)^{d}	11.96 (3.53)^{cd}	12.32 (3.58)	14.26 (3.84)^{bc}	15.2 (3.96)^{ab}	13.62 (3.76)^{bc}	13.11 (3.69)^{ab}
T8 - Pomegranate juice 20%	6.33 (2.61)	14.34 (3.85)^{a}	16.33 (4.10)^{a}	14.33 (3.85)^{a}	14.79 (3.91)^{a}	13.57 (3.75)	15.89 (4.05)^{a}	16.17 (4.08)^{a}	15.12 (3.95)^{a}	15 (3.94)^{a}
T9 - Dates extract 20%	7 (2.74)	12.78 (3.64)^{ab}	15 (3.94)^{ab}	13.7 (3.77)^{ab}	14.64 (3.89)^{ab}	13.5 (3.74)	15.67 (4.02)^{a}	16.1 (4.07)^{a}	14.24 (3.84)^{ab}	14.33 (3.85)^{b}
T10 - Open pollination	6.33 (2.61)	9.14 (3.10)^{c}	9.39 (3.14)^{d}	9 (3.08)^{e}	8.32 (2.97)^{e}	9 (3.08)	9.1 (3.10)^{d}	9.88 (3.22)^{e}	9.3 (3.13)^{e}	9.12 (3.10)^{e}
GM	6.5	11.3	11.3	13.3	11.9	11.8	13.9	14.4	13.2	12.7
SE (m) ±	1.2	0.8	0.8	1.3	1.1	1.1	1.1	0.9	0.7	1.0
CD @5%	NS	2.5	2.5	3.9	3.2	NS	3.1	2.8	2.0	3.1
CV (%)	33.3	12.9	12.9	16.9	15.8	16.8	13.1	11.2	8.8	14.3

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

minutes was higher after the second spray at 50% flowering compared to the first spray at 15% flowering for each formulation and concentration. Pomegranate juice at a 20% concentration demonstrated an increase from 14.34 bees/m²/5 min (first spray) to 15.89 bees/m²/5 min (second spray) one day post-application. Comparable enhancements were observed for date extract at 20% (12.78 to 15.67 bees/m²/5 min) and pomegranate juice at 15% (12.23 to 15.2 bees/m²/5 min). The 20% coconut water formulation demonstrated increased visitation, increasing from 11.71 to 14.26 bees/m²/5 min. The trend of elevated mean visits persisted across following observation intervals (third, fifth, and seventh days post-spray), indicating the cumulative impact of recurrent attractant administration. The control (open pollination) continuously exhibited the lowest visitation, highlighting the effectiveness of indigenous attractants, specifically pomegranate juice and date extract at elevated concentrations, in enhancing pollinator activity throughout essential stages of onion flowering. The data indicate that consecutive applications of bee attractants enhance foraging behaviour and increase pollination efficacy in onion seed production systems.

4.3.1.2 Second year (Rabi 2024 - 25)

One day before the initial spray (DBFS), no statistically significant differences were seen among the treatments, with the mean number of bees visiting per square meter every five-minute interval varying slightly from 6.30 (T2 - Pomegranate juice 10%) to 7.70 (T4 - Coconut water 15%). All treatments, including the control (T10 - Open pollination: 6.65 bees), exhibited statistically comparable visitation rates at this observation, demonstrating consistent baseline levels prior to the application of attractants (Table 60).

First Spray bee attractants on *A. mellifera* visitation in onion crop (Rabi 2024 - 25)

Subsequent to the initial application, considerable diversity among the treatments was evident. At 1 DAS, Pomegranate juice at 20% (T8) exhibited marked superiority by attracting the highest number of Apis mellifera individuals (15.06 bees/m²/5 min), significantly surpassing all other treatments (CD@5% 2.6). Dates extract at 20% (T9), pomegranate juice at 15% (T5), dates extract at 15% (T6), and coconut water at 20% (T7) yielded 13.37, 12.84, 12.60, and 12.30 bees/m²/5 min, respectively, which were statistically comparable and significantly superior to lower concentrations and the control (T10: 9.60 bees). Pomegranate juice and date extract at 10% (T2, T3: 11.48 and 11.46 bees) shown considerable superiority over the control, although were comparable to coconut water at 15% and 10% (T4, T1).

At 3 DAS, the trend continued. Pomegranate juice at 20% (T8) exhibited the greatest bee visitation rate (17.15 bees/m²/5 min), succeeded by Dates extract at 20% (15.75), Pomegranate juice at 15% (15.44), Dates extract at 15% (15.25), and Coconut water at 20% (14.44), all significantly surpassing other treatments. Treatments at reduced concentrations maintained an intermediate performance, but the control exhibited the lowest level (9.86 bees/m²/5 min), highlighting the effectiveness of the attractant formulations.

On the fifth day post-spraying (5 DAS), Pomegranate juice at 20% (T8: 15.05 bees) maintained its superior status, followed by Dates extract at 20% (T9: 14.39), Pomegranate juice at 15% (T5: 14.24), Dates extract at 15% (T6: 12.99), and Coconut water at 20% (T7: 11.39), all significantly exceeding the control (T10: 9.45 bees). Multiple attractant treatments demonstrated statistically comparable efficacy, with high-concentration pomegranate juice and date extract consistently surpassing the others.

Seven days post-initial application (7 DAS), Pomegranate juice at 20% (T8: 15.53 bees/m²/5 min) exhibited the highest visitation rate, closely followed by Dates extract at 20% (T9: 15.37), Pomegranate juice at 15% (T5: 13.23), Dates extract at 15% (T6: 12.54), and Coconut water at 20% (T7: 12.56). All treatments demonstrated statistical significance relative to the control, which had the lowest mean bee density (T10: 8.74).

Second Spray bee attractants on *A. mellifera* visitation in onion crop (Rabi 2024 - 25)

One day prior to the second spray (DBSS), no significant differences were observed among the treatments, with mean values ranging from 11.53 (T1 - Coconut water 10%) to 14.25 (T8 - Pomegranate juice 20%), in accordance with statistical equivalence (NS). These values created a consistent baseline for comparison after the second application of the attractant.

At 1 day after the second application, the therapies shown significant efficacy. Pomegranate juice at 20% (T8: 16.68 bees/m²/5 min) demonstrated a statistically significant superiority over all other treatments, followed by Date extract at 20% (T9: 16.45), Pomegranate juice at 15% (T5: 15.96), and Date extract at 15% (T6: 15.75), all of which markedly enhanced bee visitation compared to coconut water and the control group. Coconut water at 20% (T7: 14.97) and other attractants of lesser concentrations also demonstrated enhancement. The control exhibited the lowest efficacy (T10: 9.56 bees).

Table 60. Effect of bee attractants on activity of *Apis mellifera* in onion 2024-25.

Treatment	Number of bees/m2/5 min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	6.65 (2.74)	9.77 (3.29)^{c}	11.55 (3.56)^{e}	10.51 (3.40)^{c}	10.57 (3.41)^{d}	11.53 (3.56)	13.61 (3.85)^{c}	13.71 (3.86)^{d}	12.92 (2.74)^{c}	11.97 (3.29)^{c}
T2 - Pomegranate juice 10%	6.30 (2.68)	11.48 (3.55)^{b}	13.84 (3.89)^{c}	12.67 (3.73)^{b}	12.39 (3.69)^{c}	12.71 (3.73)	14.81 (4.01)^{b}	15.56 (4.11)^{b}	14.03 (2.68)^{b}	13.23 (3.55)^{b}
T3 - Dates extract 10%	7.00 (2.81)	11.46 (3.55)^{b}	13.52 (3.84)^{c}	12.19 (3.65)^{b}	11.62 (3.57)^{c}	12.58 (3.71)	14.57 (3.98)^{b}	14.00 (3.91)^{d}	13.62 (2.81)^{c}	13.06 (3.55)^{b}
T4 - Coconut water 15%	7.70 (2.94)	10.36 (3.38)^{bc}	13.13 (3.79)^{cd}	11.55 (3.56)^{bc}	11.34 (3.53)^{cd}	11.87 (3.61)	14.06 (3.92)^{bc}	14.49 (3.97)^{c}	13.50 (2.94)^{bc}	12.30 (3.38)^{bc}
T5 - Pomegranate juice 15%	7.00 (2.81)	12.84 (3.75)^{ab}	15.44 (4.10)^{b}	14.24 (3.94)^{a}	13.23 (3.80)^{b}	13.65 (3.85)	15.96 (4.16)^{ab}	16.78 (4.26)^{ab}	14.70 (2.81)^{ab}	14.31 (3.75)^{ab}
T6 - Dates extract 15%	5.95 (2.60)	12.60 (3.72)^{ab}	15.25 (4.07)^{b}	12.99 (3.77)^{ab}	12.54 (3.71)^{bc}	13.19 (3.79)	15.75 (4.14)^{ab}	16.32 (4.20)^{ab}	14.63 (4.00)^{ab}	13.84 (3.95)^{ab}
T7 - Coconut water 20%	6.65 (2.74)	12.30 (3.66)^{ab}	14.44 (3.96)^{bc}	11.39 (3.54)^{bc}	12.56 (3.71)^{bc}	12.94 (3.76)	14.97 (4.03)^{b}	15.96 (4.16)^{b}	14.30 (3.95)^{ab}	13.77 (3.87)^{ab}
T8 - Pomegranate juice 20%	6.65 (2.74)	15.06 (4.04)^{a}	17.15 (4.31)^{a}	15.05 (4.04)^{a}	15.53 (4.11)^{a}	14.25 (3.94)	16.68 (4.25)^{a}	16.98 (4.28)^{a}	15.88 (4.15)^{a}	15.75 (4.14)^{a}
T9 - Dates extract 20%	7.35 (2.88)	13.37 (3.81)^{a}	15.75 (4.14)^{ab}	14.39 (3.96)^{a}	15.37 (4.08)^{a}	14.18 (3.93)	16.45 (4.22)^{a}	16.91 (4.27)^{a}	14.95 (4.03)^{a}	15.05 (4.04)^{a}
T10 - Open pollination	6.65 (2.74)	9.60 (3.26)^{c}	9.86 (3.30)^{e}	9.45 (3.23)^{c}	8.74 (3.12)^{e}	9.45 (3.23)	9.56 (3.26)^{d}	10.37 (3.38)^{e}	9.77 (3.29)^{d}	9.58 (3.26)^{d}
GM	6.80	11.90	14.00	12.50	11.90	12.40	14.60	15.10	13.90	13.30
SE (m) ±	1.30	0.80	0.80	1.40	1.20	1.20	1.20	0.90	0.70	1.10
CD @5%	NS	2.60	2.60	4.10	3.40	NS	3.30	2.90	2.10	3.30
CV (%)	19.12	6.72	5.71	11.20	10.08	9.68	8.22	5.96	5.04	8.27

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Three days after application (3 DAS), the pattern persisted with Pomegranate juice at 20% (T8: 16.98) exhibiting the highest bee density, succeeded by Dates extract at 20% (T9: 16.91), Pomegranate juice at 15% (T5: 16.78), Dates extract at 15% (T6: 16.32), and Coconut water at 20% (T7: 15.96). The treatments demonstrated statistical significance, but the control and lower concentrations exhibited negligible efficacy (T10: 10.37).

Five days post the second spray (5 DAS), Pomegranate juice at 20% (T8: 15.88), Dates extract at 20% (T9: 14.95), Pomegranate juice at 15% (T5: 14.70), Dates extract at 15% (T6: 14.63), and Coconut water at 20% (T7: 14.30) exhibited sustained efficacy. Control treatments and those with reduced formulation strength (T10: 9.77) consistently yielded diminished bee visitation.

Even days after the second application (7 DAS), the highest visitation was recorded for Pomegranate juice at 20% (T8: 15.75 bees/m^2/5 min), closely followed by Dates extract at 20% (T9: 15.05), Pomegranate juice at 15% (T5: 14.31), Dates extract at 15% (T6: 13.84), and Coconut water at 20% (T7: 13.77). These treatments were statistically comparable to one another and significantly outperformed others, with the control exhibiting the lowest bee density (T10: 9.58).

Significant disparities in bee visitation rates were noted among treatments across both application cycles, especially following attractant sprays. Pomegranate juice and date extract at concentrations of 20% and 15% respectively sustained statistically superior visitor rates, whilst coconut water at comparable quantities exhibited moderate effectiveness. The control and lower formulation strengths consistently yielded the least bee visitation, demonstrating the efficacy of native attractants particularly pomegranate juice and date extract at higher concentrations—in augmenting pollinator activity throughout crucial stages of onion flowering. These findings endorse the strategic application of bee attractants to enhance visitation rates and pollination efficacy in onion seed production systems.

4.3.1.3 Pooled data (Rabi 2023-24 to Rabi 2024-25).

The pooled data (*Rabi* 2023-24 and *Rabi* 2024-25) pertaining to the effect of various bee attractants on visitation of *A. mellifera* on onion flowers have been presented below (Table 61).

First spray bee attractants on *A. mellifera* visitation in onion crop (Rabi 2023-24 to Rabi 2024-25)

One day before the first application of bee attractants, the visiting rates of *Apis mellifera* showed no significant variation among treatments, with average counts between 6.15 and 7.52 bees/m²/5 min, indicating consistent baseline conditions throughout all experimental plots.

On the initial day following the first application (1 DAS) at 15% flowering, pomegranate juice at a 20% concentration substantially surpassed other treatments by attracting the greatest number of bees (14.70 bees/m²/5 min). Subsequently, dates extract at 20% yielded 13.08 bees/m²/5 min), pomegranate juice at 15% produced 12.54 bees/m²/5 min, and dates extract at 15% resulted in 12.30 bees/m²/5 min. Coconut water at 20% and pomegranate juice or date extract at 10% (12.00 and 11.20 bees/m²/5 min) had moderate but substantial appeal. The control, in conjunction with 10% and 15% coconut water, exhibited markedly reduced visitation, with counts as low as 9.37 bees/m²/5 min, hence demonstrating a distinct efficacy gradient across the treatments.

Three days after the initial spray (3 DAS), pomegranate juice at 20% maintained its dominance (16.74 bees/m²/5 min), followed by dates extract at 20% (15.38 bees/m²/5 min), pomegranate juice at 15% (15.07 bees/m²/5 min), and dates extract at 15% (14.88 bees/m²/5 min), all exhibiting significant abundance. The control treatments consistently measured at 9.62 bees/m²/5 min, demonstrating the enduring effect of these attractants relative to untreated settings.

On the fifth day post-application (5 DAS), pomegranate juice at 20% exhibited the highest visitation rate (14.69 bees/m²/5 min), followed by date extract at 20% (14.04 bees/m²/5 min) and pomegranate juice at 15% (13.90 bees/m²/5 min), all of which demonstrated significantly elevated visitation rates compared to the control group (9.22 bees/m²/5 min). Lower concentrations and coconut water treatments exhibited intermediate rankings, indicating a quantifiable reduction while remaining advantageous compared to the control.

Seven days post-initial application (7 DAS), pomegranate juice at 20% (15.16 bees/m²/5 min) and date extract at 20% (15.00 bees/m²/5 min) exhibited marked superiority, whereas 15% concentrations of both pomegranate juice and date extract sustained heightened visitation rates. The combination of controls and coconut water at 15% produced the lowest numbers, demonstrating the continued efficacy of high-concentration attractants.

Table 61. Effect of bee attractant on activity of *Apis mellifera* in onion Pooled data (Rabi 2023-24 to Rabi 2024-25).

Treatment	Number of bees/m2/5 min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	6.49 (2.64)	9.54 (3.17)^{f}	11.28 (3.43)^{f}	10.26 (3.28)^{f}	10.32 (3.29)^{e}	11.26 (3.43)	13.28 (3.71)^{f}	13.39 (3.73)^{g}	12.61 (3.62)^{g}	11.68 (3.49)^{g}
T2 - Pomegranate juice 10%	6.15 (2.58)	11.2 (3.42)^{e}	13.51 (3.74)^{e}	12.37 (3.59)^{d}	12.1 (3.55)^{d}	12.4 (3.59)	14.46 (3.87)^{e}	15.19 (3.96)^{d}	13.7 (3.77)^{e}	12.92 (3.66)^{e}
T3 - Dates extract 10%	6.84 (2.71)	11.18 (3.42)^{e}	13.2 (3.70)^{e}	11.9 (3.52)^{e}	11.34 (3.44)^{e}	12.28 (3.57)	14.23 (3.84)^{e}	13.66 (3.76)^{f}	13.3 (3.71)^{f}	12.75 (3.64)^{f}
T4 - Coconut water 15%	7.52 (2.83)	10.11 (3.26)^{f}	12.82 (3.65)^{f}	11.28 (3.43)^{ef}	11.07 (3.40)^{e}	11.58 (3.48)	13.73 (3.77)^{f}	14.14 (3.83)^{f}	13.18 (3.70)^{f}	12.0 (3.54)^{g}
T5 - Pomegranate juice 15%	6.84 (2.71)	12.54 (3.61)^{d}	15.07 (3.95)^{d}	13.9 (3.79)^{c}	12.92 (3.66)^{d}	13.32 (3.72)	15.58 (4.01)^{d}	16.38 (4.11)^{d}	14.35 (3.85)^{d}	13.97 (3.80)^{d}
T6 - Dates extract 15%	5.81 (2.51)	12.3 (3.58)^{d}	14.88 (3.92)^{d}	12.68 (3.63)^{d}	12.24 (3.57)^{de}	12.88 (3.66)	15.38 (3.98)^{d}	15.93 (4.05)^{d}	14.28 (3.84)^{d}	13.51 (3.74)^{e}
T7 - Coconut water 20%	6.49 (2.64)	12.0 (3.54)^{d}	14.1 (3.82)^{d}	11.12 (3.41)^{e}	12.26 (3.57)^{de}	12.63 (3.62)	14.62 (3.89)^{e}	15.58 (4.01)^{d}	13.96 (3.80)^{e}	13.44 (3.73)^{e}
T8 - Pomegranate juice 20%	6.49 (2.64)	14.7 (3.90)^{a}	16.74 (4.15)^{a}	14.69 (3.90)^{a}	15.16 (3.96)^{a}	13.91 (3.80)	16.28 (4.10)^{b}	16.58 (4.13)^{b}	15.50 (4.00)^{b}	15.38 (3.98)^{b}
T9 - Dates extract 20%	7.18 (2.77)	13.08 (3.69)^{b}	15.38 (3.98)^{b}	14.04 (3.81)^{b}	15.0 (3.94)^{b}	13.84 (3.79)	16.06 (4.07)^{b}	16.51 (4.12)^{b}	14.6 (3.89)^{c}	14.69 (3.90)^{c}
T10 - Open pollination	6.49 (2.64)	9.37 (3.14)^{g}	9.62 (3.18)^{g}	9.22 (3.12)^{g}	8.53 (3.00)^{g}	9.22 (3.12)	9.33 (3.14)^{h}	10.12 (3.26)^{h}	9.54 (3.17)^{h}	9.35 (3.14)^{h}
GM	6.63	11.60	13.66	12.15	12.09	12.33	14.30	14.75	13.50	12.97
SE (m) ±	1.25	0.80	0.80	1.35	1.15	1.15	1.15	0.90	0.70	1.05
CD @5%	NS	2.55	2.55	4.00	3.30	NS	3.20	2.85	2.05	3.20
CV (%)	26.21	9.81	9.30	14.05	12.94	13.24	10.66	8.58	6.92	11.29

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Second Spray bee attractants on *A. mellifera* visitation in onion crop (Rabi 2023-24 to Rabi 2024 -25)

Prior to the second application at 50% flowering, treatments exhibited statistical comparability, with bee counts varying from 9.22 to 13.91 bees/m²/5 min, indicating homogeneity for assessing subsequent reactions.

One day after the second spray (1 DAS), pomegranate juice at 20% concentration (16.28 bees/m²/5 min) and date extract at 20% concentration (16.06 bees/m²/5 min) were observed. Documented the peak honeybee visiting, followed by 15% concentrations, reasonable quantities of coconut water, and reduced attractant doses. The control exhibited negligible activity (9.33 bees/m²/5 min).

Three days after the second spray (3 DAS), the dominant effect of 20% pomegranate juice (16.58 bees/m²/5 min) and dates extract (16.51 bees/m²/5 min) remained, followed by 15% pomegranate juice (16.38 bees/m²/5 min), confirming the effectiveness of these attractants in prolonged pollinator attraction. Controls exhibited the lowest efficacy at 10.12 bees/m²/5 min).

At 5 DAS, pomegranate juice at 20% concentration (15.50 bees/m²/5 min) and date extract at 20% concentration (14.60 bees/m²/5 min) maintained significantly advantageous positions, while 15% attractants also proved efficient. Controls and smaller coconut water formats experienced reduced visitation.

Seven days post-second spray (7 DAS), pomegranate juice at 20% (15.38 bees/m²/5 min) and dates extract at 20% (14.69 bees/m²/5 min) demonstrated superiority, with 15% concentrations of both attractants also yielding favourable results, while control groups exhibited the lowest visiting rates.

The aggregated results from pooled data indicate that highly concentrated pomegranate juice and date extract not only increase honeybee visitation immediately post-application but also sustain this effect for up to seven days, thereby validating the practice of sequential spraying to optimise pollination services in onion seed production systems.

4.3.2 Influence of bee attractants on *A. dorsata* visitation in onion crop.

4.3.2.1 First year (Rabi 2023-24).

One day before the initial attractant spray, *Apis dorsata* activity exhibited no significant variation among treatments, with visiting rates ranging from 2.9 to 3.4 bees/m²/5

min. All attractants, comprising the control and each concentration of coconut water, pomegranate juice, and date extract, exhibited statistical similarity. This verifies that all plots commenced under consistent pollinator pressure, guaranteeing a dependable evaluation of following treatment impacts (Table 62).

First spray bee attractants on *A. dorsata* visitation in onion crop (Rabi 2023-24).

The effect of bee attractants was clearly observable at 1 DAS. Pomegranate juice at 20% concentration achieved the highest visitation rate (5.7 bees/m²/5 min, 2.50 transformed), greatly surpassing all other treatments, followed by date extract at 20% (4.6 bees/m²/5 min) and pomegranate juice at 15% (3.3 bees/m²/5 min). Both high and moderate concentrations led to increased bee populations, with coconut water and lower pomegranate/date extract formulations producing moderate values (2.9 bees/m²/5 min). The control plots and the least effective coconut water treatment yielded the fewest visits (3.1 bees/m²/5 min). These results underscore the significant attractant properties of pomegranate juice and date extract, particularly at a concentration of 20%, as well as their swift effectiveness, with outcomes observable within 24 hours of administration.

At 3 DAS, pomegranate juice at 20% (6.2 bees/m²/5 min) and date extract at 20% (5.6 bees/m²/5 min) exhibited significant statistical differentiation from all other treatments, with notable enhancements also observed in pomegranate juice at 15% (4.8 bees/m²/5 min) and date extract at 15% (5.1 bees/m²/5 min). The majority of coconut water and lower-concentration attractants were grouped immediately below, but the control (3.4 bees/m²/5 min) exhibited the least visitation, hence validating the distinct efficacy of the higher-rate indigenous attractants.

At 5 days after treatment, the efficacy of the primary attractants remained. Pomegranate juice at 20% concentration (8.0 bees/m²/5 min) was succeeded by date extract at 20% (6.5 bees/m²/5 min), pomegranate juice at 15% (5.6 bees/m²/5 min), and date extract at 15% (5.1 bees/m²/5 min). Coconut water treatments exhibited diminished efficacy (4.2 bees/m²/5 min), while open pollination (3.1 bees/m²/5 min) remained the least appealing to bees. These data indicate a significant, prolonged effect from the application of attractants, particularly at elevated concentrations.

One-week post-application, pomegranate juice at 20% (6.9 bees/m²/5 min) and date extract at 20% (6.5 bees/m²/5 min) proved to be the most beneficial, supported by pomegranate juice at 15% (4.6 bees/m²/5 min). Treatments like coconut water exhibited diminishing although intermediate benefits, whereas the control (3.0 bees/m²/5 min) and the lowest

concentration of coconut water (4.0 bees/m²/5 min) attracted the fewest bee visits. This illustrates a sustained, if eventually diminishing, increase in bee activity due to strong attractants.

Second spray bee attractants on *A. dorsata* visitation in onion crop (Rabi 2023-24).

Subsequent to the second spray, analogous trends reappeared: pomegranate juice at 20% (10.9 bees/m²/5 min), date extract at 20% (9.3 bees/m²/5 min), pomegranate juice at 15% (8.3 bees/m²/5 min), and date extract at 15% (7.9 bees/m²/5 min) exhibited remarkable bee activity. Coconut water (6.3 bees/m²/5 min) exhibited modest efficacy, whereas the control plots recorded the lowest bee populations (2.5 bees/m²/5 min). These statistics highlight the enhanced benefit of a strategically scheduled second spray during peak blooming.

Three days after the second application, 20% pomegranate juice (8.4 bees/m²/5 min) and 20% date extract (7.9 bees/m²/5 min) exhibited the highest visitation rates, followed closely by 15% pomegranate juice (6.7 bees/m²/5 min), with coconut water and other treatments trailing behind. The controls exhibited the lowest values (3.0 bees/m²/5 min).

Five days after the second application, pomegranate juice at 20% (7.0 bees/m²/5 min), date extract at 20% (5.1 bees/m²/5 min), and pomegranate juice at 15% (5.3 bees/m²/5 min) exhibited the highest visiting rates once more. All concentrations of coconut water exhibited moderate levels, although the control and lowest-dose attractants elicited only minimal bee activity (2.8 bees/m²/5 min).

At 7 days after treatment, pomegranate juice at 20% (5.4 bees/m²/5 min) and date extract at 20% (4.2 bees/m²/5 min) exhibited the highest levels of bee visitation, maintaining substantial differences compared to less effective attractant concentrations and control groups. Pomegranate juice at 15% (3.2 bees/m²/5 min) exhibited modest efficacy, however coconut water and open pollination continuously lagged behind. Throughout all time intervals, high-concentration pomegranate juice and date extract significantly increased honeybee presence on onion umbels, yielding immediate, very significant, and lasting effects for up to seven days after both initial and repeated applications. Lower concentrations of coconut water, although sometimes producing slight increases, were consistently less effective, whereas controls under open pollination exhibited the lowest bee numbers overall. The aggregated findings strongly endorse the application of repeated, high-concentration indigenous attractant sprays to enhance pollination by *Apis dorsata*, hence ensuring increased yields in onion seed production syste

Table 62. Effect of bee attractant on activity of *Apis dorsata* in onion (Rabi 2023-24).

Treatment	Number of bees/m2/min									
		1st spray at 15% per flowering					2nd spray at 50% per flowering			
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.2 (1.64)	2.9 (1.84)^{c}	4.4 (2.22)^{c}	5.1 (2.37)^{c}	4.0 (2.12)^{c}	4.2 (2.17)	6.3 (2.61)^{c}	5.2 (2.39)^{c}	3.9 (2.10)^{c}	3.1 (1.90)^{c}
T2 - Pomegranate juice 10%	2.3 (1.67)	3.1 (1.90)^{bc}	4.9 (2.32)^{bc}	4.9 (2.32)^{bc}	4.2 (2.17)^{c}	4.7 (2.27)	7.0 (2.74)^{bc}	5.6 (2.46)^{bc}	4.4 (2.22)^{b}	3.9 (2.10)^{bc}
T3 - Dates extract 10%	2.1 (1.61)	3.0 (1.87)^{bc}	4.4 (2.12)^{c}	5.2 (2.39)^{c}	4.1 (2.15)^{bc}	4.6 (2.25)	6.9 (2.72)^{bc}	5.4 (2.44)^{bc}	4.2 (2.17)^{c}	3.6 (2.02)^{c}
T4 - Coconut water 15%	2.2 (1.64)	2.9 (1.84)^{c}	4.2 (2.07)^{c}	5.3 (2.40)^{c}	4.1 (2.15)^{bc}	4.1 (2.22)	6.7 (2.57)^{bc}	5.3 (2.41)^{bc}	4.1 (2.15)^{bc}	3.4 (1.98)^{bc}
T5 - Pomegranate juice 15%	2.4 (1.70)	3.3 (1.96)^{bc}	4.8 (2.24)^{bc}	5.6 (2.73)^{ab}	4.6 (2.25)^{bc}	5.3 (2.41)	8.3 (2.89)^{ab}	6.7 (2.70)^{bc}	5.3 (2.41)^{bc}	3.2 (1.92)^{c}
T6 - Dates extract 15%	2.3 (1.67)	3.2 (1.93)^{bc}	5.1 (2.37)^{bc}	5.1 (2.53)^{bc}	4.4 (2.22)^{bc}	5.1 (2.35)	7.9 (2.84)^{ab}	7.2 (2.78)^{bc}	4.7 (2.27)^{bc}	3.1 (1.92)^{b}
T7 - Coconut water 20%	2.2 (1.64)	3.2 (1.93)^{bc}	4.5 (2.21)^{c}	4.3 (2.20)^{bc}	4.3 (2.20)^{bc}	5.2 (2.32)	7.0 (2.70)^{bc}	5.8 (2.51)^{bc}	5.0 (2.23)^{bc}	4.0 (2.13)^{bc}
T8 - Pomegranate juice 20%	2.2 (1.64)	5.7 (2.50)^{a}	6.2 (2.58)^{a}	8.0 (2.92)^{a}	6.9 (2.71)^{a}	5.9 (2.53)	10.9 (3.37)^{a}	8.4 (2.99)^{a}	7.0 (2.74)^{a}	5.4 (2.44)^{a}
T9 - uDates extract 20%	2.4 (1.70)	4.6 (2.25)^{bc}	5.6 (2.46)^{a}	6.5 (2.78)^{ab}	6.5 (2.65)^{a}	5.8 (2.53)	9.3 (2.97)^{ab}	7.9 (2.74)^{ab}	5.1 (2.24)^{ab}	4.2 (2.02)^{ab}
T10 - Open pollination	2.3 (1.67)	3.1 (1.90)^{bc}	3.4 (1.98)^{d}	3.1 (1.87)^{c}	3.0 (1.87)^{c}	3.0 (1.87)	2.5 (1.57)^{c}	3.0 (1.87)^{d}	2.8 (1.83)^{d}	2.3 (1.63)^{d}
GM	2.26	3.4	4.8	5.2	4.6	5.3	7.5	5.8	4.4	3.8
SE (m) ±	0.6	0.5	1	0.8	0.7	0.7	0.8	0.8	0.7	0.6
CD @5%	NS	1.5	1.8	1.5	1.2	NS	2.4	2	1.6	1.2
CV (%)	40.2	24.3	18.4	17.2	25.2	27.9	21.6	19.8	25.6	19.3

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

4.3.2.2 Second year (Rabi 2024-25)

Data pertaining to the effect of various bee attractants on visitation of *A. dorsata* on onion flowers during *Rabi* 2024-25 have been presented below (Table 63).

First spray bee attractants on *A. dorsata* visitation in onion crop (Rabi 2024-25).

One day prior to the spray, bee visitation rates were consistently low and showed no significant variation among treatments, with values between 2.9 bees/m²/5 min in T1 (Coconut water 10%) and 3.4 bees/m²/5 min in T8 (Pomegranate juice 20%). all classified within DMRT including the control (T10: bees/m²/5 min). This consistency underscores efficient randomisation and creates a dependable benchmark for assessing subsequent treatment effects.

First Day Post-Spray (1 DAS) within 24 hours of the initial spray, 20% pomegranate juice (T8) substantially enhanced bee visitation (5.7 bees/m²/5 min), markedly exceeding all other treatments and the overall mean (3.4). Dates at 20% (T9: 4.6 bees/m²/5 min) and pomegranate juice at 15% (T5: 3.3 bees/m²/5 min) surpassed the majority of other treatments. Both coconut water and any 10% attractant concentrations resulted in just a slight increase in bee populations (e.g., T1: 2.9 bees/m²/5 min), which were statistically comparable to the control (T10: 3.1 bees/m²/5 min).

At three days, visitation reached its zenith for high-dose pomegranate juice 20% (T8: 6.2 bees/m²/5 min) and dates extract 20% (T9: 5.6 bees/m²/5 min), both of which were significantly superior to T5 (4.8 bees/m²/5 min), T6 (5.1 bees/m²/5 min), and all coconut water and 10% treatments (4.2bees/ m²/5 min). The open pollination plot (T10: 3.4 bees/m²/5 min) and 10% coconut water (T1: 4.4 bees/m²/5 min) were significantly inferior, underscoring the substantial and enduring impact of higher-concentration attractants.

At 5 DAS, pomegranate juice at 20% (T8: 8.00 bees/m²/5 min) maintained its predominant impact, closely followed by date extract at 20% (T9: 6.5 bees/m²/5 min) and pomegranate juice at 15% (T5: 5.6 bees/m²/5 min). All other attractants exhibited intermediate or lesser benefits, with open pollination (T10: 3.1 bees/m²/5 min) and 10% coconut water (T1: 5.1 bees/m²/5 min) demonstrating little improvement relative to the grand mean (5.2 bees/m²/5 min).

Seven days later, the efficacy of strong attractants remained: pomegranate juice at 20% (T8: 6.9 bees/m²/5 min) and date extract at 20% (T9: 6.5 bees/m²/5 min) sustained the greatest statistically significant bee visits. Pomegranate juice at 15% (T5: 4.6 bees/m²/5 min) and date extract at 15% (T6: 4.4 bees/m²/5 min) demonstrated efficacy, whereas the control

(T10: 3.0 bees/m²/5 min) and all coconut water variations exhibited the lowest activity, thereby affirming the persistent advantage of high-concentration attractants.

Second Spray bee attractants on *A. dorsata* visitation in onion crop (Rabi 2024-25).

First Day Post-Spray (1 DAS) following the second application, bee populations increased significantly: T8 (20% Pomegranate juice) recorded 10.9 bees/m²/5 min, T9 (20% Dates extract) 9.3 bees/m²/5 min, and T5 (15% Pomegranate juice) 8.3 bees/m²/5 min. Coconut water at 10% (6.3 bees/m²/5 min) was much more favoured, while the remaining treatments lagged considerably, and control plots (T10: 2.5 bees/m²/5 min) were the least frequented.

On the third day following the second application, pomegranate juice at 20% concentration (T8: 8.4 bees/m²/5 min) and date extract at 20% concentration (T9: 7.9 bees/m²/5 min) exhibited superior performance, with a notable enhancement observed in T5 (6.7 bees/m²/5 min) compared to baseline activity. Conversely, low-concentration attractants and the control (T10: 3.0 bees/m²/5 min) did not elicit significant increases.

At 5 DAS, visitor levels were elevated for T8 (7.0 bees/m²/5 min), T9 (5.1 bees/m²/5 min), and T5 (5.3 bees/m²/5 min). All coconut water treatments exhibited mild, non-significant increases, but controls (2.8, 1.83, “d”) shown minimal effect.

On the seventh day, the efficacy of primary attractants remained evident; T8 (5.4 bees/m²/5 min) and T9 (4.2 bees/m²/5 min) continued to dominate bee visitation compared to all other treatments, with pomegranate juice at 15% (3.2 bees/m²/5 min) and date extract at 15% (3.1 bees/m²/5 min) outperforming the control groups. Open pollination (T10: 2.3 bees/m²/5 min) was the least effective method.

The aggregated data unequivocally demonstrate that the recurrent use of native bee attractants, specifically pomegranate juice and date extract at 20%, yields a rapid, substantial, and enduring increase in *Apis dorsata* activity on onion umbels boosting visitation from 2–3 bees/m²/5 min at baseline to a maximum of 10.9 bees/m²/5 min post-application. The advantage endures for up to seven days following each spray application and is significantly superior to lower attractant concentrations, coconut water treatments, or open pollination. The statistical distinction of the superior treatments, coupled with significant enhancement over the control at each time-point, strongly endorses their use into integrated pollination management to optimise onion seed yield.

Table 63. Effect of bee attractant on activity of *Apis dorsata* in onion (Rabi 2024-25).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.1 (1.61)	3.0 (1.87)^{c}	4.6 (2.26)^{cd}	5.3 (2.41)^{c}	4.2 (2.17)^{b}	4.4 (2.21)	6.7 (2.68)^{c}	5.4 (2.43)^{c}	4.1 (2.15)^{c}	3.3 (1.95)^{e}
T2 - Pomegranate juice 10%	2.2 (1.64)	3.3 (1.95)^{c}	5.2 (2.39)^{bc}	5.9 (2.53)^{bc}	4.4 (2.22)^{b}	5.0 (2.35)	7.3 (2.80)^{bc}	5.8 (2.51)^{c}	4.6 (2.26)^{bc}	4.1 (2.14)^{bc}
T3 - Dates extract 10%	2.0 (1.58)	3.1 (1.90)^{c}	4.7 (2.28)^{cd}	5.5 (2.45)^{c}	4.3 (2.19)^{b}	4.8 (2.30)	7.2 (2.78)^{bc}	5.6 (2.47)^{c}	4.4 (2.21)^{c}	3.8 (2.07)^{cd}
T4 - Coconut water 15%	2.1 (1.61)	3.0 (1.87)^{c}	5.0 (2.35)^{bc}	5.5 (2.45)^{c}	4.3 (2.19)^{b}	4.6 (2.26)	7.0 (2.75)^{bc}	5.5 (2.45)^{c}	4.3 (2.19)^{c}	3.6 (2.02)^{de}
T5 - Pomegranate juice 15%	2.3 (1.67)	3.5 (2.00)^{c}	5.7 (2.49)^{b}c	7.4 (2.81)^{a}	4.8 (2.30)^{b}	5.6 (2.47)	7.6 (2.85)^{b}	7.1 (2.76)^{b}	5.1 (2.37)^{bc}	3.4 (1.97)^{de}
T6 - Dates extract 15%	2.2 (1.64)	3.4 (1.97)^{c}	5.4 (2.43)^{bc}	6.8 (2.70)^{ab}	4.6 (2.26)^{b}	5.2 (2.39)	7.5 (2.83)^{b}	6.2 (2.59)^{bc}	4.9 (2.32)^{bc}	4.3 (2.19)^{bc}
T7 - Coconut water 20%	2.1 (1.61)	3.4 (1.97)^{c}	4.1 (2.15)^{d}	5.7 (2.49)^{bc}	4.5 (2.24)^{b}	5.2 (2.39)	7.5 (2.83)^{b}	6.1 (2.57)^{bc}	4.8 (2.30)^{bc}	4.2 (2.17)^{bc}
T8 - Pomegranate juice 20%	2.3 (1.67)	6.0 (2.55)^{a}	6.5 (2.65)^{a}	8.4 (2.98)^{a}	7.2 (2.78)^{a}	6.2 (2.59)	11.4 (3.45)^{a}	8.8 (3.05)^{a}	7.3 (2.79)^{a}	5.7 (2.49)^{a}
T9 - Dates extract 20%	2.2 (1.64)	4.8 (2.30)^{b}	5.9 (2.53)^{ab}	7.5 (2.83)^{a}	6.8 (2.70)^{a}	6.1 (2.57)	10.8 (3.36)^{a}	8.7 (3.03)^{a}	6.2 (2.59)^{ab}	4.6 (2.26)^{b}
T10 - Open pollination	2.1 (1.61)	3.2 (1.92)^{c}	3.6 (2.02)^{e}	4.5 (2.24)^{c}	3.2 (1.92)^{c}	4.1 (2.14)	6.4 (2.63)^{c}	5.0 (2.35)^{c}	3.2 (1.92)^{d}	2.9 (1.85)^{e}
GM	2.16	3.7	5.1	6.3	4.8	5.1	7.9	6.5	4.9	4.0
SE (m) ±	0.6	0.6	0.6	0.7	0.8	0.9	1.0	0.9	0.8	0.5
CD @5%	NS	1.7	1.8	2.0	2.3	NS	3.1	2.5	2.3	1.5
CV (%)	21.1	16.2	11.8	11.1	16.7	17.6	12.7	13.8	16.3	12.5

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed value.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

4.3.2.3 Pooled data (Rabi 2023-24 to Rabi 2024-25).

First spray bee attractant on activity of *A.dorsata* (Rabi 2023-24 to Rabi 2024-25).

Pollinator activity was documented the day prior to spraying (DBFS) and thereafter at one, three, five-, and seven-days post-spray (DAS). On the day preceding the initial spray, bee visitation rates were similar among treatments, ranging from 3.1 to 3.6, with no statistically significant differences observed. Subsequent to spraying, all treatments exhibited a gradual rise in bee visits, especially in the days post-application (Table 64).

Following the initial application, a significant rise in bee activity was noted, especially in areas treated with elevated concentrations of pomegranate juice and date extract. At 1 DAS, pomegranate juice at 20% concentration exhibited the maximum activity (6.0 bees/m²/5 min), statistically surpassing other treatments. Dates exhibited a 20% extraction rate (4.8 bees/m²/5 min) and pomegranate juice demonstrated a 15% extraction rate (3.5 bees/m²/5 min), both indicating heightened activity, but coconut water and the open pollinated control varied between 3.0 and 3.4 bees/m²/5 min.

At 3 DAS, bee activity significantly escalated in all attractant-treated plots, with T8 (20% pomegranate juice) exhibiting the highest bee density (6.5 bees/m²/5 min), succeeded by T9 (20% dates extract) (5.9 bees/m²/5 min). Treatments using T5 (15% pomegranate juice) and T6 (15% date extract) exhibited elevated activity levels (5.4–5.7 bees/m²/5 min), which were statistically equivalent. The coconut water series exhibited lower counts (4.1–5.0), statistically inferior to treatments with increasing concentrations of fruit extract.

On the fifth day post-application, bee visitation reached its zenith in T8 (20% pomegranate juice) at 8.4 bees/m²/5 min, greatly surpassing all other treatments. T9 (dates extract 20%) had an efficacy of 7.5 bees/m²/5 min, while T5 (pomegranate 15%) demonstrated a little lower efficacy of 7.4 bees/m²/5 min. Lower-concentration treatments (10–15%) exhibited moderate bee activity (4.6–5.7 bees/m²/5 min), whereas open pollination (control) recorded merely 3.6 bees/m²/5 min.

On 7 DAS, despite the onset of diminishing bee activity, all treatments exhibited a progressive reduction in foraging activity. However, T8 (7.2 bees/m²/5 min) and T9 (6.8 bees/m²/5 min) consistently exhibited considerably elevated bee counts compared to others, whilst the lowest count occurred under open pollination (3.2 bees/m²/5 min). The upward trend until 5 DAS, succeeded by a decline at 7 DAS, was uniform across all treatments, indicating the steady diminishment of attractant potency.

Second spray bee attractants on *A. dorsata* visitation in onion crop (Rabi 2023-24 to Rabi 2024-25).

Comparable observations were noted during the second spray cycle. Day Before Second Spray (DBSS) counts varied from 4.1 to 6.2 bees/m²/5 min, with 20% pomegranate juice exhibiting a modest advantage.

At 1 DAS, bee visitation considerably increased for plots treated with 20% pomegranate juice (11.4 bees/m²/5 min) and 20% date extract (10.8 bees/m²/5 min), markedly exceeding all other treatments. Coconut water at 10% concentration (6.7 bees/m²/5 min) and open pollination (6.4 bees/m²/5 min) had the lowest activity levels. These were statistically equivalent and significantly superior to all other therapies. Moderate counts were observed at median doses (pomegranate 15%, dates 15%, coconut water 20%) ranging from 7.0 to 7.6 bees/m²/5 min, whilst the lowest count of 6.4 was documented under open pollination.

At 3 DAS, pomegranate juice at 20% concentration (8.6 bees/m²/5 min) and date extract at 20% concentration (8.3 bees/m²/5 min) retained the advantage. All attractant treatments surpassed the control, demonstrating both numerical and statistical superiority. Medium- concentration attractants (15%) yielded 6.1–7.1 bees/m²/5 min, but 10% solutions and open pollination exhibited somewhat lower rates of 5.0–5.8 bees/m²/5 min.

On the fifth day, the same tendency continued. Pomegranate juice at 20% concentration (T8) consistently exhibited the largest bee population at 7.2 bees/m²/5 min, followed by dates extract at 20% concentration (T9) with 6.2 bees/m²/5 min. Moderate performance was observed in 15% level attractants (4.9–5.1 bees/m²/5 min). The open pollination plots once more documented the lowest visitation rate at 3.2 bees/m²/5 min.By 7 days after treatment, the quantity of bee visitors significantly diminished across all conditions. Nonetheless, Pomegranate juice at 20% T8 (5.7 bees/m²/5 min) and date extract at 20%T9 (4.6 bees/m²/5 min) exhibited superior levels compared to all other treatments, indicating a comparatively prolonged residual appeal. The control plots exhibited the lowest density at 2.9 bees/m²/5 min.

The trend demonstrated that higher concentrations of pomegranate juice and dates extract were superior attractants, maximizing pollinator activity primarily between 3 to 5 days after spraying, followed by a decline by day 7. These results confirm that using 20% pomegranate juice or dates extract effectively boosts pollinator visitation in onion seed crops, while coconut water provides a moderate increase. Open pollination without attractants attracts the least bee activity, underscoring the benefits of these treatments in promoting better pollination and potential yield improvement.

Table 64. Effect of bee attractant on activity of *Apis dorsata* in onion (Rabi 2023- 24 to 2024-25).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.15 (1.63)	3.0 (1.87)^{c}	4.5 (2.24)^{cd}	5.2 (2.38)^{c}	4.1 (2.15)^{b}	4.3 (2.20)	6.5 (2.65)^{c}	5.3 (2.40)^{c}	3.9 (2.09)^{c}	3.2 (1.93)^{d}
T2 - Pomegranate juice 10%	2.2 (1.66)	3.2 (1.93)^{c}	5.0 (2.35)^{bc}	5.4 (2.46)^{bc}	4.3 (2.19)^{b}	4.8 (2.30)	7.2 (2.77)^{bc}	5.7 (2.49)^{c}	4.5 (2.24)^{bc}	4.0 (2.11)^{c}
T3 - Dates extract 10%	2.0 (1.90)	3.1 (1.90)^{c}	4.6 (2.26)^{cd}	5.4 (2.42)^{c}	4.2 (2.17)^{b}	4.7 (2.28)	7.0 (2.75)^{bc}	5.6 (2.48)^{c}	4.3 (2.19)^{c}	3.7 (2.04)^{cd}
T4 - Coconut water 15%	2.1 (1.61)	3.0 (1.87)^{c}	4.6 (2.21)^{bc}	5.4 (2.43)^{c}	4.2 (2.19)^{b}	4.4 (2.25)	6.8 (2.66)^{bc}	5.4 (2.43)^{c}	4.2 (2.17)^{c}	3.5 (2.00)^{d}
T5 - Pomegranate juice 15%	2.3 (1.69)	3.4 (1.97)^{c}	5.2 (2.36)^{bc}	6.5 (2.77)^{a}	4.7 (2.26)^{b}	5.4 (2.42)	7.9 (2.87)^{b}	6.5 (2.71)^{b}	5.2 (2.36)^{bc}	3.3 (1.95)^{d}
T6 - Dates extract 15%	2.2 (1.64)	3.3 (1.95)^{c}	5.3 (2.40)^{bc}	6.0 (2.62)^{ab}	4.5 (2.24)^{b}	5.1 (2.37)	7.7 (2.84)^{b}	6.7 (2.69)^{b}	4.8 (2.30)^{bc}	4.2 (2.19)^{bc}
T7 - Coconut water 20%	2.1 (1.63)	3.3 (1.95)^{c}	4.3 (2.17)^{d}	5.5 (2.44)^{bc}	4.4 (2.22)^{b}	5.2 (2.40)	7.3 (2.79)^{bc}	6.0 (2.54)^{bc}	4.8 (2.30)^{bc}	4.1 (2.14)^{c}
T8 - Pomegranate juice 20%	2.3 (1.69)	5.9 (2.52)^{a}	6.4 (2.62)^{a}	8.2 (2.95)^{a}	7.1 (2.74)^{a}	6.1 (2.57)	11.1 (3.41)^{a}	8.6 (3.02)^{a}	7.2 (2.77)^{a}	5.6 (2.47)^{a}
T9 - Dates extract 20%	2.2 (1.66)	4.7 (2.28)^{b}	5.8 (2.50)^{ab}	7.0 (2.81)^{ab}	6.7 (2.68)^{a}	6.0 (2.55)	10.1 (3.17)^{a}	8.3 (2.88)^{a}	5.7 (2.49)^{ab}	4.4 (2.22)^{b}
T10 - Open pollination	2.1 (1.63)	3.2 (1.92)^{c}	3.5 (2.00)^{e}	3.8 (2.06)^{c}	3.1 (1.90)^{c}	3.5 (2.03)	4.4 (2.21)^{c}	4.0 (2.10)^{c}	3.0 (1.87)^{d}	2.6 (1.74)^{e}
GM	2.2	3.7	5.0	6.1	4.8	5.0	7.8	6.4	4.9	4.0
SE (m) ±	0.5	0.6	0.7	0.8	0.8	0.8	0.9	0.9	0.8	0.5
CD @5%	NS	1.6	1.7	1.8	2.0	NS	3.0	2.4	2.2	1.4
CV (%)	20.8	17.5	12.0	11.5	16.5	17.0	13.0	14.0	16.0	12.0

Figures in the parenthesis are √x + 0.5 transformed values
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

4.3.3 Influence of bee attractants on *A. cerana* visitation in onion crop.

4.3.3.1 First year (Rabi 2023-24)

Data pertaining to the effect of various bee attractants on visitation of *A. cerana* on onion flowers during *Rabi* 2023-24 have been presented below (Table 65).

First spray bee attractants on *A. cerana* visitation in onion crop (Rabi 2023-24).

One day prior to the initial attractant spray, Apis cerana activity shown no notable differences between treatments, with visitation rates fluctuating between 2.9 and 3.3 bees/m²/5 min. All attractants, including the control and each concentration of coconut water, pomegranate juice, and date extract, demonstrated statistical equivalence. This confirms that all plots began under uniform pollinator pressure, ensuring a reliable assessment of subsequent treatment effects.

One day after spray (DAS), Pomegranate juice at 20% exhibited the highest Apis cerana activity, averaging 6.00 bees/m²/5 min, greatly surpassing all other treatments. The minimal activity recorded in open pollination plots was 2.33 bees/m2/min, indicating restricted attraction in the absence of treatment. Moderate bee activity was observed in treatments including 10% pomegranate juice (3.96 bees/m²/5 min), 15% pomegranate juice (4.22 bees/m²/5 min), 15% date extract (4.00 bees/m²/5 min), and 20% coconut water (4.00), suggesting that these attractants facilitate bee foraging, albeit to a lesser degree than the 20% pomegranate treatment. The 20% dates extract (5.55 bees/m²/5 min) was statistically comparable to the highest, underscoring its significant attractant potential.

At 3 days after the initial spray, the pattern persisted, with 20% Pomegranate juice exhibiting the highest activity (6.36 bees/m2/min). Open pollination exhibited the minimal visitation rate (4.20 bees/m²/5 min). Various treatments, including 10% Pomegranate juice, 10% Dates extract, 15% Pomegranate juice, and 15% Dates extract, sustained moderate visitation rates of approximately 4.6 to 4.78 bees/m2/min. Dates extracted 20% (6.21 bees/m²/5 min) remained equivalent to the greatest value. Several coconut water and other treatments exhibited visitation rates approaching those of the lowest group throughout this span, suggesting fluctuating efficacy over time.

At 5 days after the first application, 20% pomegranate juice elicited the greatest visitation rate of 7.50 bees/m²/5 min, indicating a significant residual attractant impact. The minimal numbers were seen in open pollination (4.89 bees/m²/5 min). Moderate bee activity continued in treatments of 10% Pomegranate juice, 15% Dates extract, and 20% Coconut water, with visitation values between roughly 5.18 and 5.89 bees/m²/5 min.

The 20% extract of dates was once more on par with the leading performance, highlighting its relative effectiveness.

Seven days after the initial spray, bee visits reached their zenith with 20% Pomegranate juice (7.00 bees/m²/5 min), whereas open pollination recorded the lowest frequency (4.20 bees/m²/5 min). Moderate visitation was observed in Pomegranate juice 10%, Dates extract 10%, Coconut water 15%, and Dates extract 15%, indicating a steady decrease in activity from the peak treatments, although remaining superior to untreated circumstances.

Second spray bee attractants on *A. cerana* visitation in onion crop (Rabi 2023-24).

One day prior to the second spray (DBSS), no significant differences were observed among the treatments, with mean values ranging from 4.56 (T1 - Coconut water 10%) to 6.33 (T8 - Pomegranate juice 20%), in accordance with statistical equivalence (NS). These values created a consistent baseline for comparison after the second application of the attractant.

At 1 DAS, Pomegranate juice at 20% attracted the highest number of bees (6.33), whereas open pollination yielded the lowest (4.20). Pomegranate juice had moderate action at 10%, Dates extract at 15%, and Coconut water at 20%. The 20% Dates extract was statistically comparable to the highest treatment, while lower concentration treatments such as Coconut water 10%, Dates extract 10%, and Coconut water 15% were comparable to the lowest treatment.

At 3 days after the second application, 20% pomegranate juice exhibited the greatest bee visitation rate (8.04), far surpassing other treatments, hence demonstrating its potent and enduring attractant impact. Open pollination exhibited the least visitors, recording a value of 4.89. Dates extracted 20% remained equivalent to the greatest value. Coconut water and date extract treatments remained statistically comparable to the lowest results.

Five days after the second application, Pomegranate juice at 20% (7.63) and Dates extract at 20% (7.21) predominated in bee visitation counts, underscoring their continued effectiveness. Moderate values were seen in Coconut water at 10%, Pomegranate juice at 15%, Dates extract at 15%, and Coconut water at 20%. Open pollination was the least appealing option, scoring 4.20.

At 7 days after the second application, 20% pomegranate juice exhibited the greatest mean visitation rate (5.2), although a general decrease in bee activity at this later phase.

Table 65. Effect of bee attractant on activity of *Apis cerana* in onion (Rabi 2023- 24).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.67 (1.79)	3.67 (2.04)^{c}	4.22 (2.17)^{c}	5.20 (2.39)^{c}	5.00 (2.35)^{c}	4.10 (2.14)	4.56 (2.25)^{c}	5.11 (2.37)^{c}	5.50 (2.45)^{e}	3.0 (1.87)^{d}
T2 - Pomegranate juice 10%	2.89 (1.96)	3.96 (2.11)^{bc}	4.67 (2.27)^{bc}	5.56 (2.48)^{bc}	5.33 (2.41)^{c}	4.56 (2.25)	5.00 (2.35)^{c}	5.67 (2.48)^{cd}	5.33 (2.41)^{cd}	3.4 (1.98)^{bc}
T3 - Dates extract 10%	2.89 (1.96)	3.67 (2.04)^{c}	4.60 (2.26)^{bc}	5.28 (2.40)^{c}	5.30 (2.41)^{c}	4.22 (2.17)	4.67 (2.27)^{d}	5.33 (2.41)^{cd}	5.22 (2.39)^{cd}	3.3 (1.96)^{bc}
T4 - Coconut water 15%	2.78 (1.81)	3.44 (1.98)^{c}	4.56 (2.25)^{c}	5.18 (2.38)^{c}	5.22 (2.39)^{c}	4.11 (2.14)	4.44 (2.27)^{d}	5.00 (2.37)^{cd}	5.16 (2.37)^{e}	3.1 (1.90)^{bc}
T5 - Pomegranate juice 15%	3.11 (1.90)	4.22 (2.17)^{bc}	4.78 (2.30)^{bc}	5.89 (2.53)^{bc}	5.89 (2.53)^{bc}	5.11 (2.27)	5.56 (2.47)^{d}	7.21 (2.72)^{ab}	5.98 (2.37)^{c}	3.9 (2.10)^{d}
T6 - Dates extract 15%	3.0 (1.87)	4.00 (2.12)^{bc}	4.70 (2.28)^{bc}	5.82 (2.51)^{bc}	5.56 (2.46)^{c}	4.78 (2.46)	5.22 (2.39)^{d}	7.12 (2.71)^{ab}	5.56 (2.46)^{c}	4.0 (2.12)^{c}
T7 - Coconut water 20%	3.00 (1.87)	4.00 (2.12)^{bc}	4.57 (2.25)^{c}	5.78 (2.39)^{bc}	5.18 (2.38)^{c}	4.27 (2.17)	5.22 (2.39)^{d}	7.00 (2.70)^{ab}	5.44 (2.35)^{c}	4.0 (2.10)^{bc}
T8 - Pomegranate juice 20%	3.21 (1.90)	6.00 (2.55)^{a}	6.36 (2.62)^{a}	7.50 (2.83)^{a}	7.00 (2.74)^{a}	4.56 (2.26)	6.33 (2.61)^{a}	8.04 (2.92)^{a}	7.63 (2.85)^{a}	5.2 (2.38)^{a}
T9 - Dates extract 20%	3.22 (1.93)	5.55 (2.46)^{ab}	6.21 (2.51)^{ab}	7.01 (2.63)^{ab}	6.21 (2.51)^{b}	4.81 (2.27)	5.88 (2.52)^{ab}	7.98 (2.92)^{a}	7.21 (2.83)^{a}	4.9 (2.26)^{a}
T10 - Open pollination	3.20 (2.03)	2.33 (1.54)^{d}	4.20 (2.10)^{cd}	4.89 (2.08)^{d}	4.20 (2.10)^{d}	3.83 (2.03)	4.20 (2.07)^{d}	4.89 (2.08)^{d}	4.20 (2.07)^{d}	2.37 (1.57)^{d}
GM	3	4.1	4.8	5.8	5.6	4.7	5.1	6	5.6	3.7
SE (m) ±	0.4	0.6	0.4	0.6	0.5	0.3	0.4	0.7	0.6	0.6
CD @5%	NS	1.6	1.7	2	2.3	NS	1.6	2.3	1.7	1.5
CV (%)	25.1	26.2	16.1	15.8	15	26.7	12.9	17.5	19.9	19.7

Figures in the parenthesis are √x + 0.5 transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

The visitation for open pollination decreased to the lowest level of 2.37. Moderate activity was noted with 15% Pomegranate juice, 15% Dates extract, and 20% Coconut water. The 20% dates extract was statistically comparable to the highest treatment, whereas the 10% coconut water was identical to the lowest treatment.

Pomegranate juice at a 20% concentration consistently demonstrated the most robust and prolonged attraction to *Apis cerana* on onion blossoms during both the initial and subsequent spraying. The 20% date extract closely matched various intervals, demonstrating significant potential as a bee attractant. Moderate attraction was observed with intermediate quantities of pomegranate juice, date extract, and coconut water. Open pollination (without attractants) consistently exhibited the lowest rates of bee visits, highlighting the significance of these attractants in augmenting pollinator activity. These findings correspond with established effective pollination behaviours of *Apis cerana* in onion cultivation and illustrate the augmented pollination capacity by specific bee attractants, which can boost seed set and yield in onion seed production systems.

4.3.3.2 Second year (Rabi 2024-25).

First spray bee attractant on *Apis cerana* in onion (Rabi 2024-25)

DBFS All treatments exhibited comparable moderate bee densities, ranging from 2.85 to 3.55 bees/m²/5 min. No substantial difference was observed among treatments before the spray, indicating a consistent baseline of pollinator activity (Table 66).

Post-spray 1st Day after spray bee activity elevated in all attractant plots. The most pronounced effect was noted in T8 (20% Pomegranate juice, 6.39 bees/m²/5 min), T9 (20% Dates extract, 5.88 bees/m²/5 min), and T5 (15% Pomegranate juice, 4.49 bees/m²/5 min), all significantly exceeding the control (T10, 2.48 bees/m²/5 min) and lower concentrations. The results indicate that 20% and 15% concentrations produce superior attraction shortly after application.

3rd day after spray the bee population continued to rise, with T8 (6.78 bees/m²/5 min) and T9 (6.21 bees/m²/5 min) exhibiting the most substantial and statistically significant increases, followed by T5 (5.12 bees/m²/5 min) and T6 (5.03 bees/m²/5 min). Lower concentration treatments sustained moderate exercise levels.

5th day after spray maximum apian activity was observed with T8 (7.88 bees/m²/5 min), T9 (7.43 bees/m²/5 min), T5 (6.60 bees/m²/5 min), T6 (6.18 bees/m²/5 min), and T7 (6.15 bees/m²/5 min), corroborating the prolonged impact of elevated concentrations.

7th day after spray T8 (7.42 bees/m²/5 min), T9 (6.71 bees/m²/5 min), and T5 (6.24 bees/m²/5 min) had the highest bee counts. Lower concentration treatments exhibited slight to moderate enhancements.

Second spray bee attractant on *Apis cerana* in onion (Rabi 2024-25)

Day Before Second Spray Overall bee populations increased due to crop phenology, although concentration effects mirrored those observed after the first spray, with T8 and T9 exhibiting the highest counts (5.90 bees/m²/5 min, 5.76 bees/m²/5 min).

1 DAS The utilisation of attractants once more led to a swift increase in bee populations for T8 (6.74 bees/m²/5 min), T9 (6.25 bees/m²/5 min), and T5 (5.71 bees/m²/5 min). Lower concentration treatments exhibited limited efficacy.

3 DAS T8 (8.52 bees/m²/5 min), T9 (7.67 bees/m²/5 min), and T5 (7.08 bees/m²/5 min) exhibited markedly elevated bee populations, while T6 (6.52 bees/m²/5 min) and T7 (6.38 bees/m²/5 min) also demonstrated commendable performance. These therapies consistently ranked as the best or higher, as indicated by statistical groupings

5 DAS T8 (8.11), T9 (7.33), and T5 (7.05) exhibited the most pronounced attraction effects, hence corroborating the effectiveness of pomegranate and date extracts at elevated concentrations for prolonged pollinator attraction.

7 DAS Only T8 (5.51 bees/m²/5 min), T9 (4.89 bees/m²/5 min), and T5 (4.18 bees/m²/5 min) sustained above-average bee counts, while a minor decrease was seen, potentially attributable to attractant degradation or environmental alterations. T8 (20% Pomegranate juice) and T9 (20% Dates extract) consistently demonstrated the maximum bee activity over several days following both applications. T5 (Pomegranate juice 15%), T6 (Dates extract 15%), and T7 (Coconut water 20%) elicited moderate to high bee visitation, frequently exhibiting statistical similarity among themselves, although differing from the superior treatments (T8, T9). Coconut water at 10–15% (T1, T4), and pomegranate juice and date extract at 10% (T2, T3) yielded only moderate attractiveness in comparison. Exhibited the lowest bee activity consistently on the majority of days, not statistically comparable to any high-performing treatments.

Table 66. Effect of bee attractant on activity of *Apis cerana* in onion (Rabi 2024- 25).

Treatment	Number of bees/m2/5 min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.85 (1.83)	3.88 (2.09)^{bc}	4.48 (2.23)^{c}	5.55 (2.46)^{c}	5.28 (2.40)^{c}	4.35 (2.20)	4.82 (2.31)^{c}	5.41 (2.43)^{c}	5.85 (2.52)^{b}	3.24 (1.93)^{c}
T2 - Pomegranate juice 10%	3.07 (1.89)	4.21 (2.17)^{b}	4.96 (2.34)^{b}	6.02 (2.55)^{bc}	5.65 (2.48)^{bc}	4.83 (2.31)	5.31 (2.41)^{b}	6.08 (2.57)^{b}	5.66 (2.48)^{b}	3.67 (2.04)^{bc}
T3 - Dates extract 10%	3.09 (1.89)	3.92 (2.10)^{bc}	4.91 (2.33)^{b}	5.62 (2.47)^{bc}	5.62 (2.47)^{bc}	4.48 (2.23)	4.97 (2.34)^{c}	5.68 (2.49)^{bc}	5.53 (2.45)^{b}	3.53 (2.00)^{bc}
T4 - Coconut water 15%	2.98 (1.86)	3.69 (2.04)^{bc}	4.85 (2.31)^{b}	5.50 (2.45)^{c}	5.53 (2.46)^{bc}	4.38 (2.21)	4.93 (2.33)^{c}	5.53 (2.46)^{bc}	5.41 (2.43)^{b}	3.30 (1.95)^{c}
T5 - Pomegranate juice 15%	3.32 (1.95)	4.49 (2.23)^{b}	5.12 (2.37)^{b}	6.60 (2.66)^{b}	6.24 (2.60)^{b}	5.42 (2.43)	5.71 (2.49)^{b}	7.08 (2.76)^{a}	7.05 (2.75)^{a}	4.18 (2.16)^{b}
T6 - Dates extract 15%	3.21 (1.93)	4.28 (2.19)^{b}	5.03 (2.35)^{b}	6.18 (2.58)^{b}	5.89 (2.53)^{b}	5.07 (2.36)	5.58 (2.47)^{b}	6.52 (2.65)^{ab}	5.89 (2.53)^{b}	3.95 (2.11)^{b}
T7 - Coconut water 20%	3.19 (1.92)	4.26 (2.18)^{b}	4.88 (2.33)^{b}	6.15 (2.58)^{b}	5.77 (2.50)^{b}	4.94 (2.33)	5.55 (2.46)^{b}	6.38 (2.62)^{ab}	5.55 (2.46)^{b}	3.97 (2.11)^{b}
T8 - Pomegranate juice 20%	3.55 (2.01)	6.39 (2.63)^{a}	6.78 (2.70)^{a}	7.88 (2.90)^{a}	7.42 (2.82)^{a}	5.90 (2.53)	6.74 (2.69)^{a}	8.52 (3.01)^{a}	8.11 (2.94)^{a}	5.51 (2.45)^{a}
T9 - Dates extract 20%	3.41 (1.98)	5.88 (2.53)^{a}	6.21 (2.59)^{a}	7.43 (2.82)^{a}	6.71 (2.69)^{a}	5.76 (2.50)	6.25 (2.60)^{a}	7.67 (2.86)^{a}	7.33 (2.80)^{a}	4.89 (2.32)^{a}
T10 - Open pollination	3.39 (1.97)	2.48 (1.73)^{c}	4.22 (2.17)^{c}	4.40 (2.21)^{d}	5.18 (2.38)^{c}	4.02 (2.12)	4.61 (2.26)^{c}	5.19 (2.39)^{c}	4.26 (2.18)^{c}	3.20 (1.92)^{c}
GM	3.21	4.35	5.14	6.13	5.93	4.91	5.45	6.4	6.06	3.94
SE (m) ±	0.45	0.72	0.45	0.59	0.35	0.75	0.42	0.68	0.78	0.35
CD @5%	NS	2.15	1.45	1.77	1.12	NS	1.26	2.04	2.14	1.13
CV (%)	14.02	16.55	8.75	9.62	5.90	15.27	7.71	10.63	12.87	8.88

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Pooled data (Pooled data (Rabi 2023-24 to Rabi 2024-25).

First spray bee attractant on *Apis cerana* in onion (Rabi 2023 - 24- 2025)

Day Prior to Initial Application the day prior to the initial spray, all treatments demonstrated moderate *Apis cerana* activity (2.76–3.38 bees/m²/5 min), with T8 (20% Pomegranate juice) and T9 (20% Dates extract) achieving the highest bee visitation rates (3.38 and 3.32, respectively), whereas Coconut water 10% (T1) and open pollination (T10) recorded the lowest rates (2.76 and 3.30). Most alternative treatments exhibited medium values, approximately 3.1–3.22 bees/m²/5 min, with numerous results being statistically comparable (Table no 67).

First Day Following Initial Application on the initial day post-application, T8 (20% Pomegranate juice) exhibited the highest bee activity (6.2 bees/m²/5 min), markedly surpassing all other treatments. T9 (Dates extract 20%) and T5 (Pomegranate juice 15%) exhibited elevated values (5.72 bees/m²/5 min and 4.36 bees/m²/5 min), whilst open pollination (T10) recorded the lowest value (2.41 bees/m²/5 min). The moderate range included therapies such as T2, T3, T4, T6, and T7 (3.8–4.36), with comparable values prevalent among moderate and medium treatments.

On the third day, T8 and T9 exhibited the greatest visitor rates (6.57 bees/m²/5 min and 6.21 bees/m²/5 min), whereas T1, T3, T4, T5, T6, and T7 demonstrated moderate to medium bee activity (4.7–4.95). Open pollination (T10) exhibited the lowest performance (4.21 bees/m²/5 min), statistically comparable to the least effective treatments.

The fifth day was the apex of foraging, with T8 (7.69 bees/m²/5 min) and T9 (7.22 bees/m²/5 min) as the highest, succeeded by T5 and T6 (6.24 bees/m²/5 min and 6.0 bees/m²/5 min, moderate), while other treatments fell within medium ranges (4.35 bees/m²/5 min –5.38 bees/m²/5 min). Open pollination (T10) exhibited the lowest value (4.64 bees/m²/5 min), with numerous treatments showing statistically comparable results.

Seven days post-application, T8 (7.21 bees/m²/5 min) and T9 (6.46 bees/m²/5 min) retained their superior rankings, while the majority of other attractant treatments exhibited medium to moderate values (5.14 bees/m²/5 min –6.06 bees/m²/5 min). Open pollination (T10) recorded the lowest value at 4.69. A group of moderate-value treatments (T3–T7) were equivalent.

Table 67. Effect of bee attractant on activity of *Apis cerana* in onion (Rabi 2023-24 to Rabi 2024-25).

Treatment	Number of bees/m2/ 5min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.76 (1.81)	3.78 (2.07)^{c}	4.35 (2.20)^{c}	5.38 (2.42)^{c}	5.14 (2.37)^{c}	4.22 (2.17)	4.69 (2.28)^{c}	5.26 (2.40)^{c}	5.68 (2.49)^{c}	3.12 (1.90)^{d}
T2 - Pomegranate juice 10%	2.98 (1.87)	4.08 (2.14)^{bc}	4.81 (2.30)^{bc}	5.79 (2.51)^{bc}	5.49 (2.45)^{c}	4.70 (2.28)	5.15 (2.38)^{c}	5.88 (2.53)^{c}	5.50 (2.45)^{c}	3.54 (2.01)^{bc}
T3 - Dates extract 10%	2.99 (1.87)	3.80 (2.07)^{bc}	4.76 (2.29)^{bc}	5.45 (2.44)^{bc}	5.46 (2.44)^{c}	4.35 (2.20)	4.82 (2.31)^{d}	5.50 (2.45)^{d}	5.38 (2.42)^{d}	3.42 (1.98)^{bc}
T4 - Coconut water 15%	2.88 (1.84)	3.56 (2.01)^{bc}	4.70 (2.28)^{c}	5.34 (2.42)^{c}	5.38 (2.42)^{c}	4.24 (2.18)	4.69 (2.28)^{d}	5.26 (2.40)^{d}	5.28 (2.40)^{d}	3.20 (1.92)^{bc}
T5 - Pomegranate juice 15%	3.22 (1.93)	4.36 (2.20)^{bc}	4.95 (2.33)^{bc}	6.24 (2.60)^{bc}	6.06 (2.56)^{c}	5.26 (2.40)	5.64 (2.48)^{d}	7.14 (2.76)^{c}	6.52 (2.65)^{c}	4.04 (2.13)^{d}
T6 - Dates extract 15%	3.10 (1.90)	4.14 (2.15)^{bc}	4.86 (2.32)^{bc}	6.00 (2.55)^{bc}	5.72 (2.49)^{c}	4.93 (2.33)	5.40 (2.43)^{d}	6.82 (2.71)^{c}	5.72 (2.49)^{c}	3.98 (2.12)^{c}
T7 - Coconut water 20%	3.10 (1.90)	4.13 (2.15)^{bc}	4.72 (2.28)^{c}	5.96 (2.54)^{c}	5.48 (2.45)^{c}	4.61 (2.26)	5.38 (2.42)^{d}	6.69 (2.68)^{c}	5.50 (2.45)^{c}	3.99 (2.12)^{bc}
T8 - Pomegranate juice 20%	3.38 (1.97)	6.20 (2.59)^{a}	6.57 (2.66)^{a}	7.69 (2.86)^{a}	7.21 (2.78)^{a}	5.23 (2.39)	6.54 (2.65)^{a}	8.28 (2.96)^{a}	7.87 (2.89)^{a}	5.36 (2.42)^{a}
T9 - Dates extract 20%	3.32 (1.95)	5.72 (2.49)^{ab}	6.21 (2.59)^{ab}	7.22 (2.78)^{b}	6.46 (2.64)^{a}	5.28 (2.40)	6.06 (2.56)^{a}	7.82 (2.88)^{a}	7.27 (2.79)^{a}	4.89 (2.32)^{a}
T10 - Open pollination	3.30 (1.95)	2.41 (1.71)^{d}	4.21 (2.17)^{cd}	4.64 (2.27)^{cd}	4.69 (2.28)^{d}	3.92 (2.10)	4.40 (2.21)^{d}	5.04 (2.35)^{d}	4.23 (2.17)^{d}	2.78 (1.81)^{d}
GM	3.10	4.22	5.02	5.97	5.71	4.68	5.28	6.37	5.89	3.83
SE (m) ±	0.06	0.34	0.24	0.29	0.23	0.15	0.21	0.36	0.33	0.25
CD @5%	NS	0.68	0.48	0.57	0.45	NS	0.42	0.73	0.67	0.51
CV (%)	6.51	25.36	15.23	15.19	12.50	10.46	12.69	18.04	17.87	20.96

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Second spray bee attractant on *Apis cerana* in onion (Rabi 2023 - 24- 2025)

On this pre-spray day, most treatments had moderate bee activity (4.22 bees/m²/5 min – 4.93 bees/m²/5 min), with T5-T9 and T8 showing the highest (5.23 bees/m²/5 min – 5.28 bees/m²/5 min), and Coconut water 10% (T1) and open pollination (T10) registering the lowest (4.22 bees/m²/5 min and 3.92 bees/m²/5 min). Other treatments maintained medium to at-par levels.

First initial day following the second application exhibited a significant response: T8 (6.54 bees/m²/5 min) and T9 (6.06 bees/m²/5 min) recorded the highest values, but the majority of other treatments (T1–T7) aggregated within a moderate range (4.69 bees/m²/5 min – 5.64 bees/m²/5 min). T10 (open pollination) recorded the lowest value at 4.4 bees/m²/5 min. medium treatments exhibited statistically equivalent outcomes.

Third Day Post Second Spray Pomegranate juice at 20% (T8, 8.28 bees/m²/5 min) and date extract at 20% (T9, 7.82 bees/m²/5 min) exhibited the highest activity by a significant margin. T5-T7 (6.69–7.14) exhibited moderate values, while T1-T4 grouped in the mid-range (5.04–5.64). The control T10 exhibited the lowest activity (5.04 bees/m²/5 min), comparable to other mild treatments.

Fifth Day Post Second Spray Elevated activity levels continued in T8 (7.87 bees/m²/5 min) and T9 (7.27 bees/m²/5 min). Moderate activity (6.52 – 6.82 bees/m²/5 min) was observed in the T5-T7 region. Values ranging from 4.23 bees/m²/5 min to 5.68 bees/m²/5 min were observed for T1-T4 and T10, with multiple treatments exhibiting statistical equivalence.

Seventh Day Post Second Spray on the seventh day following the second application, the treatment rankings were consistent: T8 (5.36 bees/m²/5 min) and T9 (4.89 bees/m²/5 min) were the highest, most others were moderate (3.12–4.04 bees/m²/5 min), while open pollination (T10) was the lowest (2.78 bees/m²/5 min). Moderate and medium treatments (T1–T7) were largely comparable.

The greatest bee visitation and pollination activity occurred with 20% pomegranate juice (T8) and 20% date extract (T9) throughout all days and applications. Moderate to medium activity was characteristic of coconut water and lower concentration treatments, while open pollination consistently produced the lowest results. Multiple treatments exhibited statistically comparable efficacy over the observation period, indicating similar effectiveness among those groups.

4.3.4 Influence of bee attractants on *A. florea* visitation in onion crop.

4.3.4.1 First year (Rabi 2023-24).

First spray bee attractants on *A. florea* visitation in onion crop (Rabi 2023-24).

Days Prior to Flowering Commencement the average activity of *Apis florea* (Table 68) varied from 2.67 to 3.33 bees/m²/5 min across different treatments. The highest foraging was observed in date extract at 20% (3.33), whilst coconut water at 10% (2.67) exhibited the lowest count. The treatments were statistically equivalent, suggesting consistent bee activity before spraying.

One Day Post-Spray a varied response was noted across treatments, ranging from 3.00 (dates extract 10%, open pollination) to 6.00 (pomegranate juice 20%). The most bee visits were observed in 20% pomegranate juice (6.00), followed by 20% date extract (5.67), and 15% pomegranate juice (5.33). Open pollination and 10% coconut water exhibited the lowest activity, both recording a value of 3.00. Marked disparities were apparent (CD=1.07).

Three Days Post-Spray bee activity significantly increased, with pomegranate juice at 20% (9.00 bees/m²/5 min) and date extract at 20% (8.67) exhibiting the highest visitation rates, both statistically superior to other treatments. Pomegranate juice at 15% and date extract at 15% also elicited significant bee activity (8.33, 8.00). Coconut water at 10% concentration exhibited moderate activity (5.67). The minimum count of 5.00 was observed in open pollination plots (CD=2.28).

Five Days Post Spray Maximum foraging was seen in pomegranate juice at 20% (10.33), dates extract at 20% (9.32), and pomegranate juice at 15% (10.00), with these values considerably exceeding those of other treatments (CD=1.93). All attractant treatments enhanced bee visitation compared to open pollination (5.00 bees/m²/5 min).

Seven Days Post-Spray Foraging activity diminished; nevertheless, pomegranate juice at 20% (7.92 bees/m²/5 min) and date extract at 20% (6.18 bees/m²/5 min) maintained statistical superiority over other treatments. The lowest bee counts were seen with 10% coconut water (5.00 bees/m²/5 min) and open pollination (4.28 bees/m²/5 min).

Second spray bee attractants on *A. florea* visitation in onion crop (Rabi 2023-24).

Days Prior to second application bee activity was similar across treatments, varying from 7.00 (coconut water 10%) to 8.89 (pomegranate juice 20%). Pomegranate juice and date extract each have the highest concentrations at 20% (8.89 bees/m²/5 min, 8.56 bees/m²/5 min), while coconut water at 10% demonstrates the lowest concentration (7.00 bees/m²/5 min). The variations were not statistically significant.

Table 68. Effect of bee attractant on activity of *Apis florea* in onion (Rabi 2023-24).

Treatment	Number of bees/m2/5 min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.67 (1.78)	3.34 (1.96)^{c}	5.67 (2.48)^{c}	7.12 (2.76)^{c}	5.00 (2.35)^{d}	7.00 (2.74)	6.00 (2.55)^{c}	4.89 (2.53)^{d}	4.70 (2.32)^{d}	3.89 (2.10)^{d}
T2 - Pomegranate juice 10%	2.78 (1.81)	4.00 (2.12)^{bc}	6.33 (2.61)^{bc}	7.90 (2.90)^{bc}	5.90 (2.35)^{c}	7.44 (2.82)	6.44 (2.65)^{bc}	6.00 (2.51)^{c}	5.78 (2.51)^{c}	4.33 (2.20)^{bc}
T3 - Dates extract 10%	3.00 (1.87)	3.89 (2.10)^{c}	6.00 (2.55)^{c}	7.50 (2.83)^{c}	5.46 (2.44)^{bc}	7.22 (2.78)	6.22 (2.59)^{c}	6.50 (2.61)^{c}	5.46 (2.39)^{bc}	4.00 (2.12)^{bc}
T4 - Coconut water 15%	2.89 (1.84)	3.78 (2.07)^{c}	6.00 (2.55)^{c}	7.20 (2.77)^{c}	5.22 (2.39)^{bc}	7.11 (2.76)	6.11 (2.57)^{c}	5.89 (2.36)^{c}	5.00 (2.33)^{bc}	4.11 (2.15)^{bc}
T5 - Pomegranate juice 15%	3.11 (1.90)	5.33 (2.42)^{ab}	8.33 (2.97)^{ab}	10.00 (3.16)^{ab}	7.00 (2.74)^{bc}	8.44 (2.99)	7.23 (2.83)^{ab}	7.00 (2.84)^{bc}	6.33 (2.54)^{c}	4.00 (2.13)^{bc}
T6 - Dates extract 15%	3.22 (1.93)	4.67 (2.27)^{bc}	8.00 (2.92)^{ab}	9.00 (3.00)^{ab}	5.67 (2.35)^{c}	8.11 (2.93)	7.00 (2.77)^{ab}	6.44 (2.63)^{bc}	5.67 (2.37)^{bc}	4.11 (2.15)^{bc}
T7 - Coconut water 20%	3.00 (1.87)	4.22 (2.17)^{bc}	7.67 (2.88)^{bc}	9.00 (3.00)^{bc}	6.20 (2.59)^{bc}	7.67 (2.87)	6.67 (2.84)^{c}	6.64 (2.63)^{bc}	5.82 (2.41)^{c}	4.15 (2.16)^{bc}
T8 - Pomegranate juice 20%	3.16 (1.91)	6.00 (2.55)^{a}	9.00 (3.08)^{a}	10.33 (3.29)^{a}	7.92 (2.90)^{a}	8.89 (3.06)	9.00 (3.08)^{a}	8.33 (2.97)^{a}	8.42 (2.99)^{a}	6.00 (2.55)^{a}
T9 - Dates extract 20%	3.33 (1.96)	5.67 (2.48)^{ab}	8.67 (3.03)^{ab}	9.32 (3.13)^{ab}	6.18 (2.58)^{a}	8.56 (3.01)	8.00 (2.90)^{a}	7.65 (2.60)^{a}	6.85 (2.86)^{a}	5.00 (2.49)^{a}
T10 - Open pollination	3.00 (1.87)	3.00 (1.73)^{d}	5.00 (2.35)^{c}	5.00 (2.35)^{d}	4.28 (2.09)^{d}	6.78 (2.60)	5.00 (2.24)^{d}	4.54 (2.13)^{d}	4.11 (1.89)^{d}	3.00 (1.78)^{d}
GM	3.01	4.31	7.08	7.97	6	7.72	7.05	6.6	5.98	4.35
SE (m) ±	0.41	0.47	0.85	0.72	0.59	0.61	0.58	0.82	0.63	0.29
CD @5%	NS	1.07	2.28	1.93	1.58	1.41	1.35	1.92	1.47	0.64
CV (%)	23.54	18.46	20.79	15.52	18.39	21.23	15.26	16.81	23.95	21.01

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

On the first day following the second spray, significant increases in bee activity were seen, with pomegranate juice at 20% (9.00 bees/m²/5 min) leading, followed by dates extract at 20% (8.00), pomegranate juice at 15% (7.23 bees/m²/5 min), and dates extract at 15% (7.00 bees/m²/5 min). Coconut water at 10% and open pollination yielded the lowest results (6.00 bees/m²/5 min, 5.00 bees/m²/5 min).

Three days post spray optimal bee activity was sustained by 20% pomegranate juice (8.33 bees/m²/5 min), 20% date extract (7.65 bees/m²/5 min), and 15% pomegranate juice (7.00 bees/m²/5 min), all statistically superior to alternative treatments. Open pollination was the least appealing option, scoring 4.54 bees/m²/5 min.

Five days post spray bee visitation gradually reduced but remained highest in pomegranate juice 20% (8.42 bees/m²/5 min), dates extract 20% (6.85 bees/m²/5 min), and pomegranate juice 15% (6.33 bees/m²/5 min). Coconut water 10% and open pollination again showed lower activity (4.70 bees/m²/5 min, 4.11 bees/m²/5 min).

7 DAS on the seventh day after the second spray, bee activity continued to fall, with pomegranate juice 20% (6.00 bees/m²/5 min) retaining superiority, followed by dates extract 20% (5.00 bees/m²/5 min) and coconut water treatments (4.11-4.15 bees/m²/5 min). Open pollination was lowest (3.00 bees/m²/5 min).

Across all observation points, pomegranate juice 20% and dates extract 20% consistently recorded the highest *Apis florea* activity, especially from 3 to 5 days after each spray. Lower concentrations and coconut water treatments were less effective, while open pollination always resulted in the lowest bee visitation.

4.3.4.2 Second year (*Rabi* 2024-25)

The effect of different bee attractants on the activity of Apis florea in onion during the Rabi 2024-25 season was systematically evaluated by recording the number of bees per m² per minute at various intervals before and after the first and second sprays. The results reveal significant differences in bee activity across treatments, with pomegranate juice and dates extract emerging as the most effective attractants, especially at higher concentrations (Table 69).

First Spray bee attractants on *A. florea* visitation in onion crop (Rabi 2024-25).

At this stage, bee activity was relatively low across all treatments, reflecting the baseline foraging behavior prior to attractant application.

Table 69. Effect of bee attractant on activity of *Apis florea* in onion (Rabi 2024-25).

	Number of bees/m2/5 min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.82 (1.82)	3.48 (1.99)^{c}	5.88 (2.53)^{c}	6.98 (2.73)^{bc}	5.18 (2.38)^{c}	7.21 (2.78)	6.22 (2.59)^{cd}	6.05 (2.56)^{c}	4.98 (2.34)^{c}	3.95 (2.11)^{cd}
T2 - Pomegranate juice 10%	2.92 (1.84)	4.18 (2.16)^{bc}	6.58 (2.67)^{bc}	8.12 (2.94)^{b}	6.15 (2.58)^{b}	7.72 (2.87)	6.72 (2.69)^{bcd}	6.77 (2.70)^{bc}	5.95 (2.54)^{bc}	4.55 (2.24)^{bc}
T3 - Dates extract 10%	3.12 (1.90)	4.02 (2.13)^{bc}	6.25 (2.60)^{bc}	7.38 (2.81)^{b}	5.68 (2.49)^{bc}	7.45 (2.82)	6.45 (2.64)^{bcd}	6.55 (2.66)^{bc}	5.42 (2.43)^{c}	4.18 (2.16)^{c}
T4 - Coconut water 15%	3.05 (1.88)	3.92 (2.10)^{bc}	6.22 (2.59)^{bc}	7.42 (2.82)^{b}	5.38 (2.42)^{bc}	7.32 (2.80)	6.32 (2.61)^{bcd}	6.08 (2.57)^{c}	5.18 (2.38)^{c}	4.28 (2.19)^{c}
T5 - Pomegranate juice 15%	3.25 (1.94)	5.58 (2.47)^{ab}	8.65 (3.02)^{ab}	8.92 (3.07)^{ab}	7.28 (2.79)^{a}	8.75 (3.04)	7.82 (2.89)^{ab}	7.88 (2.90)^{ab}	6.58 (2.67)^{b}	4.12 (2.15)^{c}
T6 - Dates extract 15%	3.38 (1.97)	4.85 (2.31)^{b}	8.28 (2.96)^{ab}	8.62 (3.02)^{ab}	6.92 (2.73)^{ab}	8.42 (2.98)	7.38 (2.81)^{bc}	7.25 (2.78)^{b}	6.32 (2.61)^{bc}	5.28 (2.40)^{ab}
T7 - Coconut water 20%	3.15 (1.91)	4.38 (2.21)^{b}	7.95 (2.91)^{ab}	8.22 (2.95)^{b}	6.42 (2.63)^{b}	7.95 (2.91)	6.92 (2.73)^{bc}	6.68 (2.68)^{bc}	6.12 (2.57)^{bc}	4.72 (2.28)^{bc}
T8 - Pomegranate juice 20%	3.32 (1.95)	6.25 (2.60)^{a}	9.35 (3.14)^{a}	10.72 (3.35)^{a}	8.22 (2.95)^{a}	9.25 (3.12)	9.38 (3.14)^{a}	8.68 (3.03)^{a}	8.75 (3.04)^{a}	6.25 (2.60)^{a}
T9 - Dates extract 20%	3.48 (1.99)	5.92 (2.54)^{a}	9.02 (3.09)^{a}	9.68 (3.19)^{a}	6.42 (2.63)^{b}	8.88 (3.06)	8.88 (3.06)^{a}	6.48 (2.65)^{bc}	7.98 (2.91)^{a}	5.92 (2.54)^{a}
T10 - Open pollination	3.12 (1.90)	3.12 (1.90)^{c}	5.18 (2.38)^{c}	6.42 (2.63)^{c}	4.45 (2.22)^{c}	7.02 (2.75)	4.72 (2.28)^{d}	4.72 (2.28)^{d}	4.25 (2.18)^{d}	3.12 (1.90)^{d}
GM	3.16	4.57	7.34	8.25	6.21	8	7.08	6.71	6.15	4.64
SE (m) ±	0.42	0.49	0.88	0.75	0.66	0.98	0.62	0.65	0.84	0.56
CD @5%	NS	1.44	2.58	2.2	1.94	NS	1.82	1.91	2.46	1.64
CV (%)	13.29	10.72	11.99	9.09	10.63	12.25	8.76	9.69	13.66	12.07

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

The highest activity was observed in the Dates extract 20% treatment (3.48 bees/m²/5 min), followed by Pomegranate juice 20% (3.32) and Dates extract 15% (3.38). Coconut water treatments showed moderate activity, with Coconut water 10% recording the lowest count (2.82). The open pollination control had 3.12 bees/m²/5 min, indicating that natural attractants alone were insufficient to stimulate high bee visitation.

Immediately after the first spray, there was a noticeable increase in bee activity, especially in treatments with pomegranate juice and dates extract. Pomegranate juice 20% recorded the highest activity (6.25 bees/m²/5 min), followed by Dates extract 20% (5.92) and Pomegranate juice 15% (5.58). Coconut water treatments showed moderate increases, with Coconut water 20% reaching 4.38. The open pollination control remained low at 3.12 bees/m²/5 min, highlighting the limited natural attraction of onion flowers without external attractants.

By the third day, bee activity peaked in several treatments. Pomegranate juice 20% achieved the highest count (9.35 bees/m²/5 min), closely followed by Dates extract 20% (9.02) and Pomegranate juice 15% (8.65). Dates extract 15% also showed high activity (8.28). Coconut water treatments were less effective, with Coconut water 20% reaching 7.95. The open pollination control had only 5.18 bees/m²/5 min, underscoring the importance of attractants in enhancing bee visitation.

At this stage, Pomegranate juice 20% continued to dominate with 10.72 bees/m²/5 min, followed by Dates extract 20% (9.68) and Pomegranate juice 15% (8.92). Dates extract 15% and Coconut water 20% showed moderate activity (8.28 and 8.22, respectively). The open pollination control had 6.42 bees/m²/5 min, indicating that attractants significantly boosted bee activity compared to natural conditions.

By the seventh day, bee activity began to decline but remained higher in attractant treatments. Pomegranate juice 20% recorded 8.22 bees/m²/5 min, followed by Dates extract 15% (6.42) and Pomegranate juice 15% (7.28). Coconut water treatments showed moderate activity, with Coconut water 20% at 6.42. The open pollination control had the lowest activity at 4.45 bees/m²/5 min, demonstrating the sustained effect of attractants on bee visitation.

Second Spray bee attractants on *A. florea* visitation in onion crop (Rabi 2024-25).

Prior to the second spray, bee activity was generally higher than before the first spray, reflecting increased floral resources. Pomegranate juice 20% recorded the highest activity (9.25 bees/m²/5 min), followed by Dates extract 20% (8.88) and Pomegranate juice 15% (8.75). Coconut water treatments showed moderate activity, with Coconut water 20% at 7.95.

The open pollination control had 7.02 bees/m²/5 min, indicating some natural attraction but still lower than attractant treatments.

Immediately after the second spray, bee activity surged in attractant treatments. Pomegranate juice 20% achieved the highest count (9.38 bees/m²/5 min), followed by Dates extract 20% (8.88) and Pomegranate juice 15% (8.75). Dates extract 15% and Coconut water 20% showed moderate increases (7.38 and 7.95, respectively). The open pollination control had 7.02 bees/m²/5 min, highlighting the limited natural attraction of onion flowers.

By the third day, Pomegranate juice 20% maintained the highest activity (8.68 bees/m²/5 min), closely followed by Pomegranate juice 15% (7.88) and Dates extract 15% (7.38).

Dates extract 20% and Coconut water 20% showed moderate activity (6.48 and 6.68, respectively). The open pollination control had 4.72 bees/m²/5 min, indicating that attractants significantly enhanced bee visitation.

At this stage, Pomegranate juice 20% continued to dominate with 8.75 bees/m²/5 min, followed by Dates extract 20% (7.98) and Pomegranate juice 15% (6.58). Dates extract 15% and Coconut water 20% showed moderate activity (6.32 and 6.12, respectively). The open pollination control had 4.25 bees/m²/5 min, demonstrating the sustained effect of attractants on bee activity.

By the seventh day, bee activity began to decline but remained higher in attractant treatments. Pomegranate juice 20% recorded 6.25 bees/m²/5 min, followed by Dates extract 20% (5.92) and Pomegranate juice 15% (4.12). Dates extract 15% and Coconut water 20% showed moderate activity (5.28 and 4.72, respectively). The open pollination control had the lowest activity at 3.12 bees/m²/5 min, underscoring the importance of attractants in sustaining bee visitation.

4.3.4.3 Pooled data (Pooled data (Rabi 2023-24 to Rabi 2024-25).

The table shows the pooled effect of different bee attractants on the activity of *Apis florea* in onion over two consecutive Rabi seasons (2023-24 and 2024-25), measured in number of bees per m² per minute at various intervals relative to the first spray (at 15% flowering) and second spray (at 50% flowering). Values in parentheses are square root plus 0.5 transformed ($\sqrt{x} + 0.5$) means, and letters indicate statistical grouping from DMRT (p=0.05) (Table no.70).

Table 70. Effect of bee attractant on activity of *Apis florea* in onion (Rabi 2023-24 to Rabi 2024-25).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	2.75 (1.87)	3.41 (2.00)^{d}	5.78 (2.51)^{d}	7.05 (2.71)^{d}	5.09 (2.38)^{d}	7.11 (2.77)	6.11 (2.58)^{d}	5.47 (2.56)^{d}	4.84 (2.33)^{d}	3.92 (2.13)^{d}
T2 - Pomegranate juice 10%	2.85 (1.88)	4.09 (2.14)^{c}	6.46 (2.63)^{c}	8.01 (2.88)^{c}	6.03 (2.40)^{c}	7.58 (2.83)	6.58 (2.69)^{c}	6.39 (2.67)^{c}	5.87 (2.54)^{c}	4.44 (2.22)^{c}
T3 - Dates extract 10%	3.06 (1.91)	3.96 (2.13)^{d}	6.13 (2.60)^{cd}	7.44 (2.79)^{cd}	5.57 (2.39)^{cd}	7.34 (2.80)	6.34 (2.65)^{c}	6.52 (2.68)^{bc}	5.44 (2.39)^{cd}	4.09 (2.16)^{c}
T4 - Coconut water 15%	2.97 (1.89)	3.85 (2.12)^{d}	6.11 (2.60)^{cd}	7.31 (2.80)^{cd}	5.30 (2.38)^{cd}	7.22 (2.78)	6.22 (2.62)^{d}	5.99 (2.59)^{d}	5.09 (2.36)^{cd}	4.20 (2.17)^{c}
T5 - Pomegranate juice 15%	3.18 (1.92)	5.46 (2.44)^{a}	8.49 (3.02)^{a}	9.46 (3.11)^{a}	7.14 (2.81)^{b}	8.60 (3.05)	7.53 (2.90)^{ab}	7.44 (2.91)^{ab}	6.46 (2.66)^{b}	4.06 (2.15)^{c}
T6 - Dates extract 15%	3.30 (1.94)	4.76 (2.27)^{b}	8.14 (3.00)^{ab}	8.81 (3.06)^{ab}	6.30 (2.64)^{bc}	8.27 (3.00)	7.19 (2.81)^{bc}	6.85 (2.74)^{bc}	6.00 (2.61)^{bc}	4.70 (2.40)^{ab}
T7 - Coconut water 20%	3.08 (1.91)	4.30 (2.19)^{bc}	7.81 (2.95)^{bc}	8.61 (3.00)^{bc}	6.31 (2.63)^{bc}	7.81 (2.91)	6.80 (2.74)^{c}	6.66 (2.70)^{bc}	5.97 (2.57)^{bc}	4.44 (2.22)^{c}
T8 - Pomegranate juice 20%	3.24 (1.94)	6.13 (2.57)^{a}	9.18 (3.12)^{a}	10.53 (3.31)^{a}	8.07 (2.97)^{a}	9.07 (3.14)	9.19 (3.12)^{a}	8.51 (3.03)^{a}	8.59 (3.04)^{a}	6.13 (2.57)^{a}
T9 - Dates extract 20%	3.41 (1.95)	5.80 (2.52)^{ab}	8.85 (3.06)^{ab}	9.50 (3.11)^{ab}	6.30 (2.66)^{bc}	8.72 (3.07)	8.44 (2.95)^{ab}	7.07 (2.70)^{bc}	7.42 (2.90)^{ab}	5.46 (2.54)^{ab}
T10 - Open pollination	3.06 (1.91)	3.06 (1.91)^{d}	5.09 (2.41)^{d}	5.71 (2.63)^{d}	4.37 (2.24)^{d}	6.90 (2.68)	4.86 (2.30)^{d}	4.49 (2.28)^{d}	4.18 (2.23)^{d}	3.06 (1.91)^{d}
GM	3.09	4.71	7.40	8.23	6.19	7.86	7.06	6.66	6.01	4.50
SE (m) ±	0.42	0.48	0.87	0.74	0.63	0.79	0.60	0.74	0.74	0.48
CD @5%	NS	1.26	2.42	2.10	1.80	NS	1.76	2.32	2.34	1.52
CV (%)	13.30	14.60	16.10	11.90	12.40	13.60	9.70	11.10	12.30	10.70

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

First spray bee attractant on activity of *Apis florea* in onion (Rabi 2023-24 to Rabi 2024-25).

At one day before the first spray (DBFS), bee activity was relatively moderate to low across treatments, ranging from 2.75 bees/m²/5 min in Coconut water 10% (T1) to 3.41 bees/m²/5 min in Dates extract 20% (T9), with open pollination (T10) at 3.06 bees/m²/5 min. Transformed values and statistical analysis grouped most treatments similarly, except stronger attractants such as pomegranate and dates extract at 15-20%, indicating slightly higher baseline activity in these plots.

At 1 day after spraying (1 DAS), bee visits increased notably with Pomegranate juice 20% (T8) showing the highest mean of 6.13 bees/m²/5 min, closely followed by Dates extract 20% (T9) at 5.80 bees/m²/5 min and Pomegranate juice 15% (T5) at 5.46 bees/m²/5 min, both statistically superior to lower concentration and control treatments. The lowest activity was recorded in open pollination (T10) with only 3.06 bees/m²/5 min.

By 3 days after spraying (3 DAS), there was a clear peak in bee activity for the stronger attractants: Pomegranate juice 20% (T8) had 9.18 bees/m²/5 min, Dates extract 20% (T9) 8.85 bees/m²/5 min, and Pomegranate juice 15% (T5) 8.49 bees/m²/5 min, sharing the same statistical group. Dates extract 15% (T6) and Coconut water 20% (T7) followed with moderately high counts (~7.8-8.1 bees/m²/5 min), while the control and low concentration treatments had significantly lower counts around 5.1 to 6.1 bees/m²/5 min.

At 5 days after spraying (5 DAS), the highest bee populations were maintained in Pomegranate juice 20% (T8) with 10.53 bees/m²/5 min, followed by Dates extract 20% (T9) at 9.50, Pomegranate juice 15% (T5) at 9.46 bees/m²/5 min, and Dates extract 15% (T6) at 8.81 bees/m²/5 min, all significantly higher than the control (5.71 bees/m²/5 min) and coconut water treatments. This highlights strong and sustained attraction to the fruit-based extracts during peak flowering.

At 7 days after spraying (7 DAS), bee activity started to decline but remained highest in Pomegranate juice 20% (8.07 bees/m²/5 min), followed by Pomegranate juice 15% (7.14 bees/m²/5 min). Dates extract 15% and 20% showed moderate visitation (~6.3 bees/m²/5 min), with coconut water treatments lower (~5.1 bees/m²/5 min) and open pollination least active at 4.37 bees/m²/5 min, maintaining the same statistical groupings.

Second Spray bee attractant on activity of *Apis florea* in onion (Rabi 2023-24 to Rabi 2024-25).

At one day before the second spray (DBSS), bee visits were generally higher than the first spray's pre-spray counts due to accumulated flowering and earlier treatment effects. Pomegranate juice 20% topped with 9.07 bees/m²/5 min, followed closely by Dates extract

20% (8.72 bees/m²/5 min), Pomegranate juice 15% (8.60 bees/m²/5 min), and Dates extract 15% (8.27), all grouped together statistically. Control recorded lower activity (6.90 bees/m²/5 min).

After the second spray, at 1 day after spraying (1 DAS), bee activity remained highest for Pomegranate juice 20% (9.19 bees/m²/5 min), statistically significant compared to controls and coconut water treatments (~6.1-7.8 bees/m²/5 min). Dates extract treatments also maintained higher values around 6.8-8.4 bees/m²/5 min.

At 3 days after spraying (3 DAS), Pomegranate juice 20% again recorded the highest mean of 8.51 bees/m²/5 min, significantly greater than control and some coconut water treatments (~4.5-6.7 bees/m²/5 min). Pomegranate juice 15% and Dates extract treatments showed moderate activity, statistically differentiated.

At 5 days after spraying (5 DAS), bee numbers were highest in Pomegranate juice 20% (8.59 bees/m²/5 min) followed by Dates extract 20% (7.42 bees/m²/5 min) and Pomegranate juice 15% (6.46 bees/m²/5 min). Control and coconut water treatments saw significantly lower bee activity yet remained above the initial spray's corresponding day.

By 7 days after spraying (7 DAS), bee activity declined across all treatments but remained statistically highest in Pomegranate juice 20% (6.13 bees/m²/5 min), followed by Dates extract 20% (5.46 bees/m²/5 min). Control had the lowest count (3.06 bees/m²/5 min), indicating residual effects of bee attractants on sustaining visitation even one week after the second spray. The results consistently demonstrate that Pomegranate juice 20% (T8) and Dates extract

20% (T9) significantly enhance *Apis florea* foraging activity compared to coconut water treatments and open pollination. The fruit-based attractants at 15–20% concentrations consistently elicited higher bee counts and sustained peak activity for longer durations after sprays. Coconut water treatments showed moderate enhancement over open pollination but were less effective than pomegranate and dates extracts. The open pollination plots consistently recorded the lowest *Apis florea* visitation, underscoring the importance of using these natural attractants to improve pollination in onion seed production. Statistical significance by DMRT is reflected in the differing letters within columns, confirming meaningful effects of treatments on bee activity at each observation interval. SE (m), CD at 5%, and CV percentages support the reliability of these results with mostly moderate variability.

4.3.5 Influence of bee attractants on *T. iridipennis* visitation in onion crop.

4.3.5.1 First year (Rabi 2023-24).

First spray bee attractants on *T. iridipennis* visitation in onion crop (Rabi 2023-24).

The data for days before first spray (DBFS) and days before second spray (DBSS) provides a baseline for Tetragonula iridipennis activity before the use of bee attractants. For DBFS, bee counts ranged from 30.8 to 35.9 bees/m²/5 min, with the highest activity recorded in coconut water 15% (35.9 bees/m²/5 min), and the lowest in pomegranate juice 10% (30.8 bees/m²/5 min). Other treatments, including both lower and higher concentrations of coconut water, pomegranate juice, and dates extract, as well as open pollination, showed similar moderate values around the grand mean (33.4 bees/m²/5 min). This suggests a relatively uniform starting point in visitation rates among plots before any attractant application (Table 71).

At 1 day after the first spray (1 DAS), the highest bee activity was observed in T8 (Pomegranate juice 20%) with 57.7 bees/m²/5 min, followed closely by T9 (Dates extract 20%) at 56.3 bees/m²/5 min. T4 (Coconut water 15%) and T5 (Pomegranate juice 15%) showed moderate activity, recording 50.6 bees/m²/5 min and 46.9 bees/m²/5 min, respectively. T7 (Coconut water 20%), T6 (Dates extract 15%), and T3 (Dates extract 10%) recorded bee counts in the 44.5 to 46.0 bees/m²/5 min range, while T2 (Pomegranate juice 10%) and T1 (Coconut water 10%) were slightly lower at 43.7 bees/m²/5 min and 40.9 bees/m²/5 min. The open pollination control (T10) had the lowest at 35.9 bees/m²/5 min.

On the 3rd day after spraying (3 DAS), T8 again led with a substantial 69.0 bees/m²/5 min, with T9 (67.3 bees/m²/5 min) and T5 (64.6 bees/m²/5 min) also achieving high activity. T6, T7, T4, T2, and T3 ranged from 53.6–58.4 bees/m²/5 min, while T1 lagged at 47.0 bees/m²/5 min. The control (T10) was much lower at 40.2 bees/m²/5 min.

On day 5 after first spray (5 DAS), T8 (Pomegranate juice 20%) maintained the highest bee visitation at 63.3 bees/m²/5 min, followed by T9 (58.3 bees/m²/5 min), T5 (53.3 bees/m²/5 min), and T6 (52.8 bees/m²/5 min). Treatments with 10% and 15% concentrations of coconut water, dates extract, and pomegranate juice had bee counts between 49.9 bees/m²/5 min and 52.3 bees/m²/5 min. T1 (Coconut water 10%) and T10 (control) showed the lowest values at 47.6 bees/m²/5 min and 38.8 bees/m²/5 min respectively.

At 7 DAS after the first spray, T8 consistently remained highest with 51.2 bees/m²/5 min, and T9 followed with 49.0 bees/m²/5 min. T7, T6, and T5 clustered between 47.9 and 48.8, but T3, T2, T4, and T1 all recorded slightly lower values in the 34.0–45.5 bees/m²/5 min range. Open pollination again showed the lowest value at 29.0 bees/m²/5 min.

Table 71. Effect of bee attractant on activity of *T. iridipennis* in onion (Rabi 2023-24).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	33.3 (5.82)	40.9 (6.66)^{d}	47.0 (6.89)^{d}	47.6 (6.93)^{d}	34.0 (5.88)^{e}	49.7 (7.08)	41.0 (7.18)^{c}	46.0 (7.52)^{c}	48.8 (7.16)^{d}	50.0 (7.11)^{d}
T2 - Pomegranate juice 10%	30.8 (5.59)	43.7 (6.79)^{bc}	53.6 (7.36)^{c}	50.9 (7.17)^{cd}	39.9 (6.36)^{de}	52.0 (7.25)	48.8 (7.37)^{bc}	50.1 (7.66)^{bc}	51.7 (7.56)^{b}	51.8 (7.23)^{cd}
T3 - Dates extract 10%	32.4 (5.73)	45.0 (6.75)^{bc}	52.3 (7.27)^{d}	50.0 (7.11)^{cd}	50.0 (7.11)^{bc}	51.0 (7.18)	53.3 (7.33)^{ab}	53.7 (7.56)^{bc}	54.0 (7.78)^{b}	52.3 (7.27)^{b}
T4 - Coconut water 15%	35.9 (6.03)	50.6 (7.08)^{b}	48.9 (7.03)^{d}	49.9 (7.10)^{cd}	45.5 (6.79)^{cd}	50.6 (7.15)	52.9 (7.31)^{b}	57.2 (7.60)^{b}	52.0 (7.25)^{b}	50.7 (7.15)^{d}
T5 - Pomegranate juice 15%	33.1 (5.80)	46.9 (6.88)^{ab}	64.6 (8.07)^{b}	53.3 (7.34)^{c}	48.8 (7.02)^{c}	52.0 (7.24)	54.8 (7.44)^{b}	63.1 (7.98)^{ab}	55.0 (7.45)^{cd}	54.0 (7.38)^{cd}
T6 - Dates extract 15%	32.9 (5.78)	44.5 (6.71)^{bc}	58.4 (7.68)^{bc}	52.8 (7.30)^{cd}	48.0 (6.96)^{c}	51.3 (7.20)	53.3 (7.33)^{ab}	60.0 (7.78)^{ab}	53.3 (7.34)^{cd}	54.7 (7.43)^{cd}
T7 - Coconut water 20%	34.5 (5.91)	46.0 (6.82)^{c}	58.0 (7.65)^{bc}	49.9 (7.10)^{cd}	47.9 (6.96)^{c}	50.9 (7.17)	50.3 (7.34)^{bc}	60.7 (7.82)^{ab}	54.5 (7.42)^{cd}	53.7 (7.36)^{cd}
T8 - Pomegranate juice 20%	34.0 (5.87)	57.7 (7.63)^{a}	69.0 (8.34)^{a}	63.3 (7.99)^{a}	51.2 (7.19)^{bc}	52.9 (7.31)	59.2 (7.73)^{a}	67.2 (8.23)^{a}	60.3 (7.80)^{a}	58.0 (7.45)^{a}
T9 - Dates extract 20%	33.0 (5.79)	56.3 (7.54)^{a}	67.3 (8.23)^{a}	58.3 (7.67)^{b}	49.0 (7.04)^{bc}	52.8 (7.30)	59.0 (7.71)^{a}	63.5 (8.00)^{a}	59.0 (7.71)^{a}	55.3 (7.47)^{cd}
T10 - Open pollination	34.2 (5.89)	35.9 (6.04)^{d}	40.2 (6.38)^{e}	38.8 (6.27)^{e}	29.0 (5.43)^{f}	37.1 (6.13)	37.2 (6.14)^{d}	39.5 (6.33)^{d}	38.0 (6.21)^{c}	36.9 (6.12)^{e}
GM	33.4	47.1	55.9	51.5	44.3	50	52.8	58.2	54	51.4
SE (m) ±	5.6	3.3	5.8	3.2	3.6	6.7	3.7	4	3.8	3.2
CD @5%	NS	9.9	17.2	9.5	10.7	NS	11.1	11.9	11.2	9.4
CV (%)	28.9	12.2	17.9	10.7	14.1	23	12.2	11.9	12.1	10.7

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Second Spray bee attractants on *T. iridipennis* visitation in onion crop (Rabi 2023-24).

For DBSS, the values increased for all treatments compared to DBFS, indicating a natural rise in bee activity as the onion crop advanced in flowering, regardless of treatment. Numbers after the second spray ranged from 37.1 bees/m²/5 min (open pollination) up to 52.9 bees/m²/5 min (pomegranate juice 20%). Treatments with higher concentrations of attractants, notably pomegranate juice 20% (52.9 bees/m²/5 min), coconut water 10% (49.7 bees/m²/5 min), and dates extract 20% (52.8 bees/m²/5 min), remarkably surpassed the open pollination and lower concentration groups, highlighting the positive cumulative impact of attractant use across the flowering season. This pattern demonstrates that repeated application at increased flowering not only sustains but may further boost *T. iridipennis* visitation rates in onion fields.

After the second spray, at 1 day after spraying (1 DAS), activity peaked in T8 (Pomegranate juice 20%) at 59.2 bees/m²/5 min, followed by T9 (Dates extract 20%) at 59.0 bees/m²/5 min. T5, T6, and T7 showed moderate activity (54.8–53.3 bees/m²/5 min), while T2 (48.8 bees/m²/5 min), T4 (52.9 bees/m²/5 min), and T3 (53.3 bees/m²/5 min;-) were slightly lower but similar. T1 (Coconut water 10%) and the open control (T10) recorded the lowest, with 41.0 and 37.2 respectively.

At 3 DAS after the second spray, T8 showed the highest bee activity at 67.2, T9 and T6 (63.5 bees/m²/5 min and 60.0 bees/m²/5 min), and T7 (60.7 bees/m²/5 min) also exhibited elevated activity. T5 (63.1 bees/m²/5 min), T4 (57.2 bees/m²/5 min), and T3 (53.7 bees/m²/5 min) followed, while lower values were found for T1 (46.0 bees/m²/5 min) and T10 (39.5 bees/m²/5 min).

On day 5 after the second spray (5 DAS), T8 again led with 60.3 bees/m²/5 min, T9 (59.0 bees/m²/5 min), and T6 (53.3 bees/m²/5 min) remained strong, while T5 and T7 also showed high counts ranging from 54.5–55.0 bees/m²/5 min T4 and T2 had moderate bee visitation, and T1 and T10 had lowest values at 48.8 bees/m²/5 min and 38.0 bees/m²/5 min, respectively.

At 7 DAS after the second spray, activity was highest for T8 (58.0 bees/m²/5 min), T9 (55.3 bees/m²/5 min), and T6 (54.7 bees/m²/5 min). T7, T5, and T3 were close behind, while T2, T4, and T1 registered moderate bee counts between 50.0 bees/m²/5 min and 53.7 bees/m²/5 min Once again, T10 (open pollination) showed the lowest bee activity at 36.9 bees/m²/5 min. These results consistently highlight that 20% pomegranate juice (T8) and 20% dates extract (T9) are the most effective bee attractants for increasing the activity of *T. iridipennis* on onion umbels, while coconut water 10% (T1) and open pollination control have

the least effect.

4.5.3.2 Second year (Rabi 2024-25).

First spray bee attractants on *T. iridipennis* visitation in onion crop (Rabi 2024-25).

Day before first spray all treatments were statistically at par for bee visitation with coconut water 15% (T4, 37.7 bees/m²/5 min), coconut water 20% (T7, 36.4 bees/m²/5 min), open pollination (T10, 36.0 bees/m²/5 min), pomegranate juice 20% (T8, 35.8 bees/m²/5 min), coconut water 10% (T1, 35.4 bees/m²/5 min), and dates extract 20% (T9, 34.7 bees/m²/5 min) showing highest values, while pomegranate juice 15% (T5, 34.8 bees/m²/5 min), dates extract 15% (T6, 34.5 bees/m²/5 min), and dates extract 10% (T3, 33.7 bees/m²/5 min) had medium counts. Pomegranate juice 10% (T2, 32.0 bees/m²/5 min) recorded the lowest but was not statistically distinct at this baseline (Table 72).

1 Day after first spray pomegranate juice 20% (T8, 61.7 bees/m²/5 min) and dates extract 20% (T9, 59.5 bees/m²/5 min) showed the highest and statistically superior bee counts compared to other treatments. Coconut water 15% (T4, 52.0 bees/m²/5 min), pomegranate juice 15% (T5, 50.5 bees/m²/5 min), coconut water 20% (T7, 48.3 bees/m²/5 min), and pomegranate juice 10% (T2, 48.1) maintained moderate levels. Coconut water 10% (T1, 46.3 bees/m²/5 min), dates extract 15% (T6, 46.8 bees/m²/5 min), and dates extract 10% (T3, 47.0 bees/m²/5 min) were medium and at par. Open pollination (T10, 37.3 bees/m²/5 min) was consistently the lowest.

3 Days after first spray bee counts peaked for pomegranate juice 20% (T8, 73.5 bees/m²/5 min) and dates extract 20% (T9, 71.3 bees/m²/5 min), both highest and statistically superior. Pomegranate juice 15% (T5, 68.9 bees/m²/5 min) ranked moderate, while coconut water 15% (T4, 51.8 bees/m²/5 min), coconut water 20% (T7, 61.5), dates extract 15% (T6, 61.9bees/m²/5 min), dates extract 10% (T3, 56.9 bees/m²/5 min), coconut water 10% (T1, 50.1 bees/m²/5 min) and pomegranate juice 10% (T2, 57.2 bees/m²/5 min) formed medium and at par groups. Open pollination (T10, 42.4 bees/m²/5 min) remained the lowest.

5 Days after first spray pomegranate juice 20% (T8, 66.8 bees/m²/5 min) and dates extract 20% (T9, 61.4 bees/m²/5 min) retained highest bee activity post-spray. Pomegranate juice 15% (T5, 57.0 bees/m²/5 min), dates extract 15% (T6, 55.9 bees/m²/5 min), coconut water 20% (T7, 52.9 bees/m²/5 min), and coconut water 15% (T4, 52.6 bees/m²/5 min) showed moderate results. Dates extract 10% (T3, 52.8 bees/m²/5 min), coconut water 10% (T1, 49.8 bees/m²/5 min), and pomegranate juice 10% (T2, 53.5 bees/m²/5 min) formed the medium group. Open pollination (T10, 40.9) remained the lowest.

7 Days after first spray the highest bee counts at 7DAS remained in pomegranate juice

20% (T8, 54.5 bees/m²/5 min) and dates extract 20% (T9, 52.3 bees/m²/5 min). Pomegranate juice 15% (T5, 51.6 bees/m²/5 min), dates extract 10% (T3, 53.1 bees/m²/5 min), coconut water 20% (T7, 50.5 bees/m²/5 min), coconut water 15% (T4, 48.7 bees/m²/5 min), and dates extract 15% (T6, 51.3 bees/m²/5 min) were moderate and at par. Coconut water 10% (T1, 36.2 bees/m²/5 min) and pomegranate juice 10% (T2, 42.4 bees/m²/5 min) were medium, and open pollination (T10, 30.7 bees/m²/5 min) was the lowest.

Second Spray bee attractants on *T. iridipennis* visitation in onion crop (Rabi 2024-25).

Before the second spray, bee visitation was statistically at par for most attractant treatments: pomegranate juice 20% (T8, 55.9 bees/m²/5 min), dates extract 20% (T955.5 bees/m²/5 min), dates extract 10% (T3, 53.2 bees/m²/5 min), coconut water 20% (T7,53.8 bees/m²/5 min), coconut water 15% (T4, 53.0 bees/m²/5 min), coconut water 10% (T1, 52.1 bees/m²/5 min), dates extract 15% (T6, 53.5 bees/m²/5 min), pomegranate juice 15% (T5, 54.3 bees/m²/5 min), and pomegranate juice 10% (T2, 54.3 bees/m²/5 min). These moderate and medium activity levels were much higher than open pollination (T10, 39.0 bees/m²/5 min), which had the lowest bee count.

1 Day after second spray pomegranate juice 20% (T8, 62.8 bees/m²/5 min) and dates extract 20% (T9, 62.5 bees/m²/5 min) demonstrated the highest and statistically significant bee visitation after the second spray. Coconut water 20% (T7, 56.0 bees/m²/5 min), pomegranate juice 15% (T5, 58.0 bees/m²/5 min), dates extract 15% (T6, 56.1 bees/m²/5 min), coconut water 15% (T4, 55.2 bees/m²/5 min), dates extract 10% (T3, 55.5 bees/m²/5 min), coconut water 10% (T1, 53.0 bees/m²/5 min), and pomegranate juice 10% (T2, 56.1 bees/m²/5 min) yielded moderate to medium counts, most at par. Open pollination (T10, 39.0 bees/m²/5 min) remained the lowest.

3 Days after second spray again, pomegranate juice 20% (T8, 71.9 bees/m²/5 min) and dates extract 20% (T9, 67.7 bees/m²/5 min) produced the highest bee counts at this interval, with statistically significant superiority. Pomegranate juice 15% (T5, 67.2 bees/m²/5 min), coconut water 20% (T7, 64.5 bees/m²/5 min), and dates extract 15% (T6, 63.3 bees/m²/5 min) recorded moderate to high values. Coconut water 15% (T4, 60.6 bees/m²/5 min), dates extract 10% (T3, 59.8 bees/m²/5 min), pomegranate juice 10% (T2, 62.0 bees/m²/5 min), and coconut water 10% (T1, 58.5 bees/m²/5 min) were in the medium and at par ranges. Open pollination (T10, 41.5 bees/m²/5 min) had the lowest bee visitation.

Table 72. Effect of bee attractant on activity of *T. iridipennis* in onion (Rabi 2024-25).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	35.4 (6.00)	46.3 (6.84)^{b}	50.1 (7.12)^{b}	49.8 (7.09)^{b}	36.2 (6.06)^{c}	52.1 (7.25)	53.0 (7.31)^{b}	58.5 (7.68)^{b}	53.1 (7.32)^{b}	52.3 (7.27)^{ab}
T2 - Pomegranate juice 10%	32.0 (5.70)	48.1 (6.97)^{b}	57.2 (7.60)^{b}	53.5 (7.34)^{b}	42.4 (6.55)^{bc}	54.3 (7.40)	56.1 (7.52)^{b}	62.0 (7.90)^{b}	59.5 (7.75)^{ab}	54.2 (7.40)^{ab}
T3 - Dates extract 10%	33.7 (5.85)	47.0 (6.89)^{b}	56.9 (7.58)^{b}	52.8 (7.30)^{b}	53.1 (7.32)^{ab}	53.2 (7.33)	55.5 (7.48)^{b}	59.8 (7.77)^{b}	63.1 (7.98)^{ab}	54.9 (7.44)^{ab}
T4 - Coconut water 15%	37.7 (6.18)	52.0 (7.25)^{ab}	51.8 (7.23)^{b}	52.6 (7.29)^{b}	48.7 (7.01)^{ab}	53.0 (7.31)	55.2 (7.46)^{b}	60.6 (7.82)^{b}	54.8 (7.43)^{b}	53.4 (7.34)^{ab}
T5 - Pomegranate juice 15%	34.8 (5.94)	50.5 (7.14)^{ab}	68.9 (8.33)^{a}	57.0 (7.58)^{ab}	51.6 (7.22)^{ab}	54.3 (7.40)	58.0 (7.65)^{ab}	67.2 (8.23)^{a}	57.8 (7.63)^{ab}	57.0 (7.58)^{a}
T6 - Dates extract 15%	34.5 (5.92)	46.8 (6.87)^{b}	61.9 (7.90)^{ab}	55.9 (7.51)^{b}	51.3 (7.20)^{ab}	53.5 (7.35)	56.1 (7.52)^{b}	63.3 (8.00)^{ab}	56.0 (7.52)^{b}	57.6 (7.62)^{a}
T7 - Coconut water 20%	36.4 (6.07)	48.3 (6.99)^{b}	61.5 (7.87)^{ab}	52.9 (7.31)^{b}	50.5 (7.14)^{ab}	53.8 (7.36)	56.0 (7.51)^{b}	64.5 (8.06)^{ab}	57.8 (7.63)^{ab}	56.5 (7.55)^{a}
T8 - Pomegranate juice 20%	35.8 (6.02)	61.7 (7.89)^{a}	73.5 (8.60)^{a}	66.8 (8.21)^{a}	54.5 (7.42)^{a}	55.9 (7.51)	62.8 (7.96)^{a}	71.9 (8.51)^{a}	63.7 (8.02)^{a}	58.1 (7.65)^{a}
T9 - Dates extract 20%	34.7 (5.93)	59.5 (7.74)^{a}	71.3 (8.47)^{a}	61.4 (7.87)^{a}	52.3 (7.27)^{ab}	55.5 (7.48)	62.5 (7.94)^{a}	67.7 (8.26)^{a}	62.5 (7.94)^{a}	58.2 (7.66)^{a}
T10 - Open pollination	36.0 (6.04)	37.3 (6.15)^{c}	42.4 (6.55)^{c}	40.9 (6.44)^{c}	30.7 (5.59)^{c}	39.0 (6.28)	39.0 (6.28)^{c}	41.5 (6.48)^{c}	40.1 (6.37)^{c}	38.8 (6.27)^{c}
GM	35.1	49.8	59.6	54.4	47.1	52.5	55.4	61.7	56.8	54.1
SE (m) ±	3.8	4.2	5.5	4.8	4.4	3.6	4.5	5.2	4.1	3.5
CD @5%	NS	12.4	16.3	14.2	13.1	NS	13.3	15.4	12.1	10.4
CV (%)	10.8	8.4	9.2	8.8	9.3	6.9	8.1	8.4	7.2	6.5

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

At 5DAS, pomegranate juice 20% (T8, 63.7 bees/m²/5 min) and dates extract 20% (T9, 62.5 bees/m²/5 min) maintained the highest bee counts. Pomegranate juice 15% (T5, 57.8 bees/m²/5 min), coconut water 20% (T7, 57.8 bees/m²/5 min), dates extract 15% (T6, 56.0bees/m²/5 min), coconut water 15% (T4, 54.8 bees/m²/5 min), and dates extract 10% (T3, 63.1 bees/m²/5 min) were moderate and at par with each other. Pomegranate juice 10% (T2, 59.5 bees/m²/5 min), coconut water 10% (T1, 53.1 bees/m²/5 min) had medium counts. Open pollination (T10, 40.1 bees/m²/5 min) remained the lowest.

7 Days after second spray bee visits remained highest for pomegranate juice 20% (T8, 58.1 bees/m²/5 min) and dates extract 20% (T9, 58.2 bees/m²/5 min). Pomegranate juice 15% (T5,57.0 bees/m²/5 min), dates extract 15% (T6, 57.6 bees/m²/5 min), coconut water 20% (T7, 56.5 bees/m²/5 min) were moderate. Coconut water 15% (T4, 53.4 bees/m²/5 min), dates extract 10% (T3, 54.9 bees/m²/5 min), pomegranate juice 10% (T2, 54.2 bees/m²/5 min), and coconut water 10% (T1, 52.3 bees/m²/5 min) displayed medium levels all treatments but open pollination being statistically at par. The open pollination control (T10, 38.8 bees/m²/5 min) remained the lowest throughout.

4.3.5.1 Pooled data (Pooled data (Rabi 2023-24 to Rabi 2024-25).

First spray bee attractant on activity of *T. iridipennis* in onion (Rabi 2023-24 to Rabi 2024-25).

Day prior to initial application all treatments exhibited statistically comparable bee visiting rates at baseline. Coconut water at 15% (36.8 bees/m²/5 min), 20% (35.4 bees/m²/5 min),and 10% (34.4 bees/m²/5 min) open pollination (35.1 v), pomegranate juice at 20% (34.9bees/m²/5 min) and 15% (33.9 bees/m²/5 min) and dates extract at 20% (33.9 bees/m²/5 min), 15% (33.7 bees/m²/5 min), and 10% (33.1 bees/m²/5 min) had moderate to high counts. Pomegranate juice at 10% (31.4 bees/m²/5 min) was somewhat lower but not statistically significant. This verifies a consistent bee backdrop preceding application of the attractant spray (Table 73).

First day post-spray following the initial application, pomegranate juice at 20% (59.7 bees/m²/5 min) and date extract at 20% (57.9 bees/m²/5 min) exhibited the highest bee counts and statistical significance, validating their enhanced attractant efficacy. Coconut water at 15% (51.3 bees/m²/5 min), pomegranate juice at 15% (48.7 bees/m²/5 min), coconut water at 20% (47.2bees/m²/5 min), pomegranate juice at 10% (45.9 bees/m²/5 min), date extract at 10% (46.0bees/m²/5 min), coconut water at 10% (43.6 bees/m²/5 min), and date extract at 15% (45.7 bees/m²/5 min) exhibited modest results, while open pollination (36.6 bees/m²/5 min) recorded the lowest statistical outcome.

Table 73. Effect of bee attractant on activity of *T. iridipennis in* onion (Rabi 2023-24 to Rabi 2024-25).

Treatment	Number of bees/m2/min									
	1st spray at 15% per flowering					2nd spray at 50% per flowering				
	DBFS	1ST	3RD	5TH	7TH	DBSS	1ST	3RD	5TH	7TH
T1 - Coconut water 10%	34.4 (5.91)	43.6 (6.75)^{c}	48.6 (7.01)^{c}	48.7 (7.01)^{c}	35.1 (5.97)^{d}	50.9 (7.17)	47.0 (6.96)^{c}	52.2 (7.20)^{c}	51.0 (7.24)^{bc}	51.2 (7.19)^{bc}
T2 - Pomegranate juice 10%	31.4 (5.64)	45.9 (6.88)^{c}	55.4 (7.49)^{bc}	52.2 (7.25)^{ab}	41.2 (6.32)^{cd}	53.2 (7.33)	52.5 (7.38)^{c}	56.1 (7.56)^{c}	55.6 (7.54)^{bc}	53.0 (7.32)^{bc}
T3 - Dates extract 10%	33.1 (5.78)	46.0 (6.82)^{c}	54.6 (7.45)^{bc}	51.4 (7.19)^{abc}	51.6 (7.21)^{ab}	52.1 (7.13)	54.4 (7.41)^{bc}	56.8 (7.59)^{c}	58.6 (7.62)^{bc}	53.6 (7.35)^{bc}
T4 - Coconut water 15%	36.8 (6.11)	51.3 (7.174)^{bc}	50.4 (7.09)^{c}	51.3 (7.19)^{abc}	47.1 (6.90)^{bc}	51.8 (7.23)	54.1 (7.45)^{bc}	58.9 (7.83)^{bc}	53.4 (7.28)^{bc}	52.1 (7.15)^{bc}
T5 - Pomegranate juice 15%	33.9 (5.87)	48.7 (7.01)^{bc}	66.8 (8.20)^{ab}	55.2 (7.48)^{bc}	50.2 (7.10)^{bc}	53.2 (7.32)	56.4 (7.52)^{ab}	65.2 (8.12)^{ab}	56.4 (7.59)^{ab}	55.5 (7.44)^{ab}
T6 - Dates extract 15%	33.7 (5.83)	45.7 (6.80)^{c}	60.2 (7.70)^{bc}	54.4 (7.38)^{bc}	49.6 (7.02)^{bc}	52.4 (7.16)	54.7 (7.45)^{bc}	61.7 (7.86)^{bc}	54.7 (7.34)^{bc}	56.2 (7.51)^{ab}
T7 - Coconut water 20%	35.4 (6.01)	47.2 (6.90)^{bc}	59.8 (7.78)^{bc}	51.4 (7.19)^{abc}	49.2 (7.05)^{bc}	52.4 (7.20)	53.2 (7.33)^{c}	62.6 (7.91)^{ab}	56.1 (7.54)^{abc}	55.1 (7.41)^{ab}
T8 - Pomegranate juice 20%	34.9 (5.97)	59.7 (7.77)^{a}	71.3 (8.47)^{a}	65.1 (8.06)^{a}	52.9 (7.31)^{ab}	54.4 (7.35)	61.0 (7.95)^{a}	69.6 (8.37)^{a}	62.0 (8.01)^{a}	58.1 (7.55)^{a}
T9 - Dates extract 20%	33.9 (5.84)	57.9 (7.70)^{a}	69.3 (8.37)^{a}	59.9 (7.81)^{ab}	50.7 (7.06)^{bc}	54.2 (7.35)	60.8 (7.93)^{a}	65.6 (8.06)^{ab}	60.8 (7.91)^{a}	56.8 (7.52)^{ab}
T10 - Open pollination	35.1 (5.96)	36.6 (6.10)^{d}	41.3 (6.48)^{d}	39.9 (6.38)^{d}	29.9 (5.45)^{d}	38.0 (6.20)	38.1 (6.21)^{d}	40.5 (6.46)^{d}	39.1 (6.36)^{d}	37.9 (6.16)^{d}
GM	33.6	48.4	57.7	53	45.7	51.2	54	59.4	54.8	52.8
SE (m) ±	4.7	3.8	5.7	4	3.9	6.2	4.1	4.6	3.9	3.4
CD @5%	NS	11.2	16.8	11.9	11.9	NS	12.2	14.1	11.7	9.9
CV (%)	19.9	10.3	13.6	9.8	11.6	22.9	10.8	10.2	11.3	8.6

Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values.
In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT.

Third day post-application bee visits reached their zenith in the 20% pomegranate juice (71.3 bees/m²/5 min) and 20% date extract (69.3 bees/m²/5 min) treatments, markedly exceeding all other treatments. Pomegranate juice 15% (66.8), dates extract 15% (60.2 bees/m²/5 min),coconut water 20% (59.8 bees/m²/5 min), dates extract 10% (54.6 bees/m²/5 min), coconut water 10% (48.6 bees/m²/5 min), and coconut water 15% (50.4 bees/m²/5 min) yielded moderate to medium results. Open pollination (41.3 bees/m²/5 min) consistently exhibited the lowest and statistically significant differences.

Fifth day post-application pomegranate juice at 20% (65.1 bees/m²/5 min) and date extract at 20% (59.9 bees/m²/5 min) exhibited the highest levels of bee visitation. Pomegranate juice 15% (55.2 bees/m²/5 min), dates extract 15% (54.4 bees/m²/5 min), coconut water 20% (51.4bees/m²/5 min), coconut water 15% (51.3 bees/m²/5 min), dates extract 10% (51.4 bees/m²/5 min), pomegranate juice 10% (52.2 bees/m²/5 min), and coconut water 10% (48.7 bees/m²/5 min) were categorised as moderate and medium groups, while open pollination (39.9 bees/m²/5 min) remained the lowest.

Seventh day post-application by day 7, pomegranate juice at 20% (52.9 bees/m²/5 min) and date extract at 20% (50.7 bees/m²/5 min) remained the most effective, while pomegranate juice at 15% (50.2 bees/m²/5 min), date extract at 15% (49.6 bees/m²/5 min), coconut water at 20% (49.2 bees/m²/5 min), coconut water at 15% (47.1 bees/m²/5 min), date extract at 10% (51.6 bees/m²/5 min), coconut water at 10% (35.1 bees/m²/5 min), and pomegranate juice at 10% (41.2 bees/m²/5 min) exhibited modest activity. Open pollination (29.9 bees/m²/5 min) had the lowest level and was statistically distinct.

Second Spray bee attractant on activity of *T. iridipennis* in onion (Rabi 2023-24 to Rabi 2024-25).

Prior to the second application, the majority of attractant treatments exhibited moderate to medium bee counts that were statistically comparable: coconut water 10% (50.9 bees/m²/min), pomegranate juice 10% (53.2 bees/m²/min), dates extract 10% (52.1 bees/m²/min), coconut water 15% (51.8 bees/m²/min), pomegranate juice 15% (53.2 bees/m²/min), dates extract 15% (52.4 bees/m²/min), coconut water 20% (52.4 bees/m²/min), pomegranate juice 20% (54.4 bees/m²/min), dates extract 20% (54.2 bees/m²/min). Open pollination (38.0 bees/m²/min) consistently showed the lowest levels.

First subsequent day following second application, pomegranate juice at 20% (61.0 bees/m²/5 min) and date extract at 20% (60.8 bees/m²/5 min) again resulted in the largest and statistically significant bee visitation. Coconut water 20% (53.2 bees/m²/5 min), pomegranate juice 15% (56.4 bees/m²/5 min), dates extract 15% (54.7 bees/m²/5 min), coconut water 15%

(54.1 bees/m²/5 min), dates extract 10% (54.4 bees/m²/5 min), coconut water 10% (47.0 bees/m²/5 min), and pomegranate juice 10% (52.5 bees/m²/5 min) exhibited moderate effects, statistically categorised. Open pollination (38.1 bees/m²/5 min) exhibited the lowest levels.

Third day following second application the peak bee activity was sustained in 20% pomegranate juice (69.6 bees/m²/5 min) and 20% date extract (65.6 bees/m²/5 min). Pomegranate juice 15% (65.2 bees/m²/5 min), coconut water 20% (62.6 bees/m²/5 min), date extract 15% (61.7 bees/m²/5 min), coconut water 15% (58.9 bees/m²/5 min), date extract 10% (56.8 bees/m²/5 min), pomegranate juice 10% (56.1 bees/m²/5 min), and coconut water 10% (52.2 bees/m²/5 min) are categorised as moderate and medium, with open pollination (40.5 bees/m²/5 min) being the lowest.

On the fifth day following the second application, pomegranate juice at 20% (62.0 bees/m²/5 min) and date extract at 20% (60.8 bees/m²/5 min) had the greatest efficacy in attracting bees, whereas other attractants yielded moderate to medium counts: coconut water 20% (56.1 bees/m²/5 min), pomegranate juice 15% (56.4 bees/m²/5 min), dates extract 15% (54.7 bees/m²/5 min), coconut water 15% (53.4 bees/m²/5 min), dates extract 10% (58.6 bees/m²/5 min), pomegranate juice 10% (55.6 bees/m²/5 min), coconut water 10% (51.0 bees/m²/5 min). Open pollination (39.1 bees/m²/5 min) consistently had the lowest statistical values.

By day 7, pomegranate juice at 20% (58.1 bees/m²/5 min) and date extract at 20% (56.8 bees/m²/5 min) maintained the highest bee visiting rates. Pomegranate juice at 15% (55.5 bees/m²/5 min), dates extract at 15% (56.2 bees/m²/5 min), coconut water at 20% (55.1 bees/m²/5 min), coconut water at 15% (52.1 bees/m²/5 min), dates extract at 10% (53.6 bees/m²/5 min), pomegranate juice at 10% (53.0 bees/m²/5 min), and coconut water at 10% (51.2 bees/m²/5 min) exhibited moderate levels, whereas open pollination (37.9 bees/m²/5 min) consistently recorded the lowest levels.

These results illustrate the consistently greater efficacy of 20% pomegranate juice and 20% date extract as attractants for *T. iridipennis*, with open pollination consistently yielding much lower counts.

4.3.6 Influence of bee attractants on quantitative and qualitative parameters of onion.

4.3.6.1 First year (Rabi 2023-24).

Observations on the effect of bee attractants on various quantitative and qualitative parameters, *viz*., No. of umbels /plant, No. of umblets per umbel, No. of seeds per umbel, Onion seed setting increase over control (%),1000 Seed weight (g), Seed yield (g/ 5 plant), and germination percentage were noted and are presented in Table 74.

4.3.6.1.1 No. of umbels /plant

The data on number of umbels/ plants have been presented in Table. The mean number of umbels/ plants ranged from 7.5 to 7.9 and showed no significant difference among the treatments.

4.3.6.1.2 No. of seeds per umbel

The quantity of seeds per umbel in onion plants varies markedly with different bee attractant treatments, illustrating the impact of these attractants on seed production. The treatment with 20% Pomegranate juice (T8) yielded the greatest seed count, yielding 1301.1 seeds per umbel, demonstrating its significant influence on pollination and seed development. Moderate seed counts, ranging from 1100.0 to 1288.0 seeds per umbel, were reported in treatments with Dates extract and Coconut water at concentrations of 15-20% (T6, T7, T9), suggesting a decent but somewhat lesser impact compared to Pomegranate juice at 20%. Moderate seed counts, ranging from 831.7 to 1016.8 seeds, were seen in treatments with reduced concentrations of attractants (10-15%), including Coconut water, Pomegranate juice, and Dates extract (T1 to T4). The lowest seed yield occurred under open pollination without any added attractants (T10), producing only 715.3 seeds per umbel, underscoring the advantageous impact of bee attractants on seed production in onion farming. This pattern illustrates how attractants augment bee activity, hence enhancing pollination efficiency and seed set per umbel.

4.3.6.1.3 Onion seed setting increase over control (%).

The onion seed setting increase over control (%) shows a clear trend linked to the type and concentration of bee attractant used. The highest increase was recorded with 20% Pomegranate juice (T8) at 65.0%, followed closely by 20% Dates extract (T9) at 63.1%, indicating that these higher concentrations significantly boost seed set compared to the control. Moderate increases were seen with 15% Pomegranate juice (T5) at 51.8%, 15% Dates extract (T6) at 47.0%, and 20% Coconut water (T7) at 44.0%, showing that mid-to-high concentrations of these attractants promote seed setting effectively. Lower but still substantial increases were observed with 10-15% concentrations of Coconut water (T1 and T4) and 10% Pomegranate juice and Dates extract (T2 and T3), ranging from 24.4% to 35.8%. The control treatment with open pollination (T10) serves as the baseline with no increase. These results highlight the positive impact of attractant concentration on enhancing pollination efficiency and seed setting in onions (Table 75).

4.3.6.1.4 1000 Seed weight (g)

The 1000 seed weight in onion varies notably with different bee attractant treatments, reflecting their influence on seed quality and size. The highest seed weight was recorded in treatments with 20% Pomegranate juice (T8) at 6.2 g and 20% Dates extract (T9) at 6.0 g, indicating these treatments produce heavier and potentially more viable seeds. Moderate seed weights ranging from 5.4 to 5.8 g were found in 15% concentration treatments of Pomegranate juice, Dates extract, and Coconut water (T5, T6, T7), showing a good enhancement over lower concentrations. Lower seed weights between 3.9 and 4.9 g were seen in the 10-15% low-concentration treatments (T1 to T4). The lowest seed weight of 3.1 g was found in the open pollination control treatment (T10), indicating the significant role of bee attractants in improving seed weight and thereby seed quality in onion cultivation. This shows that higher concentrations of bee attractants, particularly Pomegranate juice and Dates extract, contribute to producing heavier seeds.

4.3.6.1.5 Seed yield (g/ umbel)

For seed yield per umbel, the highest value was recorded in T8 (pomegranate juice 20%) at 5.21 g (2.78), followed by T9 (dates extract 20%), which yielded 4.78 g (2.69) and both were statistically superior to other treatments. T5 (pomegranate juice 15%), T6 (dates extract 15%), T7 (coconut water 20%), T2 (pomegranate juice 10%), and T3 (dates extract 10%) produced moderate yields ranging from 2.45 to 2.69 g (2.07–2.14), indicating a positive response to increased extract concentration. Lower yields were observed for T1 (coconut water 10%) and T4 (coconut water 15%), with values close to 2.10 g (1.95–1.96), while the lowest seed yield per umbel was recorded under open pollination (T10), at just 1.56 g (1.75), showing the least effectiveness for seed production. Treatments sharing the same letter in parentheses do not differ significantly at $p = 0.05$ by DMRT, highlighting the superior performance of high-concentration pomegranate and dates extracts for onion seed yield enhancement.

Table 74. Effect of bee attractant on activity bees on seed and yield contributing characters of onion (Rabi 2023-24).

Treatment	No. of umbels /plant	No. of umblets per umbel	No. of seeds per umbel	Onion seed setting increase over control (%)	1000 Seed weight (g)	Seed yield (g/ umbel)	Seed yield (kg/ha)	Germination percentage	Percent deformed seed
T1 - Coconut water 10%	7.8 (3.29)	359.5^{d}	831.7^{de}	24.4^{e}	3.9^{d}	2.10 (1.95)^{d}	364.6^{d}	80.00^{e}	20.00
T2 - Pomegranate juice 10%	7.6 (3.26)	496.5^{b}	1016.8^{cd}	35.8^{d}	4.9^{c}	2.54 (2.09)^{c}	429.3^{cd}	89.00^{d}	11.00
T3 - Dates extract 10%	7.5 (3.24)	501.3^{a}	1007.4^{cd}	34.6^{d}	4.2^{c}	2.45 (2.07)^{cd}	407.6^{c}	88.00^{d}	12.00^{c}
T4 - Coconut water 15%	7.9 (3.31)	495.1^{b}	997.1^{ce}	33.2^{d}	4.1^{c}	2.13 (1.96)^{d}	373.8^{c}	84.00^{e}	16.00
T5 - Pomegranate juice 15%	7.8 (3.29)	476.3^{b}	1136.4^{c}	51.8^{b}	5.8^{b}	2.69 (2.14)^{c}	465.8^{b}	95.00^{b}	5.00
T6 - Dates extract 15%	7.7 (3.27)	496.3^{b}	1100.0^{bc}	47.0^{c}	5.4^{b}	2.63 (2.12)^{c}	449.8^{b}	93.00^{c}	3.00
T7 - Coconut water 20%	7.6 (3.26)	380.9^{d}	1076.1^{bd}	44.0^{c}	5.5^{b}	2.58 (2.11)^{c}	435.1^{b}	97.00^{b}	7.00
T8 - Pomegranate juice 20%	7.6 (3.26)	503.4^{a}	1301.1^{a}	65.0^{a}	6.2^{a}	5.21 (2.78)^{a}	880.1^{a}	99.00^{a}	1.00
T9 - Dates extract 20%	7.8 (3.29)	549.3^{a}	1288.0^{b}	63.1^{a}	6.0^{a}	4.78 (2.69)^{b}	828.1^{a}	97.00^{b}	3.00
T10 - Open pollination	7.7 (3.27)	313.7^{e}	715.3^{f}	_	3.1^{d}	1.56 (1.75)^{e}	267.1^{e}	76.00^{f}	24.00
GM	7.70	457.2	1047	_	5.2	2.69	490.13	89.48	–
SE (m) ±	NS	37.7	105.6	_	0.8	0.37	6.33	2.47	–
CD @5%		112	313.7	_	NS	41.01	14.32	4.84	–
CV (%)	6.7	14.3	17.5	_	26.9	8.41	40.37	8.70	–

* Figures in the parenthesis are arc sine transformed values, ** Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values, In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

4.3.6.1.6 Seed yield (kg/ha)

The seed yield (kg/ha) varied significantly across treatments. The highest yields were achieved with T8 (pomegranate juice 20%) at 880.1 kg/ha and T9 (dates extract 20%) at 828.1 kg/ha and showing clear superiority over other treatments. Intermediate yields were observed with T5 (pomegranate juice 15%), T6 (dates extract 15%), and T7 (coconut water 20%), recording 465.8, 449.8, and 435.1 kg/ha, respectively. Treatments T2 (pomegranate juice 10%), T3 (dates extract 10%), and T4 (coconut water 15%) produced yields between 407.6 and 429.3 kg/ha.. The lowest yields were seen in T1 (coconut water 10%) at 364.6 kg/ha and T10 (open pollination) at 267.1 kg/ha, with open pollination being significantly inferior to all attractant treatments. Means followed by the same letter do not differ significantly at p = 0.05 by DMRT, demonstrating substantial yield enhancements with pomegranate juice and dates extract, particularly at higher concentrations.

4.3.6.1.7 Germination percentage

The germination percentage of onion seeds varied with different bee attractant treatments, reflecting effects on seed viability and quality. The highest germination rate of 99% was recorded in the 20% Pomegranate juice treatment (T8), indicating excellent seed quality. High germination rates between 93% and 97% were observed in 15% Pomegranate juice (T5), 20% Dates extract (T9), and 20% Coconut water (T7), showing that higher concentrations of these attractants enhance seed viability. Moderate germination rates of 84% to 89% were seen in lower concentration treatments like 10-15% Coconut water, Pomegranate juice, and Dates extract (T1 to T4 and T6). The open pollination control (T10) had the lowest germination percentage at 76%, indicating the beneficial role of bee attractants in improving seed germination in onion. This pattern highlights the positive influence of bee attractant type and concentration on onion seed germination.

4.3.6.1.8 Percent deformed seed

The percent deformed seed was lowest in T8 (Pomegranate juice 20%) at 1.00%, showing the best seed quality. Slightly higher deformation occurred in T6 (Dates extract 15%) and T9 (Dates extract 20%), both at 3.00%. Moderate levels were found in T5 (Pomegranate juice 15%) at 5.00%, T7 (Coconut water 20%) at 7.00%, and T4 (Coconut water 15%) at 16.00%. Higher deformation was seen with T2 (Pomegranate juice 10%) at 11.00%, T3 (Dates extract 10%) at 12.00%, and T1 (Coconut water 10%) at 20.00%. The highest deformation was in the control T10 (Open pollination) at 24.00%. This shows clearly that 20% Pomegranate juice minimizes seed deformity most effectively.

4.3.6.2 Second year (Rabi 2024-25)

Observations on the effect of bee attractants on various quantitative and qualitative parameters, *viz*., No. of umbels /plant, No. of umblets per umbel, No. of seeds per umbel, Onion seed setting increase over control (%),1000 Seed weight (g), Seed yield (g/ 5 plant), and germination percentage were noted and are presented in Table 75.

4.3.6.2.1 No. of umbels /plant

The data on number of umbels/ plant have been presented in Table 40. The mean number of umbels/ plant ranged from 6.00 to 9.00 and showed no significant difference among the treatments.

4.3.6.2.2 No. of seeds per umbel

The number of umblets per umbel varied significantly among treatments, showing the effect of bee attractants and their concentrations on umblet formation in onion. The highest number of umblets per umbel was recorded in T9 (Dates extract 20%) with 566.8 (23.81), closely followed by T8 (Pomegranate juice 20%) at 518.6 (22.78), indicating the strong positive impact of these high-concentration attractants. Moderate and statistically similar umblet numbers around 491.2 to 516.7 were observed in T2, T3, T4, T5, and T6 (Pomegranate juice, Dates extract, and Coconut water at 10-15% concentrations). Lower values of 368.2 (19.18) and 394.5 (19.86) were found in T1 and T7 (Coconut water 10% and 20%), whereas the lowest number of umblets occurred in the open pollination control (T10) with 321.4 (17.93). These results emphasize that higher concentrations of Dates extract and Pomegranate juice attractants significantly enhance umblet production per umbel in onion.

4.3.6.2.3 Onion seed setting increase over control (%).

The increase in onion seed setting over control (%) differed significantly among treatments, reflecting how bee attractants affected pollination success. The highest increases were seen in T8 (Pomegranate juice 20%) at 68.2% (8.27), closely followed by T9 (Dates extract 20%) at 65.8% (8.15), indicating that these treatments markedly enhanced seed setting. Moderate but substantial increases between 46.9% and 54.6% were observed in T5, T6, and T7 (Pomegranate juice 15%, Dates extract 15%, and Coconut water 20%), showing the positive effect of mid- to high-concentration attractants. Lower increases ranging from 26.8% to 38.2% were recorded in T1 through T4 (10-15% concentrations of Coconut water, Pomegranate juice, and Dates extract). This data confirms the significant role of attractant concentration and type

in improving onion seed setting over the control, with higher concentrations of Pomegranate juice and Dates extract being most effective.

4.3.6.2.4 1000 Seed weight (g)

The 1000 seed weight differed significantly among the treatments involving indigenous bee attractants and open pollination in onion seed production. The highest 1000 seed weight was recorded in treatment T8 (Pomegranate juice 20%) with 6.5 g, followed closely by T9 (Dates extract 20%) at 6.3 g and T5 (Pomegranate juice 15%) at 6.1 g. Treatments with 15% and 20% concentrations of coconut water and dates extract (T6, T7) also yielded relatively high seed weights between 5.7 and 5.8 g. The lowest weight was observed in open pollination (T10) at 3.2 g, indicating the benefit of using these attractant treatments to enhance seed weight. Intermediate values were observed in treatments with 10% concentrations (T1, T2, T3) and coconut water 15% (T4), ranging from 4.1 to 5.1 g (Table 75).

4.3.6.2.5 Seed yield (g/ umbel)

Onion seed yield per umbel varied across treatments, with Coconut water 10% producing 1.51 g/umbel, Pomegranate juice 10% 2.62 g/umbel, Dates extract 10% 2.27 g/umbel, and Coconut water 15% 2.19 g/umbel. Pomegranate juice 15% increased the yield to 3.00 g/umbel, Dates extract 15% to 2.92 g/umbel, and Coconut water 20% to 2.29 g/umbel.

The highest yields were obtained with Pomegranate juice 20% (3.37 g/umbel) and Dates extract 20% (3.57 g/umbel). In contrast, the control (open pollination) recorded the lowest yield of 1.03 g/umbel. These results show that treatments containing pomegranate juice and dates extract, especially at higher concentrations, led to improved seed yields in onion compared to coconut water or open pollination alone. This demonstrates the positive impact of such bee attractant applications on onion seed production under field conditions.

Table 75. Effect of bee attractant on activity bees on seed and yield contributing characters of onion (Rabi 2024 - 25).

Treatment	No. of umbels /plant	No. of umblets per umbel	No. of seeds per umbel	Onion seed setting increase over control (%)	1000 Seed weight (g)	Seed yield (g/ umbel)	Seed yield (kg/ha)	Germination percentage	Percent deformed seed
T1 - Coconut water 10%	8.2 (3.36)	368.2^{d}	845.3^{e}	26.8	4.1 ^{d}	1.51 (1.73)^{c}	301.9^{e}	82.5^{e}	18.5^{a}
T2 - Pomegranate juice 10%	8.0 (3.33)	512.8^{c}	1038.2^{d}	38.2	5.1^{c}	2.62 (2.12)^{a}	610.2^{c}	91.2^{d}	10.2^{c}
T3 - Dates extract 10%	6.8 (3.11)	516.7^{c}	1025.8^{d}	36.9	4.4^{c}	2.27 (2.01)^{b}	606.2^{c}	90.1^{d}	11.5^{c}
T4 - Coconut water 15%	7.0 (3.15)	509.8^{c}	1015.4^{ce}	35.8	4.3^{c}	2.19 (1.98)^{c}	584.5^{d}	86.2^{e}	15.2^{b}
T5 - Pomegranate juice 15%	7.3 (3.20)	491.2^{c}	1158.7^{c}	54.6	6.1^{b}	3.00 (2.23)^{a}	799.0^{b}	97.2^{c}	4.5^{e}
T6 - Dates extract 15%	7.5 (3.24)	512.1^{c}	1122.5^{c}	49.8	5.7^{b}	2.92 (2.21)^{b}	778.3^{b}	95.1^{c}	6.2^{d}
T7 - Coconut water 20%	9.5 (3.58)	394.5^{d}	1098.2^{c}	46.9	5.8^{b}	2.29 (2.01)^{b}	686.4^{c}	98.8^{bc}	6.8^{d}
T8 - Pomegranate juice 20%	7.0 (3.15)	518.6^{a}	1325.6^{a}	68.2	6.5^{a}	3.37 (2.34)^{a}	1011.2^{a}	100.0^{a}	0.8^{f}
T9 - Dates extract 20%	5.9 (2.93)	566.8^{a}	1312.4^{a}	65.8	6.3^{a}	3.57 (2.39)^{a}	952.2^{a}	98.5^{bc}	2.5^{e}
T10 - Open pollination	6.4 (3.03)	321.4^{e}	728.9^{f}		3.2^{e}	1.03 (1.51)^{d}	274.2^{f}	78.5^{f}	22.8^{a}
GM	7.3	471.2	1067.2	47.6	5.4	2.34	611.88	91.8	9.9
SE (m) ±	NS	39.2	108.8	4.7	0.83	0.25	7.68	2.8	1.8
CD @5%		117.6	326.4	14.1	NS	0.49	15.05	8.4	5.4
CV (%)	13.84	14.6	17.8	12.4	25.8	3.24	36.78	5.3	31.2

* Figures in the parenthesis are arc sine transformed values,

** Figures in the parenthesis are $\sqrt{x} + 0.5$ transformed values

In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

4.3.6.2.6 Seed yield (kg/ha)

Seed yield per hectare for the evaluated treatments demonstrated clear differences in onion productivity. The application of Pomegranate juice 20% and Dates extract 20% resulted in the highest yields, with 1011.2 kg/ha and 952.2 kg/ha, respectively. Pomegranate juice 15% and Dates extract 15% also produced considerable yields of 799.0 kg/ha and 778.3 kg/ha. Moderate yields were observed for Coconut water 20% (686.4 kg/ha), Dates extract 10% (606.2 kg/ha), Pomegranate juice 10% (610.2 kg/ha), and Coconut water 15% (584.5 kg/ha). Coconut water 10% produced 301.9 kg/ha, while the lowest yield was under open pollination, with 274.2 kg/ha. These results underline that pomegranate juice and dates extract, especially at higher concentrations, substantially boosted onion seed yield compared to coconut water or the untreated control.

4.3.6.2.7 Germination percentage

Germination percentage showed significant variation among treatments with indigenous bee attractants and open pollination in onion seed production. The highest germination percentage was recorded in treatment T8 (Pomegranate juice 20%) with a perfect 100%, followed closely by T7 (Coconut water 20%) at 98.8% and T9 (Dates extract 20%) at 98.5%. Treatments with 15% concentrations of pomegranate juice and dates extract (T5, T6) also demonstrated high germination rates above 95%. Lower germination percentages were observed with 10% concentrations of coconut water, pomegranate juice, and dates extract (T1, T2, T3) ranging from 82.5% to 91.2%, while the lowest germination rate was found in open pollination (T10) at 78.5%. These results indicate that higher concentrations of pomegranate juice and dates extract not only improve seed yield and weight but also enhance seed germination, reflecting improved seed quality and vigor likely due to beneficial bioactive compounds that support better seed development and viability.

4.3.6.2.8 Percent deformed seed

The percentage of deformed seeds varied significantly among the treatments applying indigenous bee attractants and open pollination in onion seed production. The lowest percentage of deformed seeds was observed in treatment T8 (Pomegranate juice 20%) at 0.8%, followed by T9 (Dates extract 20%) at 2.5% and T5 (Pomegranate juice 15%) at 4.5%. Treatments with 15% and 20% concentrations of coconut water and dates extract (T6, T7) also showed low deformed seed percentages ranging from 6.2% to 6.8%. Conversely, the highest deformed seed percentages were recorded in open pollination (T10) at 22.8% and the

lowest concentration coconut water 10% treatment (T1) at 18.5%. Intermediate values were noted for lower concentrations of pomegranate juice and dates extract (T2, T3) with 10.2% to 11.5%. These results suggest that higher concentrations of pomegranate juice and dates extract not only improve seed yield and germination but also enhance seed quality by reducing the proportion of deformed seeds, likely due to improved pollination.

4.3.6.3 Pooled data (Rabi 2023-24 to Rabi 2024-25)

4.3.6.3.1 Number of umbels per plant

Onion plants treated with bee attractants developed between 6.9 and 8.5 umbels per plant. The highest was observed with T7 (Coconut water 20%, 8.5 (3.37)), indicating that high concentrations of coconut water can enhance floral initiation. Most other treatments, especially those with pomegranate juice and dates extract, produced between 7.1 and 8.0 umbels per plant, while the lowest was seen with T9 (Dates extract 20%, 6.9 (3.21)). The control (T10, open pollination) had 7.1 (3.22) umbels per plant, showing that attractant treatments tended to increase umbel formation only slightly compared to open pollination. Transformed values in parentheses support variance stabilization for robust statistical comparison (Table 76).

4.3.6.3.2 Number of umblets per umbel

The greatest number of umblets per umbel was recorded for T9 (Dates extract 20%, 558.0), T8 (Pomegranate juice 20%, 511.0), and T3 (Dates extract 10%, 508.5), demonstrating the capacity of high-concentration dates and pomegranate treatments to maximize floral reproductive sites.

4.6.3.6.3 Number of seeds per umbel

Seed set per umbel was highest for T8 (Pomegranate juice 20%, 1313.4) and T9 (Dates extract 20%, 1300.2), with other treatments like T5 (Pomegranate juice 15%) and T6 (Dates extract 15%) producing robust intermediate numbers (1147.6 and 1111.3, respectively). Coconut water and lower-concentration treatments ranged from 838.5 (T1, Coconut water 10%) to 1006.25 (T4, Coconut water 15%). The control, T10 (Open pollination), was lowest at 722.1, indicating a significant improvement in seed set by bee attractants.

4.6.3.6.4 Onion seed setting increase over control (%)

Seed setting improved dramatically across attractant treatments, from 25.6% in T1 (Coconut water 10%) to a remarkable 66.6% in T8 (Pomegranate juice 20%) and 64.5% in T9 (Dates extract 20%). All other treatments showed increases between 34.5% and 53.2%, starkly outperforming open pollination and demonstrating the role of bee attractants in maximizing fertilization efficiency (Table 76).

Table 76. Effect of bee attractants on activity bees on seed and yield contributing characters of onion (Polled data Rabi 2023-24, Rabi 2024 - 25).

Treatment	No. of umbels /plant	No. of umblets per umbel	No. of seeds per umbel	Onion seed setting increase over control (%)	1000 Seed weight (g)	Seed yield (g/ umbel)	Seed yield (kg/ha)	Germination percentage	Percent deformed seed
T1 - Coconut water 10%	8.0 (3.32)	363.9^{d}	838.5^{de}	25.6^{e}	4.0^{d}	1.81 (1.77)^{d}	333.3^{d}	81.25 (64.20)^{e}	19.25^{a}
T2 - Pomegranate juice 10%	7.8 (3.30)	504.7^{b}	1027.5^{cd}	37.0^{d}	5.0^{c}	2.58 (2.05)^{c}	519.8^{c}	90.10 (71.54)^{d}	10.60^{c}
T3 - Dates extract 10%	7.2 (3.23)	508.5^{a}	1016.6^{cd}	35.8^{d}	4.3^{c}	2.36 (1.99)^{cd}	506.9^{c}	89.05 (70.81)^{d}	11.75^{c}
T4 - Coconut water 15%	7.5 (3.27)	502.5^{b}	1006.25^{ce}	34.5^{d}	4.2^{c}	2.16 (1.95)^{d}	479.2^{c}	85.1 (67.27)^{e}	15.6^{b}
T5 - Pomegranate juice 15%	7.6 (3.28)	483.8^{b}	1147.6^{c}	53.2^{b}	6.0^{b}	2.85 (2.08)^{c}	632.4^{b}	96.10 (79.24)^{b}	4.75^{e}
T6 - Dates extract 15%	7.6 (3.28)	504.2^{b}	1111.3^{bc}	48.4^{c}	5.6^{b}	2.78 (2.08)^{c}	614.1^{b}	94.05 (76.67)^{c}	4.60^{e}
T7 - Coconut water 20%	8.5 (3.37)	387.7^{d}	1087.2^{bd}	45.5^{c}	5.7^{b}	2.44 (2.00)^{c}	560.8^{b}	97.90 (80.55)^{b}	6.90^{d}
T8 - Pomegranate juice 20%	7.3 (3.26)	511.0^{a}	1313.4^{a}	66.6^{a}	6.4^{a}	4.29 (2.58)^{a}	945.7^{a}	99.50 (83.14)^{a}	0.90^{f}
T9 - Dates extract 20%	6.9 (3.21)	558.0^{a}	1300.2^{a}	64.5^{a}	6.2^{a}	4.18 (2.54)^{a}	890.2^{a}	97.75 (80.27)^{b}	2.75^{e}
T10 - Open pollination	7.1 (3.22)	317.6^{e}	722.1^{f}	—	3.15^{e}	1.30 (1.61)^{e}	270.7^{e}	77.25 (61.63)^{f}	23.40^{a}
GM	7.5	464.2	1057.1	41.6	5.3	2.52	551	91.8	9.9
SE (m) ±	NS	38.5	107.2	4.7	0.8	0.31	7.01	2.8	1.8
CD @5%	114.8	320.1	14.1	NS	0.49	15.05	8.4	5.4	
CV (%)	10.3	14.4	17.6	12.4	26.4	5.8	38.58	7	20.2

* Figures in the parenthesis are arc sine transformed values, , ** Figures in the parenthesis are √x + 0.5 transformed values, In a column, means followed by same alphabet do not differ significantly (p= 0.05) by DMRT

4.6.3.6.5 1000 Seed weight (g)

Seed weight reached its peak in T8 (Pomegranate juice 20%, 6.4 g), closely followed by T9 (Dates extract 20%, 6.2 g), T7 (Coconut water 20%, 5.7 g), and T5 (Pomegranate juice 15%, 6.0 g). The lowest seed weights were seen in T1 (Coconut water 10%, 4.0 g) and T10 (Open pollination, 3.15 g), pointing to better developmental conditions and nutrient partitioning in attractant-enhanced plots.

4.6.3.6.6 Seed yield (g/umbel)

Per umbel seed yield was highest for T8 (Pomegranate juice 20%, 4.29 (2.58) g) and T9 (Dates extract 20%, 4.18 (2.54) g). Treatments with coconut water (T1 and T4) and the control were lowest (1.81 (1.77) g for T1, 2.16 (1.95) g for T4, 1.30 (1.61) g for T10), confirming the powerful effect of bee attractants on yield formation.

4.6.3.6.7 Seed yield (kg/ha)

Field-level seed yields reached their highest levels with T8 (Pomegranate juice 20%, 945.7 kg/ha) and T9 (Dates extract 20%, 890.2 kg/ha). Other high-performing treatments included T5 (Pomegranate juice 15%, 632.4 kg/ha), T6 (Dates extract 15%, 614.1 kg/ha), and T7 (Coconut water 20%, 560.8 kg/ha). The lowest yields occurred in T1 (Coconut water 10%, 333.3 kg/ha) and the control T10 (270.7 kg/ha), illustrating the value of targeted bee attractant application.

4.6.3.6.8 Germination percentage

Germination was optimized in T8 (Pomegranate juice 20%, 99.50 (83.14)), T7 (Coconut water 20%, 97.90 (80.55)), and T9 (Dates extract 20%, 97.75 (80.27)). Lower rates were recorded in T10 (Open pollination, 77.25 (61.63)) and T1 (Coconut water 10%, 81.25 (64.20)), signifying the influence of effective pollination on seed viability. Arc sine transformed values are shown in parentheses for statistical purposes.

4.6.3.6.9 Percent deformed seed

Deformed seeds were least prevalent in T8 (Pomegranate juice 20%, 0.90), T9 (Dates extract 20%, 2.75), T5 (Pomegranate juice 15%, 4.75), and T6 (Dates extract 15%, 4.60). The highest deformities were observed in T1 (Coconut water 10%, 19.25) and T10 (Open pollination, 23.4), confirming that improved pollination and fertilization reduce the risk of defective seed development.

Bee attractants consist of a mixture of specific pheromones, food substances, or volatile molecules derived from plants. They are employed to lure worker bees to prospective target crops that necessitate optimal pollination to enhance the quantity and quality of the yield (fruits/seeds). Research on honeybee attractants has been conducted for the past forty years (Naik, 2019). Among the several bee attractants, food and pheromone-based formulations have been developed into commercial items. The application of these items on target crops consistently stimulates honey bees to forage more energetically, hence assuring optimal pollination and ultimately leading to increased quantity and quality of agricultural production.

In this study, the efficacy of various food-based and pheromone-based bee attractants was analyzed to augment onion seed yield under field conditions (Table 77). Among all treatments, the application of a 20% pomegranate juice solution (T8) exhibited significantly higher bee visitations from *A. mellifera*, *A. florea*, *A. cerana*, *A. dorsata* and *T. iridipennis*, indicating its superior attractiveness to various bee species resulted in the highest net return of Rs. 348,758 per hectare and an impressive ICBR of 5.80, as well as a B:C ratio of 1.94. This treatment also achieved the maximum seed yield (945.65 kg/ha), the greatest additional yield over the control (80.36 kg/ha), the highest gross return (Rs. 719,288/ha), and superior values in seed quality parameters. Notably, pomegranate juice at 20% concentration consistently outperformed other food-based attractants and the open pollinated control in economic and agronomic metrics. Dates extract at 20% (T9) was the second most effective, with net returns of Rs. 336,475/ha and an ICBR of 4.98. Essential oil and lower concentration treatments showed intermediate efficacy, while control treatments generated the lowest yield, economic returns, and benefit-cost ratio (Table 78).

These results confirm that the use of high-concentration pomegranate juice as a bee attractant is not only agronomically beneficial for boosting seed yield and quality in onion but also economically viable for farmers, maximizing returns and cost-benefit ratios under practical cultivation scenarios.

The present investigation demonstrated that pomegranate juice and dates extract at 20% concentration consistently elicited the highest visitation rates from key onion pollinators including *A. mellifera, A. cerana, A. dorsata, A. florea,* and *T. iridipennis* across both Rabi seasons (2023-24 and 2024-25) in Table 79, with peak activity observed 3-5 days after each spray application at 15% and 50% flowering.

Table 77. Cost economics of different bee attractants with respect to seed yield of onion 2023-24.

Treatment	Concentration (%)	Yield (kg/ha)	Additional yield over control (kg/ha)	Value of additional yield (Rs/ha)	Cost of treatment (Rs/ha)	Total cost of cultivation (Rs/ha)	Gross return (Rs/ha)	Net return (Rs/ha)	ICBR	B:C
T1 - Coconut water	10	364.6	25.32	37980	8500	352170	5,46,900	1,94,730	4.47	1.55
T2 - Pomegranate juice	10	429.3	35.87	56505	12000	355670	6,43,950	2,88,280	4.71	1.81
T3 - Dates extract	10	407.6	37.67	53805	9500	353170	6,11,400	2,58,230	5.66	1.73
T4 - Coconut water	15	373.8	40.47	68505	12750	356420	5,60,700	2,04,280	5.37	1.57
T5 - Pomegranate juice	15	465.8	45.67	60705	18000	361670	6,98,700	3,37,030	3.37	1.93
T6 - Dates extract	15	449.8	55.37	83055	14250	357920	6,74,700	3,16,780	5.83	1.89
T7 - Coconut water	20	435.1	51.82	77730	17000	360670	6,52,650	2,91,980	4.57	1.81
T8 - Pomegranate juice	20	880.1	72.92	109380	24000	367670	13,20,150	9,52,480	4.56	3.59
T9 - Dates extract	20	828.1	65.97	98955	19000	362670	12,42,150	8,79,480	5.21	3.43
T10 - Open pollination	-	267.1	-	-	-	343670	4,00,650	56,980	-	1.81

Cost of cultivation of onion for seed production – Rs. 343670/ ha.
Onion seeds selling rate – Rs. 1500/ kg.

Table 78. Cost economics of different bee attractants with respect to seed yield of onion 2024-25.

Treatment	Concentration (%)	Yield (kg/ha)	Additional yield over control (kg/ha)	Value of additional yield (Rs/ha)	Cost of treatment (Rs/ha)	Total cost of cultivation (Rs/ha)	Gross return (Rs/ha)	Net return (Rs/ha)	ICBR	B:C
T1 - Coconut water	10	301.9	39.8	59,700	8,850	3,62,520	6,72,300	3,09,780	6.75	1.85
T2 - Pomegranate juice	10	610.2	33.1	49,650	9,880	3,64,550	6,62,250	2,97,700	5.03	1.82
T3 - Dates extract	10	606.2	48.8	73,200	19,760	3,74,430	6,85,800	3,11,370	3.7	1.83
T4 - Coconut water	15	584.5	53.4	80,100	14,820	3,69,490	6,92,700	3,23,210	5.4	1.87
T5 - Pomegranate juice	15	799	54.4	81,600	12,480	3,68,150	6,94,200	3,26,050	6.54	1.89
T6 - Dates extract	15	778.3	67.4	1,01,100	13,260	3,67,930	7,13,700	3,45,770	7.62	1.94
T7 - Coconut water	20	686.4	63.1	94,650	17,680	3,72,350	7,07,250	3,34,900	5.35	1.9
T8 - Pomegranate juice	20	1011.2	87.8	1,31,700	18,720	3,73,390	7,44,300	3,70,910	7.03	1.99
T9 - Dates extract	20	952.2	79.2	1,18,800	24,960	3,79,630	7,31,400	3,51,770	4.76	1.93
T10 - Open pollination	-	274.2	-	-	-	3,54,670	6,12,600	2,57,930	-	1.73

Cost of cultivation of onion for seed production – Rs. 3,54,670/ ha.
Onion seeds selling rate – Rs. 1500/ kg.

Table 79. Cost economics of different bee attractants with respect to seed yield of onion Pooled data Rabi 2023-24 to 2024-25.

Treatment	Concentration (%)	Yield (kg/ha)	Additional yield over control (kg/ha)	Value of additional yield (Rs/ha)	Cost of treatment (Rs/ha)	Total cost of cultivation (Rs/ha)	Gross return (Rs/ha)	Net return (Rs/ha)	ICBR	B:C
T1 - Coconut water	10	333.3	32.6	48,900	8675	357345	637588	280243	5.63	1.78
T2 - Pomegranate juice	10	519.8	34.5	51,750	10940	360110	645475	285365	4.73	1.79
T3 - Dates extract	10	506.9	43.2	64,800	14630	363800	658600	294800	4.43	1.81
T4 - Coconut water	15	479.2	46.9	70,350	13785	362955	658050	295095	5.1	1.81
T5 - Pomegranate juice	15	632.4	50.0	75,000	15240	364910	669900	304990	4.92	1.84
T6 - Dates extract	15	614.1	61.4	92,100	13755	362925	690825	327900	6.7	1.9
T7 - Coconut water	20	560.8	57.5	86,250	17340	366510	684938	318428	4.98	1.87
T8 - Pomegranate juice	20	945.7	80.4	1,20,600	21360	370530	719288	348758	5.64	1.94
T9 - Dates extract	20	890.2	72.6	1,08,900	21980	371150	707625	336475	4.95	1.91
T10 - Open pollination	-	270.7	-	–	-	349170	578748	229578	–	1.66

Cost of cultivation of onion for seed production – Rs. 349170/ ha.
Onion seeds selling rate – Rs. 1500/ kg.

Pomegranate juice 20% recorded up to 8.28 bees m^{-2} min^{-1} for *A. cerana* and 10.53 bees m^{-2} min^{-1} for *A. florea* during pooled first spray observations, significantly surpassing coconut water treatments (4.5-5.8 bees m^{-2} min^{-1}) and open pollination controls (2.4-4.6 bees m^{-2} min^{-1}). These findings closely align with (Manchare *et al.,* 2019) who reported honey solution 10% and pomegranate juice 5% as superior attractants in bitter gourd, drawing 35.88 fruits $plant^{-1}$ compared to 2.72 q ha^{-1} in open pollination, attributing enhanced foraging to sugar-rich profiles mimicking nectar rewards. Similarly, (Naik *et al.,* 2014) observed citral-based attractants boosting bee visits to 2.96 bees 10 m^2 5 min^{-1} in niger, emphasizing food-based sprays' role when crops like onion exhibit low natural allure due to protandrous dichogamy.

In the current investigation, 20% pomegranate juice and dates extract were shown to deliver maximum foraging counts across all major pollinator species, outperforming lower concentrations of both the same and alternative attractants. The enhanced activity aligns with observations by (Patil *et al.,* 2000) and (Jayaramappa and Bhargava, 2011), who documented that fruit-based and sugar- or jaggery-based attractants increased bee numbers and pollination intensity in crops like watermelon, ridge gourd, and bitter gourd. The present research also confirms that coconut water, while moderately effective, does not match the efficacy of fruit-based juice attractants a finding consistent with other Indian research on local attractants in cucurbits.

Foraging behavior across species showed rapid response post-spray, with A. dorsata peaking at 11.1 bees m^{-2} min^{-1} (pomegranate 20%) during second spray 1 DAS in pooled data, declining by 7 DAS yet remaining 2-3 fold higher than controls, indicative of prolonged volatile emission. A. florea exhibited sustained peaks (9.18-10.53 bees m^{-2} min^{-1} at 3-5 DAS), while stingless bee T. iridipennis responded robustly (73.5 bees m^2 min^{-1} at 3 DAS for pomegranate 20%), reflecting heightened sensitivity to fruit volatiles during onion's extended umbel presentation. These patterns mirror (More *et al.,* 2020) where jaggery 10% elevated A. mellifera to 15.89 bees m^2 5 min^{-1} at 1200 hrs in sunflower, with activity initiating at 0800 hrs and peaking midday, consistent with onion observations of maximal visits around floral nectar secretion peaks. Current results extend prior work on A. cerana in mustard by (Manchare *et al.,* 2020), where sprays at 10-50% flowering intensified visits up to 5-7 DAS, underscoring timing's role in synchronizing with abiotic cues like temperature that limit baseline foraging (2.7-3.4 bees m^{-2} min^{-1} DBFS).

Seed yield parameters further validated attractants' efficacy, with pomegranate 20% yielding 1011.2 kg ha^{-1} (268% over control's 274.2 kg ha^{-1}), dates 20% at 952.2 kg ha^{-1}, and

corresponding gains in umbelts umbel^{-1} (1325.6), seeds umbel^{-1} (518.6), 1000-seed weight (6.4 g), and germination (100%). Coconut water 20% moderated at 686.4 kg ha^{-1} with 98.8% germination, while controls lagged in deformed seeds (22.8%). These outcomes parallel Bijarniya's mustard thesis where Bee-Q 1.25% and jaggery 10% boosted siliqua plant^{-1} to 186.44 and seeds siliqua^{-1} to 15.70 versus exclusion plots, linking enhanced pollination to 35-61% yield uplift via cross-pollination. Pomegranate and dates outperformed in seed setting increase (68.2% and 65.8% over control), aligning with (Abrol and Kapil, 1996) who noted A. dorsata and A. florea driving 80-98% crucifer pollination efficiency.bee-attractant.

The superior performance stems from chemical and biological properties of major components: pomegranate's ellagic acid, punicalagins, and anthocyanins (polyphenols with olfactory cues akin to flavonoids in bee-attractive nectar) coupled with 14-18° Brix sugars; dates extract's glucose/fructose (70-80% total sugars), phenolics, and flavonoids enhancing hygroscopic appeal; coconut water's cytokinins and electrolytes providing milder nectar mimicry. Such profiles demonstrated moderate yet significant efficacy in drawing diverse pollinators to onion umbels, whose thiamine-poor nectar limits self-attraction. Findings corroborate (Jayaramappa and Bhargava, 2015) on Bee-Q/Fruit Boost in watermelon (12.5 g L^{-1} drawing superior foragers) and Wankhede et al. (2018) where jaggery 10% yielded 69.55 q ha^{-1} via 283 seeds fruit^{-1}. Pooled two-year data affirm reproducibility, with CD values (1.6-2.4) and CV (12-25%) indicating robust field applicability.

The average amount of these attractants supplements the natural nectar resources of onion flowers, serving as a vital energy source for honeybees and substantially increasing bee visitations. However, the bee-attracting efficacy of all tested attractants declined after three days of spraying, likely due to the evaporation and volatilization of chemical components under sunlight, as reported by (Malerbo-Souza *et al.,* 2004). Interestingly, the results revealed that onion umbels attracted a greater number of bees during the second spray compared to the first. This increase can be attributed to the timing of the second spray coinciding with 50 percent flowering—a stage characterized by a higher abundance of open flowers—which provides optimal foraging conditions for bees seeking pollen and nectar (Kulkarni *et al.,* 2017).

Overall, results from this study closely align with established literature on food-based attractants augmenting pollinator services in entomophilous crops, particularly where abiotic factors constrain natural visitation. Pomegranate 20% and dates 20% emerge as cost-effective, indigenous options for onion seed production, enhancing foraging across Apis and non-Apis species while improving yield quality metrics by 2-4 fold over controls. Strategic dual-spray protocols capitalize on residual effects, bridging gaps in onion's pollination deficit and

supporting sustainable intensification. Future integration with hive management could further optimize outcomes, as evidenced by (Chand and Singh, 1995) where bees alone contributed 20% mustard yield.

CHAPTER V

SUMMARY AND CONCLUSION

SUMMARY

To investigate the impact of abiotic variations on onion pollinators on different dates of planting.

The investigation documented thirty distinct insect species visiting onion flowers across four orders during Rabi 2023-24 and 2024-25, with Hymenoptera dominating at 78.42% of total forage visits, followed by Diptera (16.33%), Lepidoptera (5.67%), and Coleoptera (0.56%). Among hymenopteran visitors, *Apis mellifera* emerged as the predominant pollinator accounting for 42.14% of mean forage visits, followed by *Tetragonula iridipennis* (18.59%), *A. dorsata* (7.36%), *A. cerana* (3.82%), and *A. florea* (1.86%) across both experimental years. The investigation across seven planting dates (5 September, 20 September, 5 October, 20 October, 5 November, 20 November, and 5 December 2023) revealed that the 5th November 2023 sowing date exhibited superior pollinator activity, with *A. mellifera* achieving peak visitation rates of 12.00 bees/m²/5 min during the 7th Standard Meteorological Week, coinciding with optimal environmental conditions characterized by moderate temperatures (25-30°C), stable humidity, and gentle wind speeds.

Correlation analysis between weather parameters and bee abundance demonstrated species-specific sensitivities to abiotic factors. *Apis cerana* exhibited highly significant negative correlations with maximum temperature and evaporation, indicating marked decline in activity under elevated temperature and moisture stress conditions, while its foraging was constrained by cooler early-morning temperatures and high winds. Conversely, *A. mellifera* demonstrated moderate positive correlations with both maximum and minimum temperatures, reflecting broader thermal plasticity and superior thermoregulatory mechanisms that allowed activity across wider temperature ranges. *Tetragonula iridipennis*, despite showing negative correlations with temperature and humidity parameters, maintained relatively stable foraging activity due to its physiology as a stingless bee adapted to tropical microclimates, with smaller body size and eusocial colony structure allowing efficient foraging in shaded or semi-shaded conditions. The wild bee species *A. dorsata* and *A. florea* exhibited more variable and generally negative correlations with moisture-related factors like evaporation and humidity, reflecting their ecological niche as habitat-specialized foragers with limited ability to forage under windy or dry conditions. Periods of high rainfall and rapid evaporation were associated with

suppressed pollinator visitation across all species, with rain discouraging flight outright and altering nectar concentration while high evaporation rapidly depleted available floral rewards.

To study the role of varietal traits of onion on abundance and foraging behavior of insect pollinators (*Apis mellifera)*

The morphological characterization of seven onion varieties (Bhima Super, Bhima Red, Bhima Raj, Bhima Dark Red, Bhima Shakti, Bhima Shubra, and Bhima Shweta) revealed significant genetic variation in floral traits influencing pollinator attraction. Bhima Super and Bhima Shakti produced maximum umbels per plant (9-10 at 75 DAS), longest scapes (92.4-95.6 cm), and largest umbel diameters (35.87-37.2 cm) across both years, indicating their higher reproductive capacity and enhanced floral display for pollinators. In contrast, white varieties Bhima Shubra and Bhima Shweta consistently recorded lower morphological parameters with fewer umbels (6-7), shorter scapes (57.5-75.6 cm), and smaller umbel diameters (24.06-30.0 cm), demonstrating inferior reproductive architecture.

Foraging rate demonstrated that *A. mellifera* exhibited temporal patterns with activity starting lower in the morning (6.15-9.47 flowers visited bee/min at 08:00 h), progressively increasing to reach peak during afternoon (14.03-19.83 flowers visited bee/min at 14:00 h), and subsequently declining towards evening. Bhima Super recorded the highest mean foraging rate (14.222 flowers visited bee/min) followed by Bhima Shakti (13.700 flowers visited bee/min), while Bhima Shweta recorded the lowest (9.840 flowers visited bee/min). ANOVA revealed that main effects of onion variety ($F=193$, $P<0.001$) and time of observation ($F=1275$, $P<0.001$) were highly significant, with significant interaction between variety and time ($F=3.6$, $P<0.001$) indicating that foraging patterns across different times varied depending on onion variety. Time spent per umbel was significantly highest in Bhima Super (6.703 seconds/umbel), indicating superior floral reward quality that encouraged longer handling times and more thorough pollination.

Biochemical analysis of pollen and nectar from different onion varieties revealed that colored varieties offered superior nutritional rewards to pollinators compared to white varieties. Bhima Dark Red exhibited highest pollen protein content (40.5 mg/g), while Bhima Super recorded maximum nectar proteins (31.23 mg GAE/g for phenols and 8.28 mg QE/g for flavonoids). Bhima Shakti demonstrated highest reducing sugars in nectar (glucose 19.25%, fructose 23.19%), amino acids (45.81 mg/g), and favorable sugar ratios attractive to bee foragers. White varieties (Bhima Shubra and Bhima Shweta) consistently recorded lower biochemical quality across all parameters, explaining their reduced attractiveness to pollinators. These biochemical differences directly correlated with observed pollinator

preferences, with varieties offering richer nitrogenous compounds, antioxidants, and balanced sugar profiles attracting significantly more bee visits and longer foraging durations.

To evaluate the effect of indigenous bee attractants on pollinator activity and seed yield in onion.

The evaluation of indigenous bee attractants (pomegranate juice, dates extract, and coconut water at 10%, 15%, and 20% concentrations) demonstrated that pomegranate juice at 20% concentration elicited significantly superior pollinator visitation across all five major bee species. For *A. mellifera*, pomegranate juice 20% recorded peak counts of 71.3 bees/m²/5 min at 3 days after first spray (applied at 15% flowering) and 69.6 bees/m²/5 min following second spray (applied at 50% flowering), representing 2-4 fold increases over open pollination controls (36.6-41.3 bees/m²/5 min). Similar enhancement patterns were observed for other bee species, with dates extract 20% producing the second-highest visitation rates (69.3 and 65.6 bees/m²/5 min for *A. mellifera* at 3 days post-spray), while coconut water treatments yielded intermediate results, and open pollination controls consistently produced the lowest counts.

The attractant efficacy exhibited temporal dynamics, with peak effectiveness occurring at 3-5 days after spray application, declining thereafter due to evaporation and volatilization of chemical components under sunlight. Interestingly, bee counts during second spray applications were higher than first spray across all treatments, attributed to the timing of second spray coinciding with 50% flowering stage characterized by optimal nectar and pollen availability, providing enhanced foraging conditions for bees. *Tetragonula iridipennis* responded particularly robustly to pomegranate juice 20%, reaching 73.5 bees/m²/5 min at 3 days after spray, reflecting heightened sensitivity to fruit volatiles during onion's extended umbel presentation period.

Seed yield parameters validated the efficacy of bee attractants in translating enhanced pollinator activity into agronomic gains. Pomegranate juice 20% produced the highest pooled seed yield of 945.7 kg/ha, representing an 80.36 kg/ha increase over control and 249% increase over open pollination (270.7 kg/ha). This treatment achieved 1313.4 seeds per umbel (66.6% seed setting increase over control), 6.4 g per 1000-seed weight, 99.5% germination percentage, and minimal seed deformation (0.9%). Dates extract at 20% concentration recorded the second-highest performance with 890.2 kg/ha seed yield, while coconut water treatments and lower concentration applications yielded intermediate results. Open pollination controls consistently produced the lowest yields with highest seed deformation (23.4%), demonstrating the critical role of managed pollination in onion seed production.

Cost-benefit analysis revealed that pomegranate juice 20% treatment generated the highest net returns of Rs. 348,758 per hectare with an incremental cost-benefit ratio (ICBR) of 5.80 and benefit-cost (BC) ratio of 1.94, demonstrating both agronomic and economic viability. Dates extract 20% followed with net returns of Rs. 336,475/ha and ICBR of 4.98, while all attractant treatments substantially outperformed open pollination controls (net returns Rs. 201,225-257,930/ha). The superior chemical composition of pomegranate juice, rich in ellagic acid, punicalagins, anthocyanins, and 14-18 Brix sugars, and dates extract containing 70-80% glucose-fructose along with phenolics and flavonoids, provided olfactory and gustatory cues mimicking high-quality nectar, thereby stimulating intensive foraging behavior across multiple bee species.

CONCLUSION

Impact of abiotic variations on onion pollinators.

This investigation establishes that pollinator-plant interactions in onion are significantly influenced by complex interplay of abiotic factors including temperature, relative humidity, wind velocity, rainfall, evaporation, and light intensity. The dominance of *Apis mellifera* as the principal pollinator, contributing over 42% of total forage visits, underscores its critical role in onion seed production, while the consistent presence of *Tetragonula iridipennis* highlights the importance of stingless bees as reliable supplementary pollinators across diverse environmental conditions. The demonstrated species-specific responses to environmental parameters, particularly the narrow thermal tolerance of *A. cerana* (highly significant negative correlations with maximum temperature and evaporation) contrasted with the superior thermoregulatory adaptability of *A. mellifera* and *T. iridipennis* (moderate positive correlations with temperature), provide valuable insights for optimizing pollination management strategies under variable climatic scenarios.

The identification of early November sowing as the optimal planting window offers practical guidance for maximizing pollinator activity and subsequent seed set through strategic phenological alignment. This planting date achieved synchrony between peak onion bloom and favorable meteorological conditions (moderate temperatures 25-30°C, stable humidity, gentle winds, and sustained nectar production), creating an exceptionally attractive landscape for foragers and providing favorable energy balance where bees expended less energy on thermoregulation. The aggregated findings offer actionable recommendations that aligning sowing schedules such that peak onion bloom coincides with anticipated windows of moderate temperature, sunshine, and stable low winds will naturally enhance pollinator visitation and

seed set. The differential responses of managed (*A. mellifera*) versus wild bee species (*A. dorsata*, *A. florea*) to environmental variability emphasize the importance of supporting diverse pollinator communities to buffer against climatic perturbations and ensure resilient pollination services.

Role of varietal traits on pollinator abundance and foraging behavior.

The superior performance of Bhima Super and Bhima Shakti varieties, characterized by enhanced morphological attributes (increased umbel number, larger umbel diameter, longer scapes) and enriched biochemical profiles (elevated proteins, amino acids, phenols, flavonoids, and reducing sugars in nectar and pollen), demonstrates that genetic selection for pollinator-attractive traits can significantly enhance foraging activity and pollination efficiency. The pronounced varietal preference exhibited by *A. mellifera*, with significantly higher foraging rates (14.222 flowers visited bee/min) and longer handling times (6.703 seconds/umbel) on Bhima Super umbels compared to Bhima Shweta (9.840 flowers visited bee/min), validates the hypothesis that onion genotypes differ substantially in their attractiveness to pollinators, presenting opportunities for breeding programs to incorporate pollinator-friendly traits.

The biochemical differentiation between colored and white onion varieties, with colored genotypes offering substantially richer nitrogenous and antioxidant rewards, suggests that varietal improvement programs should prioritize floral reward quality alongside agronomic performance to optimize pollinator attraction and seed productivity. The significant main effects of onion variety ($F=193$, $P<0.001$) and the variety × time interaction ($F=3.6$, $P<0.001$) on foraging patterns indicate that varietal traits not only influence overall pollinator abundance but also modulate temporal foraging dynamics throughout the day. These findings align with broader scientific understanding that pollen and nectar biochemical composition directly affects pollinator preferences and foraging decisions, with varieties providing higher protein content, balanced sugar ratios (glucose : fructose), and secondary metabolites (phenolics, flavonoids) attracting more visits and ensuring more effective pollination. Future breeding efforts should integrate morphological selection (umbel size, scape length) with biochemical trait improvement to develop onion varieties that maximize both floral display and reward quality for enhanced pollination outcomes.

Effect of indigenous bee attractants on pollinator activity and seed yield.

The remarkable efficacy of pomegranate juice and dates extract at 20% concentration as indigenous bee attractants represents a practical, cost-effective intervention for enhancing

pollinator services in onion seed production systems. The capacity of these attractants to increase *A. mellifera* visitation by approximately 2-4 fold over controls (71.3 vs. 41.3 bees/m²/5 min at peak), with sustained efficacy spanning 5-7 days post-application, demonstrates their potential to bridge pollination deficits in crops with inherently low floral attractiveness due to protandrous dichogamy and limited natural nectar production. The strategic dual-spray protocol implemented at 15% and 50% flowering stages capitalizes on residual volatile effects while synchronizing with peak umbel presentation, optimizing pollinator exposure throughout the critical pollination window.

The substantial improvements in seed yield parameters including increased seed number per umbel (1313.4 seeds), enhanced 1000-seed weight (6.4 g), elevated germination percentage (99.5%), and reduced seed deformation (0.9%) following pomegranate juice 20% application demonstrate that enhanced pollinator activity translates directly into superior seed quality and economic returns. The achievement of 945.7 kg/ha seed yield, representing a 249% increase over open pollination controls (270.7 kg/ha), coupled with net returns of Rs. 348,758/ha and ICBR of 5.80, establishes the economic viability and scalability of this technology for commercial onion seed production. These findings align with broader scientific understanding that fruit-based attractants augment pollination services in entomophilous crops by supplementing natural floral rewards through volatile organic compounds, increasing bee recruitment through enhanced olfactory cues, and extending foraging duration by providing gustatory stimulation, particularly under conditions of abiotic stress that constrain baseline pollinator visitation.

From an integrated pest and pollinator management perspective, the study validates that coordinated manipulation of planting schedules, varietal selection, and targeted application of indigenous attractants can synergistically enhance pollination efficiency while maintaining ecological sustainability. The research contributes fundamental knowledge on pollinator preferences, foraging behavior, and resource-plant interactions in *Allium cepa*, while simultaneously providing actionable recommendations for seed production stakeholders to maximize yield, quality, and profitability through evidence-based pollination management. Future research should explore integration of hive placement optimization, nesting site conservation for wild bees, and refinement of attractant formulations to further enhance pollination outcomes and support sustainable intensification of onion seed production systems under diverse agroclimatic conditions.

FUTURE LINE OF WORK

Molecular breeding: Identify QTLs for pollinator traits (umbel size, nectar sugars) using doubled-haploid lines; develop CMS hybrids with enhanced floral rewards.

Climate resilience: Breed heat/drought-tolerant varieties syncing bloom with projected 2-4°C warming; test under +2°C scenarios.

Tech integration: Deploy AI pollinator monitors (e.g., Bee Hero systems) and drones for attractant application; validate in polyhouse trials.

Wild pollinators: Conserve A. dorsata, A. florea and T. iridipennis via nesting habitats; study microbiome-pollinator interactions.

Multi-omics: LCMS nectar volatiles; GWAS for attractant response genes.

Economics/scalability: Farmer trials across agro climates; organic formulations; IPM integration minimizing pesticides during bloom.

REFERENCE

Abbasi Bastami, Y., Bakhshi, D., Torahi, A., Pourghayoumi, M., & Khalifezadeh Koureh, O. (2022). Biochemical and physicochemical properties of some date palm (Phoenix dactylifera) fruit cultivars. *Journal of Horticulture and Postharvest Research*, *5*(3), 197-206.

Abou-Shaara, H. F. (2014). The foraging behaviour of honey bees, Apis mellifera: a review. *Veterinarni medicina*, *59*(1).

Abrol, D. P., & Sharma, P. (2023). Foraging in Giant Honeybees. In *Role of Giant Honeybees in Natural and Agricultural Systems* (pp. 219-251). CRC Press.

Abrol, D.P. 2010. Foraging behaviour of *Apis florea* F., an important pollinator of *Allium cepa* L. *Journal of Apicultural Research*, 49(4): 318-325.

Abrol, D.P. 2010. Foraging. In: Honeybees of Asia. *Berlin, Heidelberg: Springer Berlin Heidelberg*, 257-292.

Abrol, D.P. 2016. Foraging strategies in honeybees, *Apis dorsata* F. and *Apis florea* F. in relation to availability of energy rewards. *Journal of Apiculture*, 31(1): 9- 18.

Abrol, D.P. and Kapil, R. P. (1996). Studies on abundance and importance of insect pollinators for oil seed production. J. Insect Sci., 9(2): 172-174.

Adel, M.R., Namsghi, H. S. and Hosseini, M. 2013. Effect of insect pollinators on onion seed production quality and quantity. *Journal of Crop Protection*, 2(4): 395-402.

Ahmad, M., Pathania, S. S., Kumar, S. and Makhdomi, I. 2020. Insect pollinator diversity of onion and its role in seed production in Kashmir Himalayas. *Journal of Experimental Zoology*, 23(2): 1623- 1626.

Ahmed, S., Rahim, M. A., Moniruzzaman, M., Khatun, M. A., Jahan, F. N., & Akter, R. (2020). Effect of bulb sizes on the seed yield of two onion (allium cepa L.) varieties. *SAARC Journal of Agriculture*, *18*(2), 51-65.

Ajibogun, O. A., & Oboma, Y. I. (2013). Biochemical composition of coconut water: Nigeria species. *Int J of Med and Bio Sci*, *1*(1), 1-4.

Akila, S. and Babu, P.C.S. 1994. Release of different dose of *Trichogramma* and its effect on internode borer, yield and quality of sugarcane. *Sugarcane (London)*, 2: 22-23.

Ali, M. A., Hossain, M. M., Zakaria, M., Naznin, A., & Islam, M. M. (2015). Effect of bulb size on quality seed production of onion in Bangladesh. *International Journal of Agronomy and Agricultural Research*, *6*(4), 174-180.

Al-Juboori, Amer Abdullah Hussein (2020). "Response of three varieties of onions (Allium cepa l.) to different plant densities and their effect on growth and yield adjectives.": 5267-5271.

Alkhoori, M. A., Kong, A. S. Y., Aljaafari, M. N., Abushelaibi, A., Erin Lim, S. H., Cheng, W. H., ... & Lai, K. S. (2022). Biochemical composition and biological activities of date palm (Phoenix dactylifera L.) seeds: A review. *Biomolecules*, *12*(11), 1626.

Al-Sahaf, F. H. 2002. Effect of planting method and rose water spray on seed production in onion (*Allium cepa* L.). *Emirates Journal of Food and Agriculture*, 14(1): 14-23.

Alshallash, K. S., Abolaban, G., Elhamamsy, S. M., Zaghlool, A., Nasr, A., Nagib, A., ... & Taha, I. M. (2023). Bee pollen as a functional product–chemical constituents and nutritional properties. *Journal of Ecological Engineering*, *24*(2), 173-183.

Anisuzzaman M, Ashrafuzzaman M, Ismail MR, Uddin MK and Rahim MA. 2009. Planting time and mulching effect on onion development and seed production, African Journal of Biotechnology, 8 (3): 412-416.

Anonymous Official Methods 969.38, Moisture in honey and bee products.

Arya, J. S., Singh, N., Arya, P., & Kant, A. (2017). Morphological variations and relationship among onion germplasm for quantitative and qualitative traits at trans-Himalaya Ladakh, India. *Australian Journal of Crop Science*, *11*(3).

Asaduzzaman M, Hasan M, Moniruzzaman M and Howlander MHK. 2012. Effect of Bulb Size and Plant Spacing on Seed Production of Onion (Allium cepa L.), Bangladesh Journal of Agricultural Research, 37(3): 405-414.

Ashagrie, T., Belew, D., Alamerew, S., & Getachew, Y. (2014). Effects of planting time and mother bulb size on onion (*Allium cepa* L.) seed yield and quality at Kobo Woreda, Northern Ethiopia. *International Journal of Agricultural Research*.

Asritha, C., Kambrekar, D. N., Kandakoor, S. B., Hiremath, S. M., & NM, R. (2025). Influence of Pollinator Attractant Crops on Abundance of Honeybees and Yield Parameters of Onion. *International Journal of Bio-Resource & Stress Management*, *16*(3).

Badade, G. M., Nalwandikar, P. K., Sonkamble, M. M. and Shetgar, S. S. 2017. Honey bee visits on seed production in onion. *Indian Journal of Entomology*, 79(4): 436-439.

Bayram, N. E., Gercek, Y. C., Celik, S., Mayda, N., Kostić, A. Ž., Dramićanin, A. M., & Özkök, A. (2021). Phenolic and free amino acid profiles of bee bread and bee pollen with the same botanical origin–similarities and differences. *Arabian Journal of Chemistry*, *14*(3), 103004.

Belayneh, H., Riley, K. W., & Tadesse, N. (1986). The effect of sowing date, seed rate and fertilizer on seed yield of niger in central highland of Ethiopia. *J. Oilseeds Res*, *3*, 216-222.

Bezabih, G. and Gebretsadikan, K. 2014. Managed honeybees (*Apis mellifera* L.) increase onion (*Allium cepa*) seed yield and quality. *Livestock Research and Rural Development*, 26(1) : 112-114.

Bharti, V., Ahlawat, D. S., Sharma, S. K., Singh, N. V., Jitender, J., & Singh, N. (2015). Diversity, abundance and pollination efficiency of insect pollinators of fennel (Foeniculum vulgare Miller) and effect of abiotic factors on insect pollinator activity. *Journal of Applied and Natural Science*, *7*(2), 786.

Bindu, B., & Podikunju, B. (2016). Evaluation of onion (Allium cepa L.) varieties for suitability in Kollam district of Kerala. *Journal of Krishi Vigyan*, *5*(1), 117-118.

Biradar, R., Das, U., Kariuyanna, B. and Srivastava, P. 2017. Diversity and abundance of visitors/pollinators on onion (*Allium cepa* L.). *Bulletin of Environment*, Pharmacology and Life Sciences, 6(2): 201-204.

Bohart, G. E., Nye, W. P. and Hawthorn, L. R. 1970. Onion pollination as affected by different levels of pollinator activity. Utah Agricultural experiment Station Bulletin, 482: 1-63.

Boulfous, N., Belattar, H., Ambra, R., Pastore, G., & Ghorab, A. (2025). Botanical origin, phytochemical profile, and antioxidant activity of bee pollen from the mila region, Algeria. *Antioxidants*, *14*(3), 291.

Bradford, M. M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Analytical biochemistry*, *72*(1-2), 248-254.

Bryś, M. S., & Strachecka, A. (2024). The key role of amino acids in pollen quality and honey bee physiology—a review. *Molecules*, *29*(11), 2605.

Calderone, N. W. 2012. Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992–2009. *PloS one*, 7(5): e37235.

Carlson, E. (1974). Onion varieties, honeybee visitations, and seed yield. *California Agriculture*, *28*(9), 16-18.

Carter, C., Shafir, S., Yehonatan, L., Palmer, R. G., & Thornburg, R. (2006). A novel role for proline in plant floral nectars. *Naturwissenschaften*, *93*(2), 72-79.

Caselles, C., Vargas, S.V.C. and Galmarini, C. R. 2019. Effect of environmental factors on bee activity and onion (*Allium cepa* L.) seed yield. *Revista de la Facultad de Ciencias Agrarias*, 51(2): 13-26.

Chand, H. and Singh, B. (1995). Effect of pollination by Apis cerana F. on yield of mustard, Brassica juncea L. Indian Bee Journal, 57(1): 173-174.

Chandel, R. S., Thakur, R. K., Bhardwaj, N. R. and Pathania, N. 2004. Onion seed crop pollination: a missing dimension in mountain horticulture. *In: XXVI International Horticultural Congress: Issues and Advances in Transplant Production and Stand Establishment Research*, 631: 79-86.

Chandran, N. 2009. Evaluation of indigenous bee attractants in enhancing the yield parameters of sesame and niger. M.Sc. (Agri.), *Thesis, University of Agricultural Sciences, Dharwad (Karnataka, India).*

Chandrashekar, G. S. and Sattagi, H. N. 2009. Influence of bee attractants on bee pollination on seed yield and yield in radish. *Karnataka Journal of Agricultural Sciences*, 22(4): 777-780.

Chavan, V., Viraktamath, S. and Bhamare, V. 2016. Effect of different bee attractants on bee visitation and seed yield of lucerne. *Journal of Insect Science*, 29: 293-300.

Cook, S. M., Awmack, C. S., Murray, D. A., & Williams, I. H. (2003). Are honey bees' foraging preferences affected by pollen amino acid composition?. *Ecological Entomology*, *28*(5), 622-627.

Currah, L. (1981). Onion flowering and seed production. *Scientific Horticulture, 32*, 26-46.

Dafni, A. (1992). *Pollination Ecology: A Practical Approach.* IRL Press at Oxford University Press, Oxford, UK, pp. 1–286.

Demisie Rand Tolessa K. 2018. Growth and bulb yield of onion (Allium cepa L) in response to plant density and variety in Zimma, south west Ethiopia, Advances in Crop Science and Technology, 6(2): 357.

Devi, S. Gulati, R., Tehri, K. and Asha, P. 2014. Diversity and abundance of insect pollinators on *Allium cepa* L. *Journal of Entomological and Zoological Studies*, 2(6): 34-38.

Di Pasquale, G., Salignon, M., Le Conte, Y., Belzunces, L. P., Decourtye, A., Kretzschmar, A., ... & Alaux, C. (2013). Influence of pollen nutrition on honey bee health: do pollen quality and diversity matter?. *PloS one*, *8*(8), e72016.

Dinesh, B. K. 2003. Resource partitioning by honey bees in different crops with special reference to cucumber (*Cucumis sativa* L.) and impact of bee pollination on cucumber yield. *Ph. D. thesis submitted to University of Agricultural Sciences, Bengaluru*, 1-152. Corpus ID: 92552439.

Divija, S. D., & Kamala Jayanthi, P. D. (2022). Pollination efficiency and foraging behaviour of honey bees and flies to onion Allium cepa L. *Journal of Apicultural Research*, *61*(5), 688-694.

Divija, S. D., Jayanthi, K. P. D., Belavadi, V. V. and Yogeesha, H. S. 2022. Diversity and foraging behaviour of floral visitor assemblages in onion *Allium cepa* L. *Journal of Apicultural Science*, pp. 1–3.

Dormann, C. F., Schweiger, O., Arens, P., Augenstein, I., Aviron, S. T., Bailey, D., Baudry, J., Billeter, R., Bugter, R., Bukacek, R. and Burel, F., 2008. Prediction uncertainty of environmental change effects on temperate European biodiversity. *Ecology Letters*, 11(3): 235-244.

Elfalleh, W., Tlili, N., Ying, M., Sheng-Hua, H., Ferchichi, A., & Nasri, N. (2011). Organoleptic quality, minerals, proteins and amino acids from two Tunisian commercial pomegranate fruits. *International Journal of Food Engineering*, *7*(4).

Elgubbi, H. S., & Mlitan, A. M. (2015). Colorimetric method for determination of amino acids on thin layer and filter paper chromatography using a modified Ninhydrin reagent. *J Agric Sci Technol*, *5*, 190-193.

El-Helaly MA and Karam SS. 2012. Influence of Planting Date on the Production and Quality of Onion Seeds, Journal of Horticultural Science & Ornamental Plants, 4 (3): 275-279.

Ellis, A., & Ellis, J. D. (2020). The benefits of pollen to honey bees. *EDIS*, 2020(6), ENY-152.

Evans, D. E., Taylor, P. E., Singh, M. B., & Knox, R. B. (1991). Quantitative analysis of lipids and protein from the pollen of Brassica napus L. *Plant science*, *73*(1), 117-126.

Faegri, K. and Van der Piji. L., 1971. Principles of pollination ecology. *Pergamon, Oxford*.

Farooqi, M. A., Aslam, M. N., Sajjad, A., Akram, W., & Maqsood, A. (2021). Impact of abiotic

factors on the foraging behavior of two honeybee species on canola in Bahawalpur, Punjab-Pakistan. *Asian Journal of Agriculture and Biology*, *2021*(01).

Free, J. B. 1993. Insect pollination of crops. *Academic Press, London, UK*, 1-554.

FSSAI Manual of Methods of Analysis of Foods - Honey & Other Bee Hive Products.

Gage, S. L., Spivak, M., & William, P. (2020). Pollen alters amino acid levels in the honey bee brain and fat body. *Frontiers in Neuroscience*, 14, 231.

Gebremedhn, H., Tadesse, A., & Belay, T. (2014). Relating climatic factors to foraging behavior of honeybees (Apis mellifera) during blooming period of Guizotia abyssinica (LF). *Livestock Research for Rural Development*, *26*(4), 2-7.

Ghosh, S., Jeon, H., & Jung, C. (2020). Foraging behaviour and preference of pollen sources by honey bee (Apis mellifera) relative to protein contents. *Journal of Ecology and Environment*, *44*(1), 4.

Ghramh, H. A., & Khan, K. A. (2023). Honey bees prefer pollen substitutes rich in protein content located at short distance from the apiary. *Animals*, *13*(5), 885.

Gill, M. C., & Walters, K. F. (2023). Potential use of floral nectar sugar characteristics in plant selection for pollinator habitats. *Journal of Apicultural Research*, *62*(2), 266-273.

Ginoya AV, Patel JB, Delvadiya IR and Jethva AS. 2018. Effect of bulb size and plant spacing on seed quality parameters of onion (Allium cepa L.) cv. GJWO, Journal of Pharmacognosy and Phytochemistry7(3): 2511-2515.

Godley, E.J. 1979. Flower biology in New Zealand. *New Zealand Journal of Botany*, 17(4): 441-466.

González-Teuber, M., & Heil, M. (2009). Nectar chemistry is tailored for both attraction of mutualists and protection from exploiters. *Plant signaling & behavior*, *4*(9), 809-813.

Goodwin, M. (2012). *Pollination of crops in Australia and New Zealand* (p. 121). Wagga Wagga, Australia: RIRDC.

Gosai JA, Rathawa SN, Dhakad RK, Jatav A and Verma RL. 2018. Evaluation of different varieties of Onion (Allium cepa L.) under North Gujarat Condition, International Journal of Current Microbiology and Applied Sciences, 7(5):3775-3780.

Goulson, D., Lye, G. C. and Darvill, B. 2008. Decline and conservation of bumble bees. *Annual Review of Entomology*, 53: 191-208.

Hadhramie, A. Z. M. S. A., Mazrooei, F. R. A. A., Mamari, S. A., Humaid, S. H. J. A., Khan, S., & Akhtar, M. J. (2023). Physicochemical evaluation to assess the quality of honey samples marketed in Oman.

Hagler, J. R., Cohen, A. C., & Loper, G. M. (1990). Production and composition of onion nectar and honey bee (Hymenoptera: Apidae) foraging activity in Arizona. *Environmental entomology*, *19*(2), 327-331.

Hamma, IL. 2013. Growth and yield of onion as influenced by planting and dates and mulching types in Samarau, Zaria, International Journal of Advance Agricultural Research.

1:22-26.

Hanif, R., Yaqoob, M., Mir, S. H., Ahmad, I., Lone, L. A., Wani, F. J. and Anayat, R. 2023. Role of indigenous attractants in enhancing quantitative parameters of cucumber (*Cucumis sativus* L.). *Emerging Life Sciences Research*, 9(1): 159-163.

Hendrickx, F., Maelfait, J. P., Van Wingerden, W., Schweiger, O., Speelmans, M., Aviron, S., Augenstein, I., Billeter, R., Bailey, D., Bukacek, R. and Burel, F., 2007. How landscape structure, land-use intensity and habitat diversity affect components of total arthropod diversity in agricultural landscapes. *Journal of Applied Ecology*, 44(2): 340-351.

Hendriksma, H. P., & Shafir, S. (2016). Amino acid and carbohydrate tradeoffs by honey bee nectar foragers and their implications for plant–pollinator interactions. *Journal of Insect Physiology*, 98, 67–75.

Hosamani, R. M., Patil, B. C., & Ajjappalavara, P. S. (2010). Genetic variability and character association studies in onion (Allium cepa L.). *Karnataka Journal of Agricultural Sciences*, *23*(2).

Hosamani, V., Reddy, M. S., Venkateshalu, H. B., Lingamurthi, K. R., Ravikumar, B. and Ashoka, N. 2019. Pollinator diversity, abundance and their stay time in onion, *Allium cepa* L. *Journal of Entomology and Zoology Studies*, 7(6): 158-161.

Hosamani, V., Venkateshalu, Jagadeesha, N., Reddy, M. S., Gangadarappa, P.M. and Ravikumar, B. 2020. Effect of bee pollination and attractants on quantitative and qualitative parameters of onion (*Allium cepa*) seed yield and quality. International *Journal of Current Microbiology and Applied Sciences*, 9(2): 1885-1892.

Howlett, B. G., Kitching, R. L. and Boulter, S. L. 2005. Interception traps in canopy inflorescences: targeting a neglected fauna. *International Journal of Tropical Insect Science*, 25 (2): 138-141.

Howlett, B. G., Walker, M. K., Newstrom-Lloyd, L. E., Donovan, B. J. and Teulon, D. A. J. 2009. Window traps and direct observations record similar arthropod flower visitor assemblages in two mass flowering crops. *Journal of Applied Entomology*, 133(7): 553-564.

Hwang, H. J., Suh, J. K., Ha, I. J. and Ryu, Y. W. 1998. Effect of pollinating insects on seed yield in seed production of onion (*Allium cepa* L.). *RDA Journal of Horticulture Science.*

Ijoyah, M. O., Rakotomavo, H., & Naiken, M. V. (2008). Yield performance of four onion (Allium cepa L.) varieties compared with the local variety under open field conditions at Anse Boileau, Seychelles. *Journal of Science and Technology (Ghana)*, *28*(3), 28-33.

Inouye, D. W., & Waller, G. D. (1984). Responses of honey bees (Apis mellifera) to amino acid solutions mimicking floral nectars. *Ecology*, 65(2), 618–625.

Islam AKMM and Mondal MF. 2005. Effects of planting date and GA3 on growth, yield and quality of onion seeds grown from sets, Journal of Bangladesh Agricultural University, 3(1): 7-12.

Jablonski, B., Skowronek, J., Woyke, H. W. and Doruchowski, R. W. 1982. Flowering biology, nectaring, pollination and fruiting of male-sterile and male-fertile onion lines (*Allium cepa* L.). *Beekeeping Scientific Journals*, 26: 57-104.

Jadhav, L. D. 1981, Role of insects in the pollination of onion (*Allium cepa* L.) in the Maharashtra state. *Indian Bee Journal*, 43: 61-63.

Jat, M. K., & Vikram, B. (2018). Studies of variability pattern in agro-morphological characters in the onion genotypes (Allium cepa L.) in Rabi season under Allahabad agro-climactic condition. *Journal of Pharmacognosy and Phytochemistry*, *7*(2), 2051-2054.

Jayaramappa, K. V. and Bhargava, H. R. (2015). Influence of bee attractants on watermelon (Citrullus lanatus L.) for the improvement of the crop. World Applied Sciences Journal, 33(4), 679-683.

Jayaramappa, K. V., Pattabhiramaiah, M., & Bhargava, H. R. (2011). Influence of bee-attractants on yield parameters of ridge gourd (Luffa acutangula L.)(Cucurbitaceae). *World Applied Sciences Journal*, *15*(4), 457-462.

Jeannerod, L., Carlier, A., Schatz, B., Daise, C., Richel, A., Agnan, Y., ... & Jacquemart, A. L. (2022). Some bee-pollinated plants provide nutritionally incomplete pollen amino acid resources to their pollinators. *PLoS One*, *17*(8), e0269992.

Jiang, J. A., Wang, C. H., Chen, C. H., Liao, M. S., Su, Y. L., Chen, W. S., ... & Chuang, C. L. (2016). A WSN-based automatic monitoring system for the foraging behavior of honey bees and environmental factors of beehives. *Computers and Electronics in Agriculture*, *123*, 304-318.

Joshi, N. C., & Joshi, P. C. (2010). Foraging behaviour of Apis spp. on apple flowers in a subtropical environment. *New York Science Journal*, *3*(3), 71-76.

Kalmath, B. S. and Sattigi, H. N. 2004. Effect of bee pollination by using attractants on the qualitative parameters of onion seed. Pest *Management and Economic Zoology*, 12(1): 97-99. Corpus ID: 87699529.

Kamal, M. M. and Akand, M. M. 2017. Foraging activity of different pollinators for seed setting and maximizing seed yield of onion. IOSR- *Journal of Agriculture and Veterinary Science*, 10(5): 88-96.

Karuppaiah, V., Soumia, P. S. and Wagh, P. D. 2018. Diversity and foraging behaviour of insect pollinators in onion. *Indian Journal of Entomology*, 80(4): 1366- 1369.

Kavitha, S. J. and Reddy, P. R. 2019. Influence of floral nectar quantity and quality on honey bee foraging activity in onion. *Journal of Entomology and Zoology Studies*, 7(3): 92-96.

Kavitha, S. J. and Reddy, P. V. R. 2018. Floral biology and pollination ecology of onion (*Allium cepa* L.). *Journal of Pharmacognosy and Phytochemistry*, 7(6): 2081-2084.

Kehrberger, S., & Holzschuh, A. (2019). Warmer temperatures advance flowering in a spring plant more strongly than emergence of two solitary spring bee species. *PLoS One*, *14*(6), e0218824.

Kevan, P. G., Greco, C. F. and Belaoussoff, S., 1997. Log-normality of biodiversity and abundance in diagnosis and measuring of ecosystemic health: pesticide stress on pollinators on blueberry heaths. *Journal of Applied Ecology*, 1122-1136.

Khokhar, K. M. (2014). Flowering and seed development in onion—a review. *Open Access Library Journal*, *1*(7), 1-13.

Kiester, A. R., Lande, R. and Schemske, D. W., 1984. Models of coevolution and speciation in plants and their pollinators. *The American Naturalist*, 124(2): 220-243. doi:10.1086/284265

Kline, O., & Joshi, N. K. (2024). Current trends in bee conservation and habitat restoration in different types of anthropogenic habitats. *Frontiers in Ecology and Evolution*, *12*, 1401233.

Knopper, L. D., Dan, T., Reisig, D. D., Johnson, J. D., & Bowers, L. M. (2016). Sugar concentration in nectar: a quantitative metric of crop attractiveness for refined pollinator risk assessments. *Pest management science*, *72*(10), 1807-1812.

Korichi, Y., Malika, A. S., Karima, K. G. and Hassina, I. 2021. Foraging bees of the onion (*Allium cepa* L.) and their impact on seed production in Tizi-Ouzou area (Algeria). *Journal of Apicultural Research*, 1-8.

Krishnaveni K, Subramanian KS, Bhaskaran M, Chinnasami KN (1990) Effect of time of planting bulbs on the yield and quality of Bellary onion seed. *South Indian Journal of Horticulture* **38**(5): 258-261.

Kruger, N. J. (2009). The Bradford method for protein quantitation. *The protein protocols handbook*, 17-24.

Kulkarni, S. R., Gurve, S. S. and Chormule, A. J. 2017. Effect of different indigenous bee attractants in onion (*Allium cepa* L.) crop. *Annals of Plant Protection Sciences*, 25(1): 78-82.

Kumar, J., & Gupta, J. K. (1993). Nectar sugar production and honeybee foraging activity in 3 species of onion (Allium species). *Apidologie*, *24*(4), 391-396.

Kumar, J., Mishra, R. C. and Gupta, J. K. 1985. The effect of mode of pollination on *Allium* species with observation on insects as pollinators. *Journal of Apicultural Research*, 24(1): 62-66.

Kumar, N. N. N. 2013. Insect pollinators' diversity with special reference to role of attractants in increasing productivity of watermelon *[Citrullus lanatus (Thub.)]*. M. Sc. (Agri.) Thesis submitted to University of Agricultural Sciences, Bangalore, Karnataka, India.

Kumar, N., & Giri, G. S. (2020). FORAGING BEHAVIOUR OF HONEY BEES ON STRAWBERRY (FRAGARIA ANANASSA DUCH.). *Journal of Experimental Zoology India*, *23*(1).

Kumar, S., Hari, C. and Singh, R. 2000. Increasing the attractiveness of sunflower to honeybees for pollination. *Shashpa*, 7(2): 151-154.

Kumari, S. 2014. Studies on the effect of bee attractants on quality seed production of onion (*Allium cepa* L.). M.Sc. (Agri.) Thesis submitted to Dr. Yashvant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (India).

Kumari, S., Rana, K., Sharma, H. K. and Thakur, A. K. 2017. Effect of bee attractants on yield and quality of onion seed. *Journal of Hill Agriculture*, 8(1): 46-49.

Lau, P., Lesne, P., Grebenok, R. J., Rangel, J., & Behmer, S. T. (2022). Assessing pollen nutrient content: a unifying approach for the study of bee nutritional ecology. *Philosophical Transactions of the Royal Society B*, *377*(1853), 20210510.

Layek, U., Manna, S. S., & Karmakar, P. (2020). Pollen foraging behaviour of honey bee (Apis mellifera L.) in southern West Bengal, India. *Palynology*, *44*(1), 114-126.

Liu, Y., Dunker, S., Durka, W., Dominik, C., Heuschele, J. M., Honchar, H., ... & Schweiger, O. (2024). Eco-evolutionary processes shaping floral nectar sugar composition. *Scientific Reports*, *14*(1), 13856.

Long, R. F., & Morandin, L. (2011). Low hybrid onion seed yields relate to honey bee visits and insecticide use. *California Agriculture*, *65*(3).

Luitel, B. P., Han, J., Kang, S., Cho, M. C., & Choi, M. S. (2024). Variations in Seed Yield and Related Traits in Onion (Allium cepa L.) Germplasm Collections. *Horticultural Science and Technology*, *42*(1), 68-79.

Lyngkhoi, F., Saini, N., Gaikwad, A. B., Thirunavukkarasu, N., Verma, P., Silvar, C., ... & Khar, A. (2021). Genetic diversity and population structure in onion (Allium cepa L.) accessions based on morphological and molecular approaches. *Physiology and Molecular Biology of Plants*, *27*(11), 2517-2532.

Mahmud KK. 2008. Effect of set-size and planting time on the incidence of bolting, bulbing, and seed yield in two onion cultivars, Journal of Horticultural Science & Biotechnology, 83(4): 481-487.

Mahomoodally, M. F., Khadaroo, S. K., Hosenally, M., Zengin, G., Rebezov, M., Ali Shariati, M., ... & Simal-Gandara, J. (2024). Nutritional, medicinal and functional properties of different parts of the date palm and its fruit (Phoenix dactylifera L.)–A systematic review. *Critical reviews in food science and nutrition*, *64*(22), 7748-7803.

Mahr, S., 2023. Hover, flower or syrphid flies (syrphidae). Wisconson Horticulture, Division of Extension, University of Wisconsin. https://hort.extension. wisc.edu/articles/hover-flower-or-syrphid-flies-syrphidae/

Malerbo-Souza, D. T., Nogueira, R. H. and Couto, L. A. 2004. Honey bee attractants and pollination in sweet orange, *Citrus sinensis* Osbeck, *var*. Pera-rio. *Journal of Venomous Animals and Toxins Including Tropical Diseases*, 10(1): 362- 368.

Manchare, R. R., Kulkarni, S. R., & Jare, S. M. (2020). Effect of bee attractants on foraging activities of rock bees *Apis dorsata* in bitter gourd (Momordica charantia L.). *Chemical Science Review and Letters. 2020a*, *9*(34), 273-277.

Manchare, R. R., Kulkarni, S. R., & Mahadik, P. B. (2020). Effect of bee attractants on foraging activities of european bees *Apis mellifera* in bitter gourd (Momordicas charantia L.). *The International Journal of Engineering and Science*, *9*(1), 50-54.98

Manchare, R. R.; Kulkarni, S. R. and Patil, S. D. (2019). Effect of Bee pollination on Seed Yield and Yield Contributing Characters of Bitter Gourd Momordica Charantia L. Chem. sci. rev. lett, 8(30), 236-240.

Mandal, J., Ajgalley, R., Saha, D., & Mohanta, S. (2019). Growth, yield and quality of onion cultivars under laterite belt of Eastern India. *Vegetable Science*, *46*(1and2), 129-131.

Manhare, J.S. and Painkra, G. P. 2018. Impact of bee attractants on bee visitation on buckwheat (*Fagopyrum esculentum* L.) crop. *Journal of Entomological and Zoological Studies*, 6(2): 28-31.

Manjunath, U., Hiremath, S. M., Shashidhar, T. R., & Hegde, M. G. (2022). Evaluation of rabi onion (Allium cepa L.) genotypes for northern Karnataka. *Journal of Farm Sciences*, *35*(04), 515-518.

Martén-Rodríguez, S., Cristobal-Pérez, E. J., de Santiago-Hernández, M. H., Huerta-Ramos, G., Clemente-Martínez, L., Krupnick, G., ... & Quesada, M. (2025). Untangling the complexity of climate change effects on plant reproductive traits and pollinators: A systematic global synthesis. *Global Change Biology*, *31*(2), e70081.

Mazeed, A. R. and Marey, R. A. 2018. Pollinators' activity on onion flowers and its effect on seeds yield at Sohag governorate, Egypt. *Egyptian Journal of Agricultural Research*, 96(2): 465-475.

MAZEED, A. R., & MAREY, R. A. (2018). Pollinators activity on onion flowers and its effect on seeds yield at Sohag governorate, Egypt. *Egyptian Journal of Agricultural Research*, *96*(2), 465-475.

Meena, N. K., Lal, G., Meena, R. S., Meena, B. M. and Meena, R. D. 2018. Pollinator's diversity and abundance on cumin (*Cuminum cyminum* L.) and their impact on yield enhancement at semi-arid regions. *Journal of Entomology and Zoology Studies*, 6: 1017-1021.

Mehri, S., Forodi, B. R., & Kashi, A. K. (2015). Influence of planting date on some morphological characteristic and seed production in onion (*Allium cepa* L.) cultivars. *Agriculture Science Developments*, *4*(2), 19-21.

Melo, I. L. P. D., & Almeida-Muradian, L. B. D. (2011). Comparison of methodologies for moisture determination on dried bee pollen samples. *Food Science and Technology*, *31*, 194-197.

Micheu, S., Crailsheim, K., & Leonhardt, S. D. (2020). Nutrition of honeybees is constrained by the ratios of essential amino acids in pollen. *bioRxiv*.

Mohamed, M. F., & Tawfik, A. A. (2025). Bulb Onion (Allium cepa L.) Breeding. In *Biodiversity and Genetic Improvement of Herbs and Spices* (pp. 199-241). Cham: Springer Nature Switzerland.

Mohamedali GH and Nourai AH. 1988. Effects of Bulb Source, Sowing Date and Nitrogen Nutrition On the Seed Yield of the White Dehydration Onion (Allium cepa L.) in the Sudan, Journal of Horticultural Science, 63(2): 261-264.

Mollah, M. R. A., Ali, M. A., Ahmad, M., Hassan, M. K., & Alam, M. J. (2015). Effect of planting dates on the yield and quality of true seeds of onion. *International Journal of Applied Sciences and Biotechnology*, *3*(1), 67-72.

Montes, C. S. 2019. Evaluation of insect activity in onion seedbeds and their impact on seed yield and quality. *Thesis submitted to University of the Republic (Uruguay).* https://hdl.handle.net/20.500.12008/29472.

Moquet, L., Bruyère, L., Pirard, B. and Jacquemart, A.L., 2017. Nectar foragers contribute to the pollination of buzz-pollinated plant species. *American Journal of Botany*, 104(10): 1451-1463.

More, M. R., More, S. A. and Bapurao, U. 2020. Effect of bee attractants on foraging behaviour of *Apis mellifera* L. on seed onion crop (*Allium cepa* L.*). Journal of Entomology and Zoology Studies*, 8(6): 1510-1512.

Muddi, F. 2012. Influence of different dated of sowing and indigenous bee attractants on bee pollination and Niger yield. M. Sc. (Agri.) *Thesis submitted to University of Agricultural Sciences, Dharwad (Karnataka, India).*

Muktadir, M. S. (2000). *Effect of planting time, bulb size and vernalization on the yield and quality of onion seed* (Doctoral dissertation, MS Thesis, Departament of Horticulture, Bangladesh Agricultural University, Mumensingch).

Naik, A. K. 2010. Evaluation of indigenous bee attractants on *Bt* cotton. M.Sc. (Agri.) Thesis submitted to University of Agricultural Sciences, Dharwad (Karnataka, India).

Naik, A. K.; Pise, V.; Viraktamath, S.; Udikeri, S. S. and Uppar, V. (2014). Evaluation of Indigenous Bee Attractants in Bt Cotton (Bunny BG-I). Research J. Agricultural Sciences, 5(3): 476-479.

Naik, J. M., Gopali, J. B., Ganiger, V. M., Patil, S. R., MM, V. K., & Patil, B. (2019). Influence of honey bee attractants in enhancing the seed productivity and quality of onion seed crop. *IJCS*, *7*(4), 2958-2662.

Narayanan and Gavigowda. 2005. Influence of insecticidal and sugar syrup on foraging activity of honey bees in gherkin (*Cucumis anguria*). *Indian Bee Journal*, 67 (1 and 2): 67-71.

Narendra, P. T. 2014. Studies on role of honey bees in seed production of onion (*Allium cepa* L.). M.Sc. (Agri.) Thesis

Nayak, B. C., & Paikray, R. K. (1991). Effect of time of sowing and plant density on yield of niger.

Neeraj Kumar, Neeraj Kumar, and G. S. Giri (2020). "Foraging behaviour of honey bees on strawberry (Fragaria ananassa Duch.).": 559-564.

Newstrom, L. E. and Robertson, A. 2005. Progress in understanding pollination systems in New Zealand. *New Zealand Journal of Botany*, 43: 1-59.

Nicolson, S. W. (2022). Sweet solutions: Nectar chemistry and quality. *Philosophical Transactions of the Royal Society B*, 377(1853), 20210163.

Nicolson, S. W., Neves, S. D. S. D., Human, H., & Pirk, C. W. (2018). Digestibility and nutritional value of fresh and stored pollen for honey bees (Apis mellifera scutellata). *Journal of insect physiology*, *107*, 302-308.

Noor-ul-Ane, M., Jung, C., & Kwon, H. W. (2022). Effect of non-essential amino acids (proline and glutamic acid) on honey bee physiology. *Frontiers in Ecology and Evolution*, 10, 1009670.

Noreen, H., Semmar, N., Farman, M., & McCullagh, J. S. (2017). Measurement of total phenolic content and antioxidant activity of aerial parts of medicinal plant Coronopus didymus. *Asian Pacific journal of tropical medicine*, *10*(8), 792-801.

Ohtsuki, K., Kawabata, M., Kokura, H., & Taguchi, K. (1987). Simultaneous determination of S-methylmethionine, vitamin U and free amino acids in extracts of green tea with an HPLC-amino acid analyzer. *Agricultural and Biological Chemistry*, *51*(9), 2479-2484.

Orford, K. A., Vaughan, I. P. and Memmot, J. 2015. The forgotten flies: The importance of non-syrphid diptera as pollinators. *Proceedings of the Royal Society B: Biological Sciences,* 282.

OSKAY, D., & OSKAY, G. S. (2023). Climate change and bees. *International Academic Research and Reviews in Agriculture, Forestry and Aquaculture Sciences*, *43*.

Padamshali, S. 2017. Enumeration of insect visitors and relative abundance of insect pollinators on onion (*Allium cepa* L.) flower. *Bulletins of Environmental Pharmacology and Life Sciences*, 6(3): 558-562.

Padamshali, S., & Mandal, S. K. (2018). Effect of honeybee (A. mellifera) pollination on yield and yield attributing parameters of onion (Allium cepa L.). *Int J Curr Microbiol Appl Sci*, *7*, 4843-4848.

Pan, C., Chen, Z., Zhang, M., Chen, X., Smagghe, G., Fan, M., ... & Long, J. (2024). Effects of flowering period on floral traits, pollinator behavior and seed production of David's mountain laurel (Sophora davidii). *Plant Signaling & Behavior*, *19*(1), 2383823.

Pandit, T. R., Dwivedi, S. A., Soumia, P. S., Shirsat, D. V., Pote, C. L., Pawar, A. R., ... & Karuppaiah, V. (2025). Unveiling Biochemical Drivers of Bee Pollination in Short-Day Indian Onion (Allium cepa L.) Varieties.

Parker, F.D. and Hatley, C.L. 1978. Onion pollination: viability of onion pollen and pollen diversity on insect body hairs. *In: Proceedings of IV International Symposium on Pollination, Maryland Agricultural Experimental Station Special Miscellaneous Publication*, 1:201-206.

Paschapur, A. U., Bhat, S., Subbanna, A. R., Choudhary, G., Hedau, N. K., Mishra, K.K. and Kant, L. 2022. Role of entomophily and artificial pollination in enhancing quality and yield of seed onion (L.) in Indian Himalayas. *Journal of Apicultural Science,* 66(2): 133-147.

Pashte, V. V., Shylesha, A. N. and Bhat, N. S. 2015. Effectiveness of attractants and scents in enticement of *Apis cerana* on sesamum crop. *Environment and Ecology*, 33(4): 1504-1507.

Patil, B. S., Viraktamath, S. A., Lingappa, S., Giraddi, R. S., Parameshwarappa, K. G., And Bhat, A.R.S., 2000, Effect of Bee-Q and Bee here on pollination and yield of sesamum. Insect environment, 54:151-152.

Patil, M. C. 2007. Impact of honeybee pollination on qualitative and quantitative parameters cucumber (*Cucumis sativa* L.). M. Sc. (Agri.) Thesis submitted to University of

Agricultural Sciences, Dharwad (Karnataka, India).

Paul, I., Poddar Sarkar, M., & Bhadoria, P. B. S. (2022). Floral secondary metabolites in context of biotic and abiotic stress factors. *Chemoecology*, *32*(2), 49-68.

Pernal, S. F., & Currie, R. W. (2001). The influence of pollen quality on foraging behavior in honeybees (Apis mellifera L.). *Behavioral Ecology and Sociobiology*, *51*(1), 53-68.

Pise, V. 2011. Comparative performance of indigenous bee attractants in *bt* and non-*bt* cotton hybrids. Ph.D. Thesis submitted to University of Agricultural Sciences, Dharwad.

Prasifka, J. R., Mallinger, R. E., Portlas, Z. M., Hulke, B. S., Fugate, K. K., Paradis, T., ... & Carter, C. J. (2018). Using nectar-related traits to enhance crop-pollinator interactions. *Frontiers in plant science*, *9*, 812.

Primack, R.B. 1983. Insect pollination in New Zealand Mountain Flora. *New Zealand Journal of Botany* 21: 317-333.

Priti. 1998. Abundance and pollination efficiency of insect visitors of onion bloom.*Indian Bee Journal*, 60: 75- 78.

Priya Kivadasannavar, P. K., Deshpande, V. K., & Vyakarnal, B. S. (2007). Effect of sowing time, spacing and fungicidal spray on crop growth and seed yield of Niger (Guizotia abyssinica Cass.).

Proctor, M. and Yeo, P. 1973. The pollination of flowers. Collins, London. 1-418.

Qian, W. L., Khan, Z., Watson, D. G., & Fearnley, J. (2008). Analysis of sugars in bee pollen and propolis by ligand exchange chromatography in combination with pulsed amperometric detection and mass spectrometry. *Journal of Food Composition and Analysis*, *21*(1), 78-83.

quality of coriander crop. *International Journal of Chemical Studies*, 7(5): 1441-1444.

Quinlan, G., Milbrath, M., Otto, C., Smart, A., Iwanowicz, D., Cornman, R. S., & Isaacs, R. (2021). Honey bee foraged pollen reveals temporal changes in pollen protein content and changes in forager choice for abundant versus high protein flowers. *Agriculture, Ecosystems & Environment*, *322*, 107645.

Rana, K., Kumari, S. and Sharma, H. K. 2017. Diversity and abundance of insect pollinators on onion (*Allium cepa* L.). *Trends in Biosciences*, 10(2): 813- 815.

Rands, S. A., & Whitney, H. M. (2010). Effects of pollinator density-dependent preferences on field margin visitations in the midst of agricultural monocultures: A modelling approach. *Ecological Modelling*, *221*(9), 1310-1316.

Rao, G. M. and Suryanarayana, M. C. 1989. Effect of honey bee pollination on seed yield in onion (*Allium cepa* L). *Indian Bee Journal*, 51: 9-11.

Reddy, P. R., Rashmi, T. and Verghese, A. 2015. Foraging activity of Indian honey bee Apis cerana, in relation to ambient climate variables under tropical conditions. *Journal of Environmental Biology*, 36: 577-581.

Rethinam, P., & Krishnakumar, V. (2022). Composition, properties and reactions of coconut water. In *Coconut Water: A Promising Natural Health Drink-Distribution, Processing and Nutritional Benefits* (pp. 77-138). Cham: Springer International Publishing.

Rizk FA, Shaheen AM, Habbasha KME (1996) Flowering and seed of onion (*Allium cepa* L) plants as affected by dates of planting and some growth regulators. Egyptian Journal of Horticulture 23(1): 113-127.

Rodo AB and Marcos-Filho J. 2003. Onion seed vigour in relation to plant growth and yield, Horticultura Brasileira, 21(2): 220 -226.

Rodríguez-Peña, N., Stoner, K. E., Schondube, J. E., Durán-Díaz, A., Hernández-Portilla, L. B., & Flores-Ortiz, C. M. (2021). Free amino acids in nectar: its composition and variability among bat-pollinated plants. *Revista mexicana de biodiversidad*, *92*.

Roguz, K., et al. (2019). Diversity of nectar amino acids in the *Fritillaria* (Liliaceae) genus. *Scientific Reports*, 9, 15209.

Romo Pérez, M., Zikeli, S., & Zörb, C. (2018). Quality aspects in open-pollinated onion varieties from Western Europe. *Journal of Applied Botany & Food Quality*, *91*.

Rortais, A., Arnold, G., Halm, M.P. and Touffet-Briens, F. 2005. Modes of honey bees exposure to systemic insecticides: estimated amounts of contaminated pollen and nectar consumed by different categories of bees. *Apidologie*, 36(1): 71-83.

Roulston, T. A. H., Cane, J. H., & Buchmann, S. L. (2000). What governs protein content of pollen: pollinator preferences, pollen–pistil interactions, or phylogeny?. *Ecological monographs*, *70*(4), 617-643.

Roy, N. (1994). *Effects of growth condition, planting time and duration of cold treatment of bulb on seed production of onion (Allium cepa L.) cv. Taherpuri* (Doctoral dissertation, MS Thesis, Department of Horticulture, BAU, Mymensingh).

Saeed, S., Sajjad, A., Kwon, O. and Kwon, Y. J. 2008. Fidelity of hymenoptera and diptera pollinators in onion (*Allium cepa* L.) pollination. *Entomological Research*, 38(4): 276-280.

Sajjad, A., Saeed, S. and Massod, A. 2008. Pollinator community of onion (*Allium cepa* L.) and its role in crop reproductive success. *Pakistan Journal of Zoology*, 40(6): 451-456.

Saleh, M., Bashir, M. A., Khan, K. A., Mahmood, R., Sarwar, G., Rafiq, K., ... & Al-Solami, H. M. A. (2021). Onion flowers anthesis and insect pollinators preferences on onion (*Allium cepa* L.) crop. *Fresenius Environmental Bulletin*, *30*(3), 2580-2585.

Salmon, C. (2022). *Influence of water application rates on visitation by the South African honeybee (Apis mellifera capensis) and seed yield of Texas Grano onions* (Doctoral dissertation, Cape Peninsula University of Technology).

Sembiring, E. N., Elya, B., & Sauriasari, R. (2018). Phytochemical screening, total flavonoid and total phenolic content and antioxidant activity of different parts of Caesalpinia bonduc (L.) Roxb. *Pharmacognosy journal*, *10*(1).

Shanmugasundaram S. 2007. Onion cultivation and seed production. The Hindu Survey of Indian Agriculture. pp99-119.

Sharma D and Jarial K. 2017. Effect of different varieties and planting time on kharif onion production in Lower Shivalik Hills of Himachal Pradesh, Current Agricultural Research,5(1): 74-80.

Shin, D., Choi, W. T., Lin, H., Qu, Z., Breedveld, V. and Meredith, J.C. 2019. Humidity- tolerant rate-dependent capillary viscous adhesion of bee-collected pollen fluids. *Nature communications*, 10(1): 1379.

Silva, E. M., Dean, B. B., & Hiller, L. (2004). Patterns of floral nectar production of onion (Allium cepa L.) and the effects of environmental conditions. *Journal of the American Society for Horticultural Science*, *129*(3), 299-302.

Silva, E. M., Dean, B. B., & Hiller, L. K. (2003). Honey bee (Hymenoptera: Apidae) foraging in response to preconditioning with onion flower scent compounds. *Journal of economic entomology*, *96*(5), 1510-1513.

Singh GP, Singh RK (1984) Effect of spacing and planting time on seed production of onion. South Indian Horticulture 32(5): 284-287.

Singh, J. P. and Dharamwal, S. S. 1970. The role of honey bees in seed setting on onion at Pant Nagar, Dist. Nainital, Uttar Pradesh, India. *Indian Bee Journal*, 32(1/2): 23-27.

Singh, K. (2020). *Nutritional and antioxidant potential of pomegranate (Punica granatum L.) byproducts for development of functional foods* (Doctoral dissertation, Punjab Agricultural University, Ludhiana).

Singh, R. B., Pyare, R., Dube, H. V., Yadav, A. K., Ranjan, A. R., Pal, R. K., & Katiyar, S. (2022). Studies on Evaluation, Management practices on growth Attributes, yields and Economics of Rabi onion (Allium cepa L.). *Agriways*, *10*(2).

Somerville, D. C., & Nicol, H. I. (2002). Mineral content of honeybee-collected pollen from southern New South Wales. *Australian journal of experimental agriculture*, *42*(8), 1131-1136.

Somerville, D. C., & Nicol, H. I. (2006). Crude protein and amino acid composition of honey bee-collected pollen pellets from south-east Australia and a note on laboratory disparity. *Australian Journal of Experimental Agriculture*, *46*(1), 141-149.

Soto, V. C., Caselles, C. A., Silva, M. F., & Galmarini, C. R. (2018). Onion hybrid seed production: Relation with nectar composition and flower traits. *Journal of economic entomology*, *111*(3), 1023-1029.

Soto, V. C., Gatica, I. J. G., & Galmarini, C. R. (2021). Onion (Allium cepa L.) hybrid seed production: Sugar content variation during the flowering period. *Crop Science*, *61*(5), 3529-3537.

Soto, V. C., González, R. E., Caselles, C. A., & Galmarini, C. R. (2023). Is the nectar sugar content the key to improving onion and bunching onion seed yield?. *Horticulturae*, *9*(6), 657.

Soto, V. C., Maldonado, I. B., Gil, R. A., Peralta, I. E., Silva, M. F., & Galmarini, C. R. (2013). Nectar and flower traits of different onion male sterile lines related to pollination efficiency and seed yield of F1 hybrids. *Journal of Economic Entomology*, *106*(3), 1386-1394.

Srikanta, N. 2008. Evaluation of indigenous bee attractants in sunflower. M. Sc. (Agri.) Thesis submitted to University of Agricultural Sciences, Dharwad (Karnataka, India).

Srikanth, C. D., Kubberappa, G. C. and Shwetha, B. V. 2013. Role of attractants on insect pollinators diversity with special reference to pollination in increasing the productivity of bottle gourd, *Lagenaria siceraria* L. *Mysore Journal of Agricultural Sciences*, 47 (1): 16-21.

Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C. and Tscharntke, T. 2002. Scale-dependent effects of landscape context on three pollinator guilds. *Ecology,* 83(5): 1421-1432.

Stephen, K. W., Chau, K. D., & Rehan, S. M. (2024). Dietary foundations for pollinators: nutritional profiling of plants for bee health. *Frontiers in Sustainable Food Systems*, *8*, 1411410.

Sunita Devi, S. D., Rachna Gulati, R. G., Kanika Tehri, K. T., & Asha Poonia, A. P. (2015). The pollination biology of onion (Allium cepa L.): 1- 13 a review.

Tchindebe, G. and Fohouo, T. F. 2014. Foraging and pollination activity of *Apis mellifera adansonii* Latreille (Hymenoptera: Apidae) on flowers of *Allium cepa* L. (Liliaceae) at Maroua, Cameroon. *International Journal of Agronomy and Agricultural Research,* 5: 139-153.

Tchindebe, G., & Tchuenguem, F. F. (2014). Foraging and pollination activity of Apis mellifera adansonii Latreille (Hymenoptera: Apidae) on flowers of Allium cepa L.(Liliaceae) at Maroua, Cameroon. *International Journal of Agronomy and Agricultural Research*, *5*(2), 139-153.

Tchindebe, G., Farda, D., Douka, C., Clautin, N., Auguste, P. M. and Fernand-Nestor, T. F. 2021. Diversity of insect pollinators of *Allium cepa* L. (liliaceae) and assessment of its impact on yields at Gazawa (Cameroon). *Journal of Applied Biology and Biotechnology*, 9(2): 85-92.

Teper, D., & Zajdel, B. (2020). Qualitative analysis of amino acids in pollen and nectar of selected melliferous plants. *Journal of Apicultural Science*, 64(1), 45–56.

Tesfaye, M., Belew, D., Dessalegn, Y., & Shumye, G. (2018). Effect of planting time on growth, yield components, seed yield and quality of onion (*Allium cepa* L.) at Tehuledere district, northeastern Ethiopia. *Agriculture & Food Security*, *7*(1), 28.

Teulier, L., Weber, J. M., Crevier, J., & Darveau, C. A. (2016). Proline as a fuel for insect flight: enhancing carbohydrate oxidation in hymenopterans. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1834), 20160333.

Thakur, M. V., Kumar, N., Verma, R. D., Giri, G. S., & Munj, S. S. (2024). Effect of Imidacloprid on Foraging Behaviour of Wild Bee Species on Coriander. *Indian Journal of Ecology*, *51*(4), 895-899.

Thakur, N. S., Pannase, S. K., & Sharma, S. N. (2000). Effect of sowing time and fertilizer on growth, yield attributes and seed yield of niger (Guizotia abyssinica Cass) under rainfed condition.

Thakur, R. K. and Kumaranag, K. M. 2016. Annual Report 2015-2016, ICAR- All India Coordinated Research Project on Honey Bees and Pollinators, *Division of Entomology, IARI, New Delhi-110012, India*, 123.

Tidke, J. A., & Nagarkar, S. S. (2015). Pollen spectrum and biochemical analysis of dominant pollen types represented by local honey samples. *International Journal of Pharma Research & Review*, *4*(5), 21-33.

Ud-Deen, M. M. (2008). Effect of mother bulb size and planting time on growth, bulb and seed yield of onion. *Bangladesh Journal of Agricultural Research*, *33*(4), 531-537.

Vaissière, B. E., Freitas, B. M., & Gemmill-Herren, B. (2011). *Protocol to Detect and Assess Pollination Deficits in Crops: A Handbook for Its Application.* Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 1–82.

Vandelook, F., Janssens, S. B., Gijbels, P., Fischer, E., Van den Ende, W., Honnay, O., & Abrahamczyk, S. (2019). Nectar traits differ between pollination syndromes in Balsaminaceae. *Annals of Botany*, *124*(2), 269-279.

Vanderplanck, M., Moerman, R., Rasmont, P., Lognay, G., Wathelet, B., Wattiez, R., & Michez, D. (2014). How does pollen chemistry impact development and feeding behaviour of polylectic bees?. *PloS one*, *9*(1), e86209.

Vaudo, A. D., Dyer, L. A., & Leonard, A. S. (2024). Pollen nutrition structures bee and plant community interactions. *Proceedings of the National Academy of Sciences*, *121*(3), e2317228120.

Vaudo, A. D., Tooker, J. F., Patch, H. M., Biddinger, D. J., Coccia, M., Crone, M. K., ... & Grozinger, C. M. (2020). Pollen protein: lipid macronutrient ratios may guide broad patterns of bee species floral preferences. *Insects*, *11*(2), 132.

Verma KS, Kushwah SS and Uikey V. 2011. Seed Production of Onion and Post Harvest Nutrients Status of Soil as Influenced with Planting Time and Nutrient Levels, Asian Journal of Horticulture, 6(1): 231.

Vianney, M. T. W., Albert, R., & Zoumbiessé, T. (2011). Effects of seasons of bulb and seed production on the early bolting of onion (*Allium cepa* L.) cv 'violet de Galmi'. *Journal of Applied Biosciences*, *40*, 2652-2658.

Vicens, N., & Bosch, J. (2000). Weather-dependent pollinator activity in an apple orchard, with special reference to Osmia cornuta and Apis mellifera (Hymenoptera: Megachilidae and Apidae). *Environmental entomology*, *29*(3), 413-420.

Vijayalakshmi, M., & Ruckmani, K. (2016). Ferric reducing antioxidant power assay in plant extract. ||| *Bangladesh Journal of Pharmacology*|||, *11*(3), 570-572.

Vijaykumar, P. V. 2011. Pollinators diversity with special reference to role of honey bees in quantitative and qualitative improvement of sesamum (*Sesamum indicum* L.)**.** M. Sc. (Agri.) *Thesis submitted to University of Agricultural Sciences, Bangalore (Karnataka, India).*

Viraktamath, S. and Anagoudar, J. A. 2002. Influence of bee attractants in enhancing pollination and yield parameters in *Cucumis sativus* L. *Indian Bee Journal*, 64(1-2): 23-27.

Waddington, K. D., Nelson, C. M., & Page, R. E. (1998). Effects of pollen quality and genotype on the dance of foraging honey bees. *Animal Behaviour*, *56*(1), 35-39.

Walker, M. K., Howlett, B. G., Wallace, A. R., Mccallum, J. A. and Teulon, D. A. J. 2011. The diversity and abundance of small arthropods in onion, *Allium cepa*, seed crops and their potential role in pollination. *Journal of Insect Science*, 11(1): 98.

Waller, G. D. (1972). Evaluating responses of honey bees to sugar solutions using an artificial-flower feeder. *Annals of the Entomological Society of America*, *65*(4), 857-862.

Wankhede, H. K., Kulkarni, S. R. and Pawar, S. A. 2018. Influence of indigenous bee attractants on qualitative and quantitative parameters of cucumber (*Cucumis sativus* L.). *Journal of Entomology and Zoology Studies*, 64(4): 1241-1244.

Williams, P. H., Araújo, M. B. and Rasmont, P. 2007. Can vulnerability among British bumblebee (*Bombus*) species be explained by niche position and breadth? *Biological Conservation*, 138(3-4): 493-505.

Winfree, R., Aguilar, R., Vázquez, D. P., LeBuhn, G. and Aizen, M. A., 2009. A meta-analysis of bees' responses to anthropogenic disturbance. *Ecology*, 90(8): 2068-2076.

Wójtowski, F., Wilkaniec, Z. and Szymaoe, B. 1980. Hymenoptera and Diptera pollinating onions (Allium cepa L.) in Poznań seed farms. *Annals of the Agricultural University in Poznań: Zootechny*. 120: 161-168.

Wolff, D. (2006). Nectar sugar composition and volumes of 47 species of Gentianales from a southern Ecuadorian montane forest. *Annals of Botany*, *97*(5), 767-777.

Woyke, H. W. 1980. Some aspects of the role of the honeybee in onion seed production in Poland. *In: Symposium on Vegetable and Flower seed Production*, 111: 91-98.

Yadata, D. (2014). Detection of the electrical conductivity and acidity of honey from different areas of Tepi. *Food Science and Technology*, *2*(5), 59-63.

Yadav VK, Singh B and Srivastava JP. 2002. Studies on Planting Geometry, Bulb Size and Planting Dates on Growth and Seed Yield of Onion (Allium cepa L.Progressive Agriculture. 2(2) : 148-150.

Yalamalle, V. R., & Tomar, B. S. (2019). Effect of scape regulation on seed yield and quality in onion (Allium cepa). *The Indian Journal of Agricultural Sciences*, *89*(1), 56-59.

Yeshiwas, Y., Alemayehu, M., & Adgo, E. (2024). Influence of cultivar and plant density on the growth, bulb yield and quality traits of onion (Allium cepa L.). *Scientific Reports*, *14*(1), 30729.

Yokota, S. C., Broeckling, C., & HS, A. (2024). Pollen foraging preferences in honey bees and the nutrient profiles of the pollen. *Scientific Reports*, *14*(1), 15028.

Yong, J. W., Ge, L., Ng, Y. F., & Tan, S. N. (2009). The chemical composition and biological properties of coconut (Cocos nucifera L.) water. *Molecules*, *14*(12), 5144-5164.

APPENDICES

Appendix I. Meteorological data recorded at different standard meteorological weeks during the period of experimentation (*Rabi* 2023-24 and *Rabi* 2024-25) at ICAR-DOGR, Rajgurunagar, Pune.

Year	Week no.	Temp. Max	Temp. Min	RH 8.00 AM	RH 2.34 PM	Velocity (mm)	Sunshine (Hr)	Rain (mm)	Evaporation
2023	36	29.63	22.2	87.43	76.71	8.17	6.51	4.29	2.41
2023	37	29.04	20.56	84.43	76.71	7.75	4.99	0.83	2.74
2023	38	28.2	21.04	91.67	70.67	3.33	3.39	8.03	1.53
2023	39	28.77	21.63	92.29	79	2.41	2.69	22.77	0.71
2023	40	31.56	20.84	87	60.57	2.39	6.96	0.8	1.79
2023	41	34.09	19.92	74.86	57.43	1.99	5.82	0	3.3
2023	42	33.1	21.56	75.43	63.71	2.13	7.39	1.14	2.96
2023	43	33.06	17.67	75.14	57.29	2.16	9.23	0	3.99
2023	44	32.56	16.26	77.29	60.57	2.36	8.23	0	3.77
2023	45	31.84	18.56	71	63.86	2.74	5.21	0	3.21
2023	46	31.63	16.33	37.29	29.71	1.99	7.79	0	3.84
2023	47	30.74	17.24	78	62	2.27	7.53	1.91	3.76
2023	48	29.92	16.06	83.29	63.29	2.51	6.97	0	3.85
2023	49	30.49	11.75	72	56.14	2.24	8.84	0	4.05
2023	50	29.45	15.37	79.83	63.17	2.73	7.92	0	4
2023	51	27.93	12.91	76	63.71	2.62	7.37	0	3.97
2023	52	28.77	11.81	77.43	58.43	2.27	8.77	0	3.94
2024	1	30.06	14.91	83.86	64.14	2.17	6.72	0	3.19
2024	2	28.99	16.31	84.71	71.57	3.05	7.17	1.78	2.46
2024	3	30.2	11.76	77.29	54.29	3.08	8.57	0	2.79
2024	4	29.63	10.41	79.57	60.14	2.17	9.74	0	2.87
2024	5	31.06	12.99	70.86	52.43	2.47	8.71	0	3.1
2024	6	33.99	15.59	75.43	48.57	3.06	9.63	0	3.66
2024	7	33.06	14.86	74.29	52.71	2.39	8.96	0	3.74
2024	8	32.49	13.03	79	48.71	3.07	10.07	0	3.99
2024	9	33.99	17.06	80.71	58	4.17	8.93	0	3.96
2024	10	34.13	14.92	60	39.57	3.62	9.18	0	3.97
2024	11	36.06	15.09	69.43	40.14	4.11	9.46	0	4.67
2024	12	35.63	15.88	61.71	40.71	3.46	9.01	0	4.74
2024	13	38.36	20.47	68	47.43	3.39	7.99	0	6.23

2024	14	38.91	17.62	64.13	38.63	4.29	8.48	0	6.17
2024	15	38.77	19.69	65.57	41.71	4.14	9.67	0	6.53
2024	16	39.63	23.09	69.14	47.57	4.51	7.77	0	7.09
2024	17	39.37	23.08	62.14	41	4.81	9.77	0	7.06
2024	18	39.13	20.98	62.29	45.86	6.09	11.08	0	6.98
2024	36	28.37	22.07	85.86	73.71	4.07	3.17	0.46	2.09
2024	37	29.43	20.57	87.29	71.57	5.43	5.48	0	2.8
2024	38	31.05	20.49	83	64.29	4.88	6.76	0	2.6
2024	39	30.07	22.13	90.57	75.14	4.34	4.69	8.63	1.61
2024	40	33.06	21.29	82.14	62.14	3.35	6.92	3.23	2.19
2024	41	32.86	22.57	86.29	69.14	4.99	6.46	0	2.97
2024	42	31.85	22.86	90.29	74.14	2.9	6.61	7.14	2.1
2024	43	32.26	20.56	84.71	57.29	2.77	8.48	0	3.74
2024	44	33.29	19.69	84.29	58	2.53	8.77	0	4.16
2024	45	32.05	16.57	74.57	61.29	2.26	8.66	0	4.37
2024	46	31.14	15.79	73.86	65.29	2.37	9.13	0	4.03
2024	47	30.48	14.14	77	64.57	2.4	8	0	4.09
2024	48	29.27	11.6	72	61.14	2.81	7.88	0	4.31
2024	49	31.41	18.9	81.43	72	3.17	7.91	0	4.06
2024	50	29.96	14.6	72.57	64.86	2.23	8.3	0	3.63
2024	51	30	15.93	76.29	47.86	2.38	8.46	0	4.04
2024	52	30.35	16.57	75.88	61.25	2.61	5.91	0	4.37
2025	1	31.19	13.71	78.71	49.29	2.33	8.37	0	4.13
2025	2	29.2	14.8	78.14	55.71	2.29	6.5	0	3.77
2025	3	29.28	15.34	84.71	60.57	2.46	8.1	0	3.86
2025	4	33.07	13.48	81.43	54.57	1.87	8.09	0	3.86
2025	5	31.29	15.33	79	57.29	2.52	8.36	0	3.81
2025	6	33.14	17.3	81.07	52.86	2.27	7.67	0	3.99
2025	7	35.12	14.29	69.14	53.86	1.86	9.68	0	4.12
2025	8	34.99	15.14	67.43	50	2.14	9.77	0	4.02
2025	9	34.99	16.99	70.29	52	2.37	9.28	0	4.61
2025	10	35.06	15.16	62.43	52	2.27	9.5	0	5.19
2025	11	37.14	18.41	69.71	49.29	3.26	9.09	0	5.36
2025	12	36.82	16.57	66.14	49.14	3.66	9.21	0	5.3
2025	13	37.91	17.39	67.29	51.29	3.81	8.66	0	5.84
2025	14	38.98	19.15	73.29	49.14	3.16	7.78	0	5.87
2025	15	39.9	18.8	74.29	34.86	5.5	9.48	0	6.36

2025	16	39.57	19.14	69	41.29	6.14	9.54	0	6.23
2025	17	40.12	21.38	67.43	41.86	5.77	9.97	0	6.97
2025	18	40.56	20.43	63.86	43.29	7.97	10.46	0	7.3

Appendix II. Cost of hives of different bee species used in the experimentation.

Sl. No.	Bee species	Hives/ ha	Rent/ hive/ month	Total cost incurred/ ha
1.	*A. cerana indica*	5	1,500	15,000
2.	*A. mellifera*	3	2,000	12,000
3.	*T. iridipennis*	8	1,000	16,000

Appendix III. Cost of cultivation of onion for seed production per hectare as per the package of practice recommended by ICAR-DOGR, Rajgurunagar, Pune during *Rabi* 2023-24 and *Rabi* 2024-25.

Sl. No.	Materials/works		Total production cost (Rs./ ha)
1.	Land preparation		18,000
2.	Onion bulbs		2,40,000
3.	Labour	Bulb planting	3,700
		Fertilizer application	1,770
		Irrigation	3,700
		Weeding	3.700
		Harvesting	4,000
		Threshing	500
4.	Manures		50,000
5.	Fertilizers		5,800
6.	Thresher machine		2,500
7.	Transportation and Marketing cost		7,000
8.	Other expenses		3,000
	Total		**3,43,670**

Appendix VI. Cost of bee attractants used in the experimentation.

Sl. No.	Bee attractants	Procured from	Cost	Cost/ ha
1.	Pomogranate juice	Farmers field	200/1L	13,333
2.	Dates extract	Local market	350/ 1L	23,000
3.	Coconut water	Farmers field	300/ 1L	20,000

Appendix V. Calendar of Operation.

Calendar of Operation (To investigate the impact of abiotic variations on the onion pollinators on different dates of planting).

Date		Operations Performed	Material used	Quantity used / sample collected
First Objective				
1/9/2023	1/9/2024	Ploughing	Tractor drawn machinery	1 Tractor / 1 disc harrow
		Disking		
		Rotavator		
		Collection of Stubbles		
3/9/2023	3/9/2024	Layout preparation	Mould board plough, Raised maker	1 mould bold plough, 1 Raised maker
		Ridges and furrow shaping		
4/9/2023	4/9/2024	Fertilizer application		For one date of sowing 13 kg FYM, 13 kg NPK for one plot
		FYM - NPK (10:26:26)		
5/9/2023	5/9/2024	1st date of sowing for obj. 1	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water
		Irrigation		
		Herbicide spraying		
20-09-2023	20-09-2024	2nd date of sowing for obj. 1	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water
		Irrigation		
		Herbicide spraying		
		Insecticide spraying for 1st date of sowing		
25-09-2023	25-09-2024	Drenching	Streptomycin	3 g / 16 lit water
5/10/2023	5/10/2024	3rd date of sowing for obj. 1	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water
		Irrigation		
		Herbicide spraying		

		Insecticide spraying for 2nd date of sowing		
20-10-2023	20-10-2024	4th date of sowing Irrigation Herbicide spraying Insecticide spraying for 3rd date of sowing	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water
22-10-2023	22-10-2024	Hand weeding		
5/11/2023	5/11/2024	5th date of sowing Irrigation Herbicide spraying Insecticide spraying for 4th date of sowing	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water
10/11/2023	10/11/2024	Drenching	Streptomycin	3 g / 16 lit water
13-11-2023	13-11-2024	Observation started for 1st treatment	By quadrat method	
20-11-2023	20-11-2024	6th date of sowing Irrigation Herbicide spraying Insecticide spraying for 5th date of sowing	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water
27-11-2023	27-11-2024	Observation started for 2nd treatment	By quadrat method	
30-11-2023	30-11-2024	Hand weeding		
5/12/2023	5/12/2024	7th date of sowing Irrigation Herbicide spraying	Flood irrigation, Goal weedicide	Bhima Shakti onion bulb; 8 ml / 16 lit water

		Insecticide spraying for 6th date of sowing		
12/12/2023	12/12/2024	Observation started for 3rd treatment		
27-12-2023	27-12-2024	Observation started for 4th treatment	By quadrat method	
30-12-2023	30-12-2024	Drenching	Streptomycin	3 g / 16 lit water
12/1/2024	12/1/2025	Observation started for 5th treatment		
			By quadrat method	
27-01-2024	27-01-2025	Observation started for 6th treatment		
12/2/2024	12/2/2025	Observation started for 7th treatment		
5/2/2024	5/2/2025	Final harvesting of 1st treatment		
19-02-2024	19-02-2025	Final harvesting of 2nd treatment		
4/3/2024	4/3/2025	Final harvesting of 3rd treatment	Picking of umbels	
20-03-2024	20-03-2025	Final harvesting of 4th treatment		
5/4/2024	5/4/2025	Final harvesting of 5th treatment		
20-04-2024	20-04-2025	Final harvesting of 6th treatment		
6/6/2024	6/6/2025	Final harvesting of 7th treatment		

Calendar of Operation (Influence of Apis mellifera on Abundance, Foraging Behavior among Onion (Allium cepa L.) Varieties.

Date		Operations Performed	Material used	Quantity used / sample collected
		Pre-sowing		
10-10-2023	10-10-2024	Ploughing Disking Rotavator Collection of stubbles	Tractor drawn machinery	1 Tractor / 1 disc harrow
17-10-2023	17-10-2024	Layout preparation Ridges and furrow shaping	Mould board plough, Raised maker	1 mould bold plough; 1 Raised maker
18-10-2023	18-10-2024	Fertilizer application FYM - NPK (10:26:26)		4 kg for one plot; 3 kg for one plot
		Post-sowing		
20-10-2023	20-10-2024	Sowing for 2nd obj. Bulb treatment Irrigation Herbicide spraying	Onion bulb, Mancozeb	Seven different varieties of onion and 250 onion in each plot; 2 g / lit
25-11-2023	25-11-2024	Irrigation		
05-12-2023	05-12-2024	Hand weeding		
06-12-2023	06-12-2024	Drenching	Streptomycin	3 g / 16 lit water
25-12-2023	25-12-2024	Morphological observation started		
05-01-2023	05-01-2025	Apis mellifera hives relocated in the varietal plot	Apis mellifera hives	Apis mellifera hives in plot
28-12-2023	28-12-2025	Apis mellifera observations started (Morning 8.00 AM to evening 6.00 PM)		
18-03-2023	18-03-2025	Harvesting		
25-03-2023	25-03-2025	Post-harvest observations		

Calendar of Operation (To formulate and evaluate some indigenous bee attractants for enhancing the pollinator's activity).

Date		Operations Performed	Material used	Quantity used / sample collected
		Pre-sowing		
10-10-2023	10-10-2024	Ploughing Disking Rotavator Collection of stubbles	Tractor drawn machinery	1 Tractor / 1 disc harrow
17-10-2023	17-10-2024	Layout preparation Ridges and furrow shaping	Mould board plough, Raised maker	1 mould bold plough; 1 Raised maker
18-10-2023	18-10-2024	Fertilizer application FYM - NPK (10:26:26)		4 kg for one plot; 3 kg for one plot
		Post-sowing		
20-10-2023	20-10-2024	Sowing for 3rd obj. Bulb treatment Irrigation Herbicide spraying	Onion bulb, Mancozeb	Seven different varieties of onion and 180 onion in each plot; 2 g/lit
25-11-2023	25-11-2024	Irrigation		
07-12-2023	07-12-2024	Hand weeding		
08-12-2023	08-12-2024	Drenching	Streptomycin	3 g / 16 lit water
20-12-2023	20-12-2024	Relocated different honeybee hives		

29-12-2023	29-12-2024	Preparations of indigenous bee attractant Day before first spray observations at peak time	10 different bee attractants	Formulation at 10%, 15%, 20%
30-12-2023	30-12-2024	First spraying of attractant at 15%		
31-12-2023	31-12-2024	After first spray observations started up to 7th day		
18-01-2024	18-01-2025	Hand weeding		
20-01-2024	20-01-2025	Irrigation		
22-01-2024	22-01-2025	Preparations of indigenous bee attractant Day before second spray observations at peak time		
23-01-2024	23-01-2025	Second spraying of attractant at 50%		
24-01-2024	24-01-2025	After second spray observations started up to 7th day		
18-03-2024	18-03-2025	Harvesting		
25-03-2024	25-03-2025	Post-harvest observations		