IMPACT OF BIOCHAR AMENDMENTS ON SOIL FERTILITY AND CROP PRODUCTIVITY IN WHEAT-PIGEON PEA CROPPING SYSTEM

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Agronomy

By

Gaurav Sharma

Registration Number: 12208260

Supervised By

Dr. Chandra Mohan Mehta

(18376)

Department of Agronomy (Professor)

Lovely Professional University

Co-Supervised by

Dr. Rajeev Kumar Gupta

(30662)

Department of Agronomy (Professor)

Lovely Professional University

LOVELY PROFESSIONAL UNIVERSITY, PUNJAB

2025

DECLARATION

I, hereby declared that the presented work in the thesis entitled **"Impact of Biochar Amendments on Soil Fertility and Crop Productivity in Wheat-Pigeon Pea Cropping System"** in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under the supervision of **Prof. CHANDRA MOHAN MEHTA**, working as **Associate Dean,** in the **SCHOOL OF AGRICULTURE** of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

(Signature of Scholar)

Name of the scholar: Mr. GAURAV SHARMA

Registration No.: 12208260

Department/school: SCHOOL OF AGRICULTURE

Lovely Professional University,

Punjab, India

CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled **"Impact of Biochar Amendments on Soil Fertility and Crop Productivity in Wheat-Pigeon Pea Cropping System"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the Agronomy/ **SCHOOL OF AGRICULTURE**, is a research work carried out by **GAURAV SHARMA, (12208260)** is bonafide record of his/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.

(Signature of Supervisor)	**(Signature of Co-Supervisor)**
Name of supervisor	Name of Co-Supervisor
Prof. Chandra Mohan Mehta	Prof. Rajeev Kumar Gupta
Designation: Professor & Associate Dean	Designation: Professor
Department/school: School of Agriculture, Agriculture, Lovely Professional University	Department/school: School of Lovely Professional University

ABSTRACT

Biochar is a highly stable carbon compound created through the slow process of pyrolysis of organic materials. This study focused on the efficiency of biochar in enhancing soil fertility for wheat-pigeon pea productivity. The experiment comprised nine different treatments using varied amounts of rice husk and straw biochar along with fertilisers. The two-year research trial was conducted in the field with biochar. The treatment includes T1 (absolute control), T2 (100% RDF), T3 (100% NP), T4 (NP + rice husk biochar 5 t/ha), T5 (NP + rice husk biochar 10 t/ha), T6 (NP + rice husk biochar 15 t/ha), T7 (NP +rice straw biochar 5 t/ha), T8 (NP +rice straw biochar 10 t/ha) and T9 (NP +rice straw biochar 15 t/ha). Results indicate that biochar plays a significant role in enhancing plant growth and yield attributes compared to the control. The most significant results were reported for rice husk and rice straw biochar applied at a rate of 5 tons/ha, along with recommended doses of nitrogen and phosphorus. As compared to control, the increment for plant height (+38.2%), LAI (+126.2%), CGR (+74%), node diameter (+61.4%), RWC (+25.9%), MSI (+30.9%), spike length (+95.4%), biological yield (+65.9%), grain yield (+191.6%), straw yield (+31.8%) and harvest index (+57.1%) was recorded. Succeeding crop pigeon pea plant growth and yield attributes were also analysed using standard methods. A significant impact of biochar application on plant growth and yield was observed as compared to control (T1), biochar application at a rate of 5 t/ha (T4 and T7) was observed in increasing the plant height (+80.1%), number of primary branches (+96.9%), dry biomass (+70.2%), number of trifoliate leaves (+71.8%), stem girth (+46.1%), RWC (+23.4%), MSI (+14.7%), pod per plant (+161.8%), pod length (+55.8%) biological yield (+95%) and grain yield (+149.5).

ACKNOWLEDGEMENT

The completion of this PhD thesis marks the peak of a journey that has been both challenging and rewarding. It is a testament to the collective efforts and support of numerous individuals and organisations, without whom this achievement would not have been possible. As I reflect on the path that has led me to this milestone, I am reminded of the invaluable contributions that have shaped my research and personal growth. It is with deep appreciation that I acknowledge the following individuals and entities who have played a significant role in my academic journey.

I want to express my deepest gratitude and heartfelt appreciation to my esteemed supervisor, ***Professor (Dr.) Chandra Mohan Mehta,*** *Associate Dean of the School of Agriculture, for his exceptional guidance, unwavering support, and invaluable mentorship throughout my PhD journey. His profound knowledge and expertise have been a constant source of inspiration, shaping both my academic and professional growth.*

Professor Mehta not only provided me with the tools to navigate complex research challenges but also instilled in me the confidence and resilience to tackle problems effectively. His encouragement and dedication have played a pivotal role in my personal and professional development, making this journey truly transformative. To me, Professor Mehta has been more than a supervisor; he has been a guiding light and a source of immense motivation. For all his efforts, patience, and belief in my potential, I am eternally grateful.

I extend my heartfelt gratitude to my co-supervisor, ***Professor (Dr.) Rajeev Kumar Gupta****, for his invaluable support and guidance throughout my PhD journey. His expertise and constructive feedback significantly refined my research, providing a broader perspective and helping me overcome challenges with confidence. I sincerely appreciate his dedication and contributions to my academic growth.*

I extend my sincere gratitude to ***Lovely Professional University (LPU)*** *for providing the necessary resources and facilities. I am particularly thankful to the* ***School of Agriculture*** *and the* ***Central Instrumentation Facility (CIF)*** *for their support. Their contributions significantly enhanced the quality and success of my research.*

I gratefully acknowledge the financial support provided by the Research Institute for ***Humanity and Nature (RIHN), Japan****, through the* ***AAKASH*** *Project. The support from RIHN has been crucial in facilitating my research activities and enhancing the overall quality of this thesis.*

I want to express my sincere gratitude to ***Prof. (Dr.) Eiji Nishihara****,* ***Prof. (Dr.) Kazuyuki Inu Bushi****,* ***Prof. (Dr.) Shigeto Sudo****,* ***Prof. (Dr.) Sachiko Hayashida****,* ***Prof. (Dr.) P.K. Patra****, and* ***Prof. (Dr.) Vishnu D. Rajput*** *for their invaluable support, guidance, and encouragement throughout my PhD journey. Their expertise, constructive feedback, and insightful discussions have significantly enriched my research and contributed to its success.*

I want to express my sincere gratitude to my colleagues and peers who have supported and collaborated with me throughout my PhD journey. I am especially thankful to ***Dr Anil Duhan, Ms Ankita Sharma, Mr Diptnu Banik, Dr. Rupinder Walia, Dharminder Rai, Dr. Shweta Srivastava, Dr. Simarjot Singh, Dr Rajeev Kumar, Mr Rajkumar, and Mr. Mastu Patel*** *for their invaluable assistance, encouragement, and insightful discussions. Their guidance and camaraderie have been instrumental in helping me overcome challenges and enrich my research experience. I sincerely appreciate their contributions and support during this academic endeavour.*

I want to extend my heartfelt appreciation to my family and friends, whose unwavering support and encouragement have been a constant source of strength throughout my PhD journey. Their patience, understanding, and love have been invaluable, helping me navigate the challenges and triumphs of this academic endeavour. I am deeply grateful for their presence in my life and for the sacrifices they have made to support my pursuit of this degree.

TABLE OF CONTENTS

Chapter	Title	Page no.
	ABSTRACT	**iv**
	ACKNOWLEDGEMENT	**v-vi**
	TABLE OF CONTENTS	**vii**
	LIST OF TABLES	**viii-xi**
	LIST OF FIGURES	**xii**
	LIST OF ABBREVIATIONS	**xiii**
	LIST OF UNITS	**xiv**
	LIST OF CHEMICAL COMPOUNDS	**xv**
1	INTRODUCTION	**1-7**
2	REVIEW OF LITERATURE	**8-22**
3	MATERIAL AND METHODS	**23-40**
4	RESULTS AND DISCUSSION	**41-152**
5	SUMMARY AND CONCLUSION	**153-160**
	BIBLIOGRAPHY	**161-177**
	APPENDICES	**178-183**

LIST OF TABLES

Table no.	Title	Page no.
3.1	The initial physicochemical properties of the experimental soil.	21
3.2	The Cropping history of the experimental field.	22
3.3	Experimental details of the research trial.	22
3.4	Treatment details of the research trial.	23
3.5	The characteristics of rice husk and straw biochar.	26
4.1	Effect of different doses of biochar application at plant height (cm) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	43
4.2	Effect of different doses of biochar application on the number of tillers and productive tillers (m^2) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	46
4.3	Effect of different doses of biochar application on leaf area (m^2) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	49
4.4	Effect of different doses of biochar application at leaf area index (LAI) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	51
4.5	Effect of different doses of biochar application on node diameter (mm) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 & 2023-2024.	53
4.6	Effect of different doses of biochar application on stem diameter (mm) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 & 2023-2024.	55
4.7	Effect of different doses of biochar application on fresh biomass (g) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	57
4.7	Effect of different doses of biochar application on dry biomass (g) of wheat at 30, 60, 90, and 120 DAS during the 2022-2023 & 2023-2024 seasons.	59

4.9	Effect of different doses of biochar application on crop growth rate (CGR) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 & 2023-2024.	61
4.10	Effect of different doses of biochar application at relative water content (RWC) (%) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	65
4.11	Effect of different doses of biochar application on chlorophyll content (mg/g) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	68
4.12	Effect of different doses of biochar application on membrane stability index (%) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.	71
4.13	Effect of different doses of biochar application on spike length, grain per spike and test weight of wheat at harvest during 2022-2023 & 2023-2024.	76
4.14	Effect of different doses of biochar application on biological yield, grain yield, straw yield and harvest index of wheat at harvest, during 2022-2023 & 2023-2024.	82
4.15	Effect of different doses of biochar application on Benefit-Cost Ratio (B: C ratio) of wheat.	83
4.16	Effect of different doses of biochar application on soil pH at 45 DAS, 90 DAS, and harvest during 2022-2023 & 2023-2024.	85
4.17	Effect of different doses of biochar application on soil electrical conductivity (mmhos/cm) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	88
4.18	Effect of different doses of biochar application on soil organic carbon (%) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	91
4.19	Effect of different doses of biochar application on soil available nitrogen (Kg/ha) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	93

4.20	Effect of different doses of biochar application on soil available phosphorus (Mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	96
4.21	Effect of different doses of biochar application on soil available potassium (Mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	98
4.22	Effect of different doses of biochar application on soil available sulphur (Mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	101
4.23	Effect of different doses of biochar application on soil available calcium (Mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	103
4.24	Effect of different doses of biochar application on soil available magnesium (Mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	106
4.25	Effect of different doses of biochar application on soil available iron (Mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 & 2023-2024.	109
4.26	Effect of different doses of biochar application on plant height (cm) of pigeon pea at 30, 60, 90 and 120 DAS during 2023 & 2024.	111
4.27	Effect of different biochar application doses on pigeon pea's primary branches at 60, 90 and 120 DAS during 2023 & 2024.	113
4.28	Effect of different doses of biochar application on fresh biomass (g) of pigeon pea at 30, 60 and 90 DAS during 2023 & 2024.	115
4.29	Effect of different doses of biochar application on dry biomass (g) of pigeon pea at 30, 60 and 90 DAS during 2023 & 2024.	117
4.30	Effect of different doses of biochar application on the number of trifoliate leaves of pigeon pea at 30, 60 and 90 DAS during 2023 & 2024.	119
4.31	Effect of different doses of biochar application at stem girth (mm) of pigeon peas at 30, 60 and 90 DAS during 2023 & 2024.	121

4.32	Effect of different doses of biochar application on total chlorophyll content (mg/g) of pigeon pea at 30, 60, and 90 DAS during 2023 & 2024.	124
4.33	Effect of different doses of biochar application at relative water content (RWC) (%) of pigeon pea at 30, 60 and 90 DAS during 2023 & 2024.	126
4.34	Effect of different doses of biochar application on membrane stability index (MSI) (%) of pigeon pea at 30, 60 and 90 DAS during 2023 & 2024.	128
4.35	Effect of different doses of biochar application at pod per plant, grain per pod and pod length (cm) of pigeon pea at harvest during 2023 & 2024.	131
4.36	Effect of different doses of biochar application on seed index, biological yield, grain yield and harvest index of pigeon pea at harvest, during 2023 & 2024.	136
4.37	Effect of Different Doses of Biochar Application on Benefit-Cost Ratio (B: C Ratio).	138
4.38	Effect of different doses of biochar application at soil pH at 45 DAS, 90 DAS and harvest during 2023 & 2024.	139
4.39	Effect of different doses of biochar application on soil electrical conductivity (m mhos/cm) at 45 DAS, 90 DAS and harvest during 2023 & 2024.	142
4.40	Effect of different doses of biochar application on soil organic carbon (%) at 45 DAS, 90 DAS and harvest, during 2023 & 2024.	144
4.41	Effect of different doses of biochar application on soil available nitrogen (Kg/ha) at 45 DAS, 90 DAS and harvest, during 2023 & 2024.	146
4.42	Effect of different doses of biochar application on soil available phosphorus (g/kg) 45 DAS, 90 DAS and harvest during 2023 & 2024.	148
4.43	Effect of different doses of biochar application on soil available potassium (g/kg) at 45 DAS, 90 DAS and harvest during 2023 & 2024.	150

4.44	Effect of different doses of biochar application on soil available sulphur (g/kg) at 45 DAS, 90 DAS and harvest during 2023 & 2024.	152
4.45	Effect of different doses of biochar application on soil available calcium (g/kg) at 45 DAS, 90 DAS and harvest during 2023 & 2024.	154
4.46	Effect of different doses of biochar application on soil available magnesium (g/kg) at 45 DAS, 90 DAS and harvest during 2023 & 2024.	156
4.47	Effect of different doses of biochar application on soil available iron (g/kg) at 45 DAS, 90 DAS and harvest during 2023 & 2024.	158

LIST OF FIGURES

Figure no.	Title	Page no.
2.1	The area under the rice-wheat cropping system is in millions of hectares.	**6**
2.2	The rainfall and depletion (mm) from 1992 to 2022.	**9**
2.3	Emissions of CH_4 during different years due to rice cultivation.	**10**
2.4	Emissions of CH4 during different years due to rice residue burning.	**11**
2.5	The agricultural waste generated in different countries is in metric tons per year.	**15**
2.6	Different methods of crop residue management. Approaches include in-situ incorporation, mulching, composting, biochar production, industrial use, and bioenergy utilisation.	**16**
2.7	Alternative cropping systems to the rice–wheat system in the Indo-Gangetic Plains, as well as other diversified rotations, that enhance sustainability and resource-use efficiency.	**16**
3.1	The weather and SMW (Standard Meteorological Weeks) data were collected over two years, from 2022 to 2024.	**21**
3.2	Field layout of research trial.	**24**
3.3	FESEM image of rice husk biochar (2a, 2b) and straw biochar (2f, 2g) mapping site rice husk biochar (2c) rice straw biochar (2h), and EDS mapping of rice husk biochar (2d) and rice straw biochar (2i), different colour dotted shad represent different elemental presence. (2e, 2j) Elemental concentration of biochar.	**27**
3.4	Timeline for the cultural operations performed during the research trail.	**28**
3.5	Picture of field and cultural practices conducted during research trail	**36-41**

4.1	Effect of different biochar doses on wheat plant height (cm) at 30, 60, 90, and 120 days after sowing.	**44**
4.2	Effect of different biochar doses on the number of tillers and productive tillers per unit meter in wheat at 60, 90, and 120 days after sowing (DAS).	**47**
4.3	Effect of different biochar doses on leaf area Index of wheat at 30, 60, 90, and 120 DAS.	**50**
4.4	Effect of different biochar doses on leaf area (m^2) of wheat at 30, 60, 90, and 120 DAS.	**52**
4.5	Effect of different biochar doses on node diameter (mm) of wheat at 60, 90, and 120 DAS.	**54**
4.6	Effect of different biochar doses on Stem diameter (mm) of wheat at 60, 90, and 120 DAS.	**56**
4.7	Effect of different biochar doses on fresh biomass (gram) of wheat at 30, 60, and 90 DAS.	**58**
4.8	Effect of different biochar doses on dry biomass (gram) of wheat at 30, 60, and 90 DAS.	**60**
4.9	Effect of different biochar doses on CGR (Crop growth Rtae) of wheat at 30, 60, and 90 DAS.	**62**
4.10	Effect of different biochar doses on RWC (Relative Water Content) of wheat at 30, 60, 90, and 120 DAS.	**65**
4.11	Effect of different biochar doses on chlorophyll content (mg/g) of wheat at 30, 60, 90, and 120 DAS.	**69**
4.12	Effect of different biochar doses of biochar on MSI (%) of wheat at 30, 60, 90, and 120 DAS.	**72**
4.13	Effect of different biochar doses on yield traits of wheat crop	**76**
4.14	Effect of different biochar doses on biological yield, grain yield, and straw yield.	**80**
4.15	Effect of different biochar doses on soil pH under wheat cultivation at 45 and 90 DAS and at harvest.	**86**
4.16	Effect of different biochar doses on soil EC (ds/cm) under wheat cultivation at 45 and 90 DAS and at harvest.	**89**

4.17	Effect of different biochar doses on soil organic carbon (%) under wheat cultivation at 45 and 90 DAS and at harvest.	**91**
4.18	Effect of different biochar doses on soil available nitrogen (kg/ha) under wheat cultivation at 45 and 90 DAS and at harvest.	**94**
4.19	Effect of different biochar doses on soil phosphorus (mg/kg) under wheat cultivation at 45 and 90 DAS and at harvest.	**96**
4.20	Effect of different biochar doses on soil potassium (mg/kg) under wheat cultivation at 45 and 90 DAS and at harvest.	**99**
4.21	Effect of different biochar doses on soil sulphur (mg/kg) under wheat cultivation at 45 and 90 DAS and at harvest.	**101**
4.22	Effect of different biochar doses on soil calcium (mg/kg) under wheat cultivation at 45 and 90 DAS and at harvest.	**104**
4.23	Effect of different biochar doses on soil magnesium (mg/kg) under wheat cultivation at 45 and 90 DAS and at harvest.	**107**
4.24	Effect of different biochar doses on soil iron (mg/kg) under wheat cultivation at 45 and 90 DAS and at harvest.	**109**
4.25	Effect of different biochar doses on plant height (cm) in pigeon pea at 30, 60, 90, and 120 DAS.	**112**
4.26	Effect of different biochar doses on fresh biomass (gram) in pigeon pea at 60, 90, and 120 DAS.	**115**
4.27	Effect of different biochar doses on dry biomass in pigeon pea at 60, 90, and 120 DAS.	**118**
4.28	Effect of different biochar doses on no. of trifoliate leaf in pigeon pea at 30, 60, and 90 DAS.	**119**
4.29	Effect of different biochar doses on stem girth (mm) in pigeon pea at 30, 60, and 90 DAS.	**121**
4.30	Effect of different biochar doses on the number of primary branches in pigeon pea at 60, 90, and 120 DAS.	**122**
4.31	Effect of different biochar doses on chlorophyll content (mg/g) in pigeon pea at 30, 60, and 90 DAS.	**124**
4.32	Effect of different biochar doses on relative water content (%) in pigeon pea at 30, 60, and 90 DAS.	**126**

4.33	Effect of different biochar doses on membrane stability index (%) in pigeon pea at 30, 60, and 90 DAS.	**128**
4.34	Effect of different biochar doses on pod length, grain per pod, pod length, and seed index in pigeon pea.	**132**
4.35	Effect of different biochar doses on biological yield, grain yield and harvest index in pigeon pea.	**137**
4.36	Effect of different biochar doses on soil pH under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**140**
4.37	Effect of different biochar doses on soil EC (ds/cm) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**142**
4.38	Effect of different biochar doses on soil organic carbon (%) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**144**
4.39	Effect of different biochar doses on soil available nitrogen (kg/ha) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**146**
4.40	Effect of different biochar doses on soil phosphorus (mg/kg) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**148**
4.41	Effect of different biochar doses on soil potassium (mg/kg) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**150**
4.42	Effect of different biochar doses on soil sulphur (mg/kg) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**152**
4.43	Effect of different biochar doses on soil calcium (mg/kg) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**154**
4.44	Effect of different biochar doses on soil magnesium (mg/kg) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**156**
4.45	Effect of different biochar doses on soil iron (mg/kg) under pigeon pea cultivation at 45 and 90 DAS and at harvest.	**158**

LIST OF ABBREVIATIONS

Abbreviations	Full name
ANOVA	Analysis of variance
CD	Critical difference
Cu	Copper
DAP	Diammonium phosphate
DAS	Days after sowing
HI	Harvest index
LAI	Leaf area index
MOP	Muriate of potash
RDF	Recommended dose of fertiliser
ROS	Reactive oxygen species
pH	Negative logarithm of H^+ ions
EC	Electrical conductivity
OC	Organic carbon
N	Nitrogen
P	Phosphorus
K	Potassium
S	Sulphur
Ca	Calcium
Mg	Magnesium
Fe	Iron
Cu	Copper
Mn	Manganese
Zn	Zinc
B	Boron
EDX	Energy Dispersive X-ray (Spectroscopy)
FESEM	Field Emission Scanning Electron Microscopy

LIST OF UNITS

Units	Full name
%	Percent
cm	Centimetre
cm^2	Centimetre square
ds/m	Deci siemens per metre
g	Gram
Kg/ha	Kilograms per hectare
m^2	Metre square
mg	Millig
mg/kg	Millig per kilog
mg/L	Millig per litre
ml	Millilitre
ml/kg	Millilitre per kilog
mM	Millimolar
N	Normality
nm	Nanometre
q/ha	Quintal per hectare
rpm	Revolutions per minute

LIST OF CHEMICAL COMPOUNDS

Chemical formula	Chemical name
$CaCO_3$	Calcium carbonate
EDTA	Ethylene diamine tetraacetic acid
$FeCl_3.6H_2O$	Ferric chloride
Fritted glass	Zinc frits
H_2SO_4	Sulphuric acid
HCl	Hydrochloric acid
$HClO_4$	Perchloric acid
HEDTA	Hydroxy ethyl ethylene diamine triacetic acid
HNO_3	Nitric acid
KNO_3	Potassium nitrate
$MgSO_4$	Magnesium sulphate
$Na_2ZnEDTA$	Disodium Zn EDTA
NaCl	Sodium chloride
NaH_2PO_4	Monosodium phosphate/ sodium dihydrogen phosphate
NaZnEDTA	Sodium Zn EDTA
NaZnHEDTA	Sodium Zn HEDTA
$Zn(NH_3)_4SO_4$	Ammoniated Zn
$Zn(NO_3)_2.3H_2O$	Zinc nitrate
$Zn_3(PO_4)_2$	Zinc phosphate
$ZnCl_2$	Zinc chloride
$ZnCl_2$	Zinc chloride
$ZnCO_3$	Zinc carbonate
ZnO	Zinc oxide
$ZnO.ZnSO_4$	Zinc oxysulphate
$ZnSO_4$	Zinc sulphate
$ZnSO_4.4Zn(OH)_2$	Basic zinc sulphate
$ZnSO_4.7H_2O$	Zinc sulphate heptahydrate
$ZnSO_4.H_2O$	Zinc sulphate monohydrate

CHAPTER-I

INTRODUCTION

The rice-wheat cropping system constitutes the predominant agricultural practice in the Indo-Gangetic Plains, encompassing regions of India, Pakistan, Nepal, and Bangladesh. In India, this system extends over ten million hectares, primarily in Punjab, Haryana, Bihar, Uttar Pradesh, and Madhya Pradesh. It contributes approximately 75% of India's national food grain output and serves as the principal basis for the country's food self-sufficiency (Jha et al., 2023). Within India, the rice-wheat system covers approximately 9.1 million hectares, accounting for 32% of the total rice area and 42% of the total wheat area. Average rice yields in this system range from 2.5 to 4 tons per hectare, while wheat yields typically range from 3 to 6 tons per hectare. Rice production alone accounts for roughly 20% of India's total agricultural gross domestic product (GDP) (Jat et al., 2022).

The rice-wheat cropping system remains central to agricultural production in South Asia, especially within the Indo-Gangetic Plains. Despite its significance, the system faces critical challenges that undermine its sustainability and productivity, including declining groundwater levels and the prevalent practice of crop residue burning (Chauhan et al., 2022). These challenges not only reduce agricultural output but also generate significant environmental and public health concerns. Recent studies indicate that productivity growth is stagnating, with some regions experiencing declines attributed to soil degradation, water scarcity, and increased pest pressures (Kumar et al., 2023). For example, continuous cultivation has resulted in reductions of soil organic matter by up to 50% in specific areas.

Excessive dependence on groundwater for irrigation has resulted in significant declines in water tables. For instance, groundwater levels in Punjab have decreased by approximately one meter annually over the past two decades. As of 2020, an estimated 60% of irrigated areas in these states rely on groundwater, rendering them highly vulnerable to water scarcity (Duhan et al., 2017). This depletion threatens rice and wheat production, as both crops require considerable water for optimal yields. With projections indicating that South Asia will need to feed an additional 20 million people per year by 2030, pressure on water resources is likely to intensify. As a result, farmers are encountering greater challenges in sustaining yields. Research indicates that wheat yields may decline by up to 10% for each degree Celsius increase in temperature during critical growth stages (Zhao et al., 2020).

Crop residue burning, a common practice for field clearance after harvest, poses a significant environmental challenge. This practice contributes substantially to air pollution and greenhouse gas emissions. In India, burning crop residues is estimated to release approximately 150 million tons of carbon dioxide annually (Sharma et al., 2022). Additionally, residue burning results in the loss of organic matter that could otherwise improve soil fertility and structure. The environmental consequences are considerable; research demonstrates that this practice can elevate particulate matter concentrations in the air by up to 30%, thereby deteriorating air quality and public health (Jain et al., 2022). The World Health Organisation (WHO) has linked poor air quality to an increased incidence of respiratory and cardiovascular diseases.

Integrated strategies focusing on sustainable intensification and resource conservation are being implemented to address the challenges in rice-wheat cropping systems. Technologies such as laser land levelling, zero-till farming, and direct seeding of rice are increasingly adopted by farmers seeking to enhance productivity while conserving resources (Kumar et al., 2023). Zero-till farming, for instance, improves soil health by minimising erosion and increasing moisture retention. Empirical evidence shows that zero-till practices can increase wheat yields by up to 15% compared to conventional tillage. Furthermore, direct seeding of rice reduces water consumption by approximately 30% relative to traditional puddled transplanting methods.

Promoting crop diversification can help mitigate the risks associated with monocropping systems. Integrating legumes or oilseeds into existing cropping patterns enhances soil fertility through biological nitrogen fixation, offering additional income opportunities for farmers (Jayaraman et al., 2022). Straw burning further diminishes soil fertility and productivity, negatively impacting crop yields and food security. Despite initiatives to diversify cropping patterns, rice cultivation remains more profitable for many farmers, limiting the effectiveness of diversification efforts. Policymakers and agricultural specialists are developing strategies to address these challenges, including establishing reliable markets and price support for alternative crops such as maize, cotton, sunflower, pigeon pea, and mung bean.

Integrating pigeon peas into rice-based cropping systems can enhance soil fertility, crop yields, energy efficiency, soil organic carbon, water use efficiency, and overall soil health. Evaluating the advantages of pigeon pea-based systems supports the adoption of sustainable agricultural practices in the Indo-Gangetic Plains (Singh et al., 2005). In recent years, South Asia has undergone a gradual shift toward crop diversification, with a growing emphasis on high-value commodities, including fruits, vegetables, and livestock. A survey of 1,400 farms revealed a significant increase in the cultivation of high-value crops, driven by evolving market demands and government policies aimed at improving agricultural productivity and smallholder incomes. The Diversity Index for crop diversification in South Asia increased from 0.59 in 1981-82 to 0.64 in 1999-2000, reflecting a positive trend toward more varied cropping systems. However, the rate of diversification differs considerably among countries in the region (Jha et al., 2022).

Countries such as India and Nepal are increasingly incorporating diverse cropping patterns into their agricultural strategies. Economic incentives are a primary driver, as farmers are more likely to diversify when non-cereal crops offer higher returns. Infrastructure improvements, including enhanced market access and transportation, have also facilitated the adoption of diversified cropping systems (Khan et al., 2024). Socio-economic factors, such as secure land tenure and access to credit, further influence farmers' decisions regarding diversification. Many smallholder farmers, operating on less than one hectare, encounter obstacles such as limited access to advanced technologies and fragmented markets. Consequently, although some farmers express interest in diversification, they often lack the necessary resources or institutional support to implement it effectively.

Transitioning to alternative crops in place of rice has become increasingly important in response to challenges such as climate change, water scarcity, and soil degradation. This shift is crucial for enhancing food security and promoting sustainable agricultural systems that are resilient to environmental stressors. In South Asia, crops such as maize, sorghum, millets, cassava, cotton, and legumes, including chickpeas, pigeon peas, and lentils, are being considered as viable alternatives (Kumar et al., 2020). Leguminous crops, in particular, offer high protein content and enhance soil fertility through biological nitrogen fixation (ICAR-NIASM 2021). For instance, millets require approximately 50% less water than rice during cultivation. Incorporating legumes into cropping systems also increases soil organic matter and reduces dependence on chemical fertilisers. These practices support sustainable agriculture and maintain long-term productivity while conserving natural resources.

Rice residue management techniques include ploughing, animal feeding, mulching, biochar production, and composting. Among these approaches, biochar production is a new and ecologically benign process that uses pyrolysis, a high-temperature treatment without oxygen, to turn leftovers into biochar (Khan et al., 2022). In 1870, a European geologist made the first reference to the "discovery" of biochar when he observed locations in South America with vibrant soils, as opposed to the ordinary acidic soils that were capable of only brief periods of productivity. According to anthropological studies, biochar-enriched soils may have generated areas of extraordinarily high productive output to support successive societies in densely populated portions of South America. Archaeological research has revealed the presence of biochar-enriched soils in the Amazon Basin dating back to approximately 8000 BC. Terra-preta, a carbon-rich soil combination, is still found in many areas of the Amazon Basin (Pandey, 2016).

Biochar is rich in carbon, with the highest surface area, porosity, and Cation Exchange Capacity (Hossain et al., 2017). Rice residue can be converted to biochar with superior physicochemical and structural properties, including increased carbon content, enhanced surface area, porosity, and ion exchange capacity, making rice straw-derived biochar a promising bio-based precursor for adsorbents (Wang et al., 2022). Biochar may serve two functions: enhancing soil health when put into the soil and providing a sustainable energy source when used as a fuel. Rice husk, a byproduct of rice milling, is widely available worldwide. Biochar generated at 400°C is typically alkaline and has a high cation exchange capacity, making it ideal for use as a fertiliser and soil amendment. Biochar made from rice straw exhibits turbostatic crystallites at 400°C and a high degree of aromatisation at 500°C, which affects soil physicochemical properties, microbial populations, and enzymatic activity. Biochar treatment also enhances phosphorus availability, exchangeable cations, and cation exchange capacity in the soil, increasing plant height, tiller number, dry biomass weight, and rice production. (Zhang et al., 2020). Plant growth promotion: Biochar treatment has been shown to increase plant growth, particularly in infertile soils. For example, adding rice straw biochar to soil can boost plant height, tiller numbers, and biomass output in wheat.

The rice-wheat cropping system in the Indo-Gangetic Plains is increasingly constrained by groundwater depletion, crop residue burning, declining soil fertility, and stagnating yields. Most existing research has concentrated on monocropping systems dominated by rice or wheat, with limited attention to diversified rotations such as wheat–pigeon pea, which offer agronomic and ecological advantages. There is a notable lack of systematic data on the effects of biochar on soil fertility, crop yield, and economic returns within wheat–pigeon pea systems under the region's agroecological conditions. Addressing this knowledge gap is crucial for developing sustainable alternatives to residue burning, improving resource-use efficiency, and enhancing the long-term resilience of cereal–pulse systems in South Asia. Accordingly, the present study **investigates the impact of biochar amendments on soil fertility and crop productivity in the wheat–pigeon pea cropping system**, with the following objectives:

1. To evaluate the impact of biochar application on soil properties.

2. To analyse the response of biochar on growth, yield, and quality attributes of the wheat-pigeon pea cropping system.

3. To assess the economic viability of biochar on the wheat-pigeon pea cropping system.

CHAPTER -II

REVIEW OF LITERATURE

1. Rice-Wheat Cropping System (RWCS)

Overview of the RWCS: The Rice-Wheat Cropping System is a predominant agricultural practice in South Asia, particularly within the Indo-Gangetic Plains (IGP), which spans parts of India, Pakistan, Nepal, and Bangladesh. This system involves the sequential cultivation of rice during the kharif (monsoon) season, followed by wheat in the rabi (winter) season (Ladha et al., 2019). The significance of the Rice-Wheat Cropping System in South Asia cannot be overstated. It plays a critical role in food security, with rice and wheat accounting for about 85% of cereal production and nearly 60% of caloric intake in the region. The productivity gains from this system have been pivotal in feeding a rapidly growing population (Kumar et al., 2024). Economically, the Rice-Wheat Cropping System supports millions of livelihoods and provides stable income for farmers, particularly in northwestern India, where it is the backbone of agricultural production.

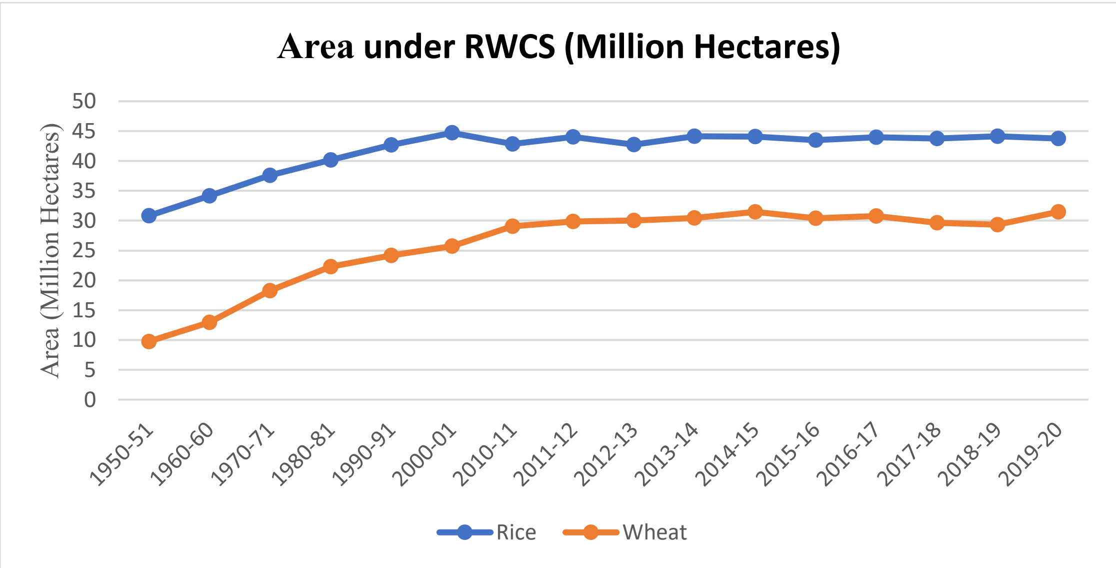


Figure 2.1 The area under the rice-wheat cropping system in millions of hectares. (Source: https://www.indiastat.com/data/agriculture/rice)

Historical Context: The Rice-Wheat Cropping System emerged as a dominant agricultural practice in the Indo-Gangetic Plains during the early 1970s, primarily due to the Green Revolution, which introduced high-yielding varieties of rice and wheat, along with improved agronomic practices (Bhatt et al., 2022). This period saw a dramatic increase in cereal production, with rice and wheat becoming staple foods that supported the nutritional needs of a burgeoning population. Farmers rapidly adopted this system by leveraging favourable agroclimatic conditions, irrigation facilities, and access to modern agricultural technologies, leading to substantial productivity increases. For instance, rice production in India surged from approximately 87.4 million tons in 1961 to over 324 million tons by 2019, showcasing the effectiveness of this cropping system in enhancing food security. The historical development of the Rice-Wheat Cropping System illustrates its importance in supporting food security in South Asia and the necessity for continued innovation to ensure its sustainability for future generations.

Geographical Distribution: Punjab and Haryana are known for their high agricultural productivity, attributed to the adoption of modern farming techniques and high-yielding varieties introduced during the Green Revolution (Khan et al., 2024). In addition to India, the Rice-Wheat Cropping System is significant in Pakistan, where it is practised in regions like Punjab and Sindh. The system has gained importance over the years due to its ability to meet the food demands of a growing population. In Nepal, rice-wheat cropping systems are prevalent in the Terai region, where farmers have increasingly adopted wheat cultivation alongside traditional rice farming. Bangladesh also features rice-wheat systems, although rice remains the dominant crop in its agricultural landscape (Zhang et al., 2023). As agricultural practices evolve to address emerging challenges such as climate change and resource depletion, understanding the geographical dynamics of the Rice-Wheat Cropping System will be essential for developing sustainable agricultural strategies that can maintain productivity while safeguarding environmental health.

2. Challenges of the Rice-Wheat Cropping System

Soil Health Decline: Soil health decline is a critical concern associated with the Rice-Wheat Cropping System, primarily driven by nutrient depletion and soil compaction from continuous cropping practices. The intensive nature of this system, where rice and wheat are grown sequentially on the same land year after year, leads to a significant loss of essential nutrients from the soil. Over time, this cropping system results in imbalances in nutrient availability, nitrogen, phosphorus and potassium, which are essential for optimal crop growth. Additionally, continuous cropping practices contribute to soil compaction due to heavy machinery use and a lack of crop rotation. Compacted soils exhibit reduced porosity and aeration, adversely affecting root development and water infiltration (Gürsoy et al., 2021). This compaction can hinder microbial activity essential for nutrient cycling and organic matter decomposition, further exacerbating soil health issues. The decline in soil structure affects not only the physical properties of the soil but also its biological and chemical characteristics, leading to a vicious cycle of declining fertility (Carlesso et al., 2019). Moreover, the increased prevalence of soil-borne pathogens and pests in continuously cropped fields can lead to further challenges for farmers, as these organisms thrive in nutrient-depleted environments.

Water Scarcity: Water scarcity is a pressing challenge facing the Rice-Wheat Cropping System in South Asia, particularly due to the over-exploitation of groundwater resources, leading to alarming water table declines. The Rice-Wheat Cropping System, predominantly practised in the Indo-Gangetic Plains, relies heavily on irrigation to meet the water demands of both rice and wheat crops (Sathre et al., 2022). As rainfall is often insufficient to sustain these high-water-requiring crops, farmers have increasingly turned to groundwater sources, exacerbating the depletion of aquifers. In states like Punjab and Haryana, where the Rice-Wheat Cropping System is most prevalent, excessive irrigation practices have resulted in groundwater extraction rates that far exceed natural recharge rates (Sidhu et al., 2020). Reports indicate that groundwater levels have declined significantly in these regions, with some areas experiencing drops of over one meter per year. The situation is compounded by the subsidised rates for electricity and water, which incentivise farmers to over-irrigate their fields. This practice depletes groundwater reserves and contributes to soil degradation and water-induced land degradation issues such as salinisation and sodification (Pandey et al., 2016). The result is a vicious cycle in which declining water availability adversely affects crop yields, prompting farmers to extract more groundwater to maintain productivity. Consequently, this over-reliance on groundwater threatens the sustainability of the Rice-Wheat Cropping System, as diminishing water resources can lead to increased competition among users and potential conflicts over access. Furthermore, the decline in water tables has broader implications for the region's agricultural resilience and food security (Shaikh et al., 2024). With climate change intensifying weather patterns and altering precipitation regimes, the pressure on already strained water resources is expected to intensify.

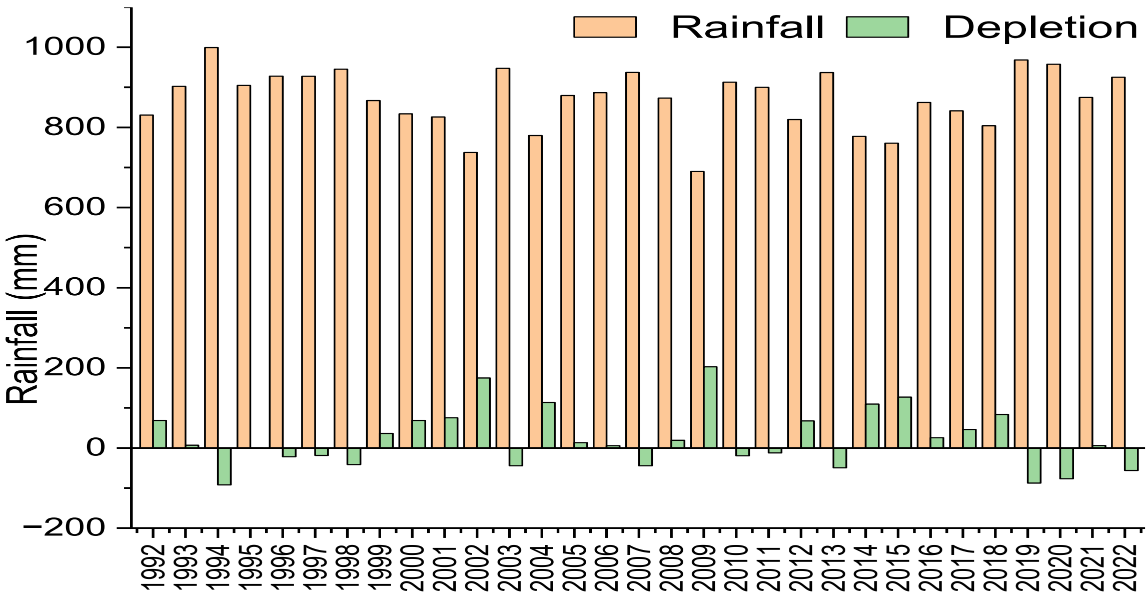


Figure 2.2 The rainfall and depletion (mm) from 1992 to 2022. (Source: https:// Mausam. indigo v. in/)

Labour Shortages: Labour shortages have emerged as a significant challenge within the Rice-Wheat Cropping System, adversely affecting timely agricultural operations and overall productivity. The increasing difficulties in labour availability are attributed to several factors, including rural-urban migration, changing employment patterns, and the seasonality of agricultural work (Asfaw et al., 2010). Many agricultural workers migrate to urban areas in search of better livelihood opportunities, resulting in a pronounced imbalance between labour demand and supply during critical farming periods (Choithani et al., 2021). This migration often delays essential activities such as sowing, weeding, and harvesting, which are time-sensitive and crucial for maximising crop yields. Farmers frequently report that labour scarcity leads to untimely operations, resulting in inefficiencies that can severely impact crop growth and overall farm productivity. These include hiring labour from other regions at higher wages, increasing mechanisation of farm operations, and utilising family labour more intensively (Collins et al., 2019). With timely agricultural operations crucial for maintaining soil health and crop yields, persistent labour shortages could lead to long-term declines in productivity and profitability.

Environmental Concerns: Environmental concerns associated with the Rice-Wheat Cropping System are increasingly prominent, particularly due to pollution from crop residue burning and resulting greenhouse gas emissions. In regions such as northwestern India, where the Rice-Wheat Cropping System is extensively practised, the burning of rice straw has become a common practice among farmers. This method is often employed to clear fields quickly after harvest, facilitating the timely sowing of wheat (Mishra et al., 2021). However, this practice has severe environmental repercussions, contributing significantly to air pollution and soil nutrient loss. Approximately 2 million farmers in these regions annually burn an estimated 23 million tons of rice residue, resulting in elevated levels of particulate matter in the air. In some urban areas, air quality measurements have revealed that particulate pollution levels can exceed safe daily thresholds by more than five times, posing serious health risks to both rural and urban populations. Agriculture in India accounts for around 16% of total greenhouse gas emissions, with rice cultivation alone responsible for approximately 36.9% of these emissions due to methane release during anaerobic decomposition in flooded fields (Martínez-Eixarch et al., 2021). The use of chemical fertilisers and pesticides in conventional farming practices within the Rice-Wheat Cropping System leads to soil degradation and water pollution. The combination of these factors threatens local ecosystems and undermines the long-term sustainability of agricultural practices in the region.

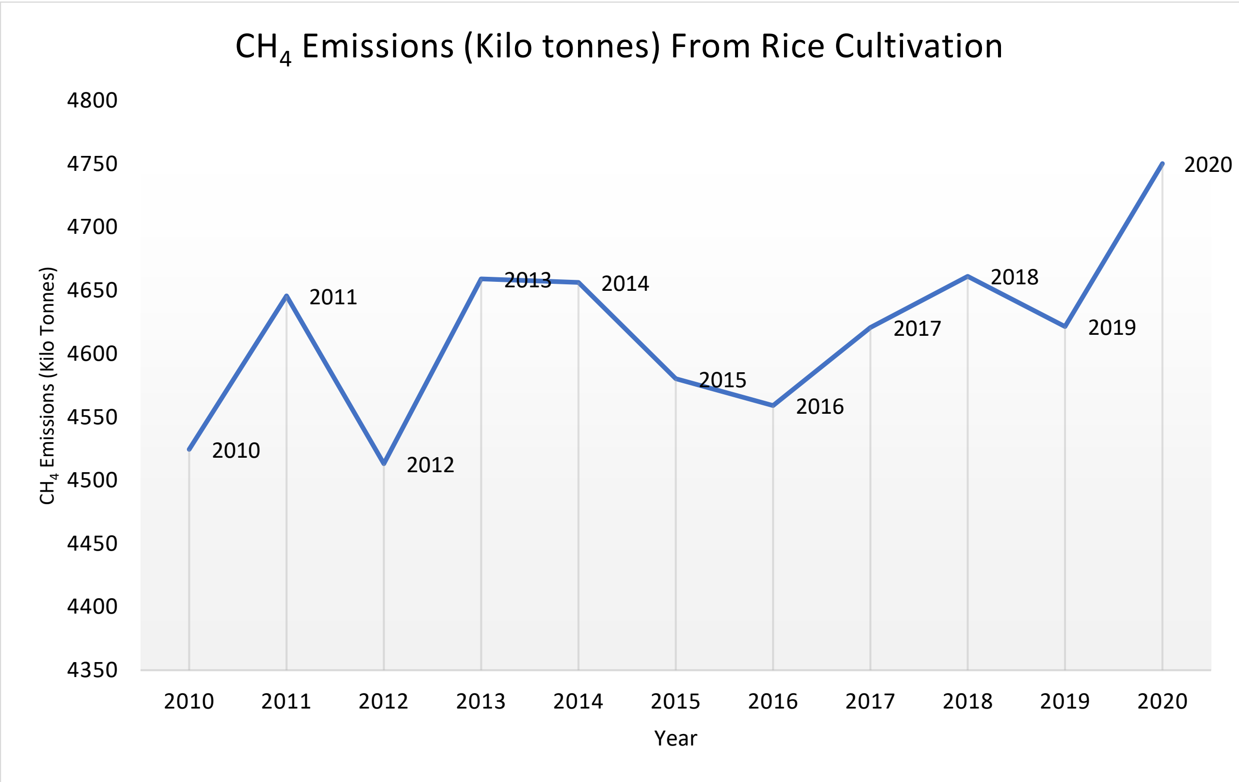


Figure 2.3: **Emissions of CH4 over different years resulting from rice cultivation.**

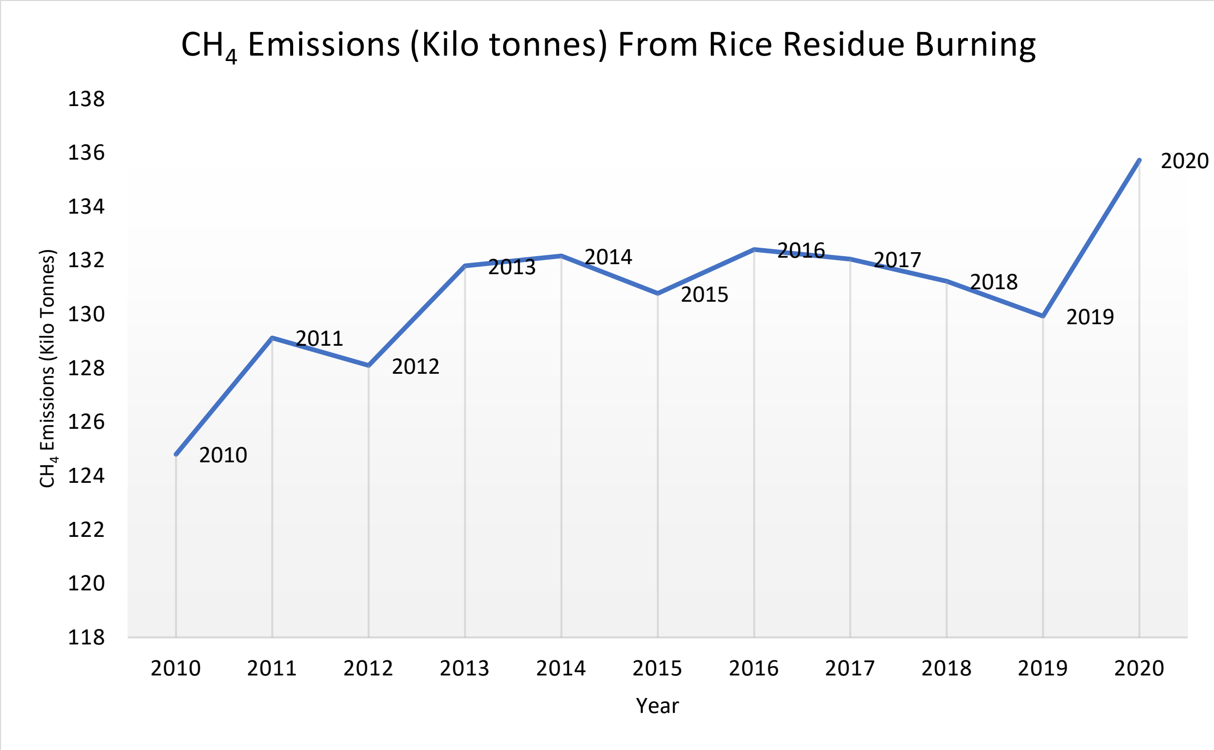


Figure 2.4 Emissions of CH4 during different years due to rice residue burning.

Climate Vulnerabilities: Climate vulnerabilities significantly impact the Rice-Wheat Cropping System in South Asia, with climate change adversely affecting crop yields and farming practices. As global temperatures rise, the region experiences increasing frequency and intensity of extreme weather events, including droughts, floods, and erratic rainfall patterns (Seneviratne et al., 2021). These climatic shifts have been shown to reduce agricultural productivity. For instance, research indicates that rice yields may decline by up to 15% under projected climate scenarios due to higher temperatures and altered precipitation patterns (Kogo et al., 2021). Due to rising temperatures, the DSSAT and APSIM crop models predict reductions of 15.2% in rice and 14.1% in wheat yields by mid-century, with some regions facing even steeper declines (Lal Niwas et al.,2024). For example, heat stress during critical growth stages can hinder seed germination and reduce grain weight. At the same time, drought conditions adversely affect reproductive stages, leading to lower spikelet numbers and grain size (Hill et al., 2024). Such challenges threaten food security and compel farmers to seek alternative crops or practices that may not align with their traditional knowledge or available resources. Moreover, the socio-economic implications of these climatic changes are profound. Many farmers lack access to the technology and information needed to implement effective adaptation strategies, making them particularly vulnerable to the impacts of climate variability (Abegunde et al., 2019). As agricultural productivity declines, there is an increasing risk of food insecurity and economic instability for rural populations reliant on the Rice-Wheat Cropping System for their livelihoods.

3. The Major Challenge with Rice Cultivation

Puddling and Soil Structure: Puddling, a common practice in rice cultivation, significantly affects soil structure and aeration, leading to issues such as soil compaction that can adversely impact subsequent crops in the rice-wheat cropping system (Nawaz et al., 2019). This process involves mixing soil and water to create a saturated environment, intended to improve rice growth conditions by minimising nutrient leaching and enhancing water retention. However, while puddling offers immediate benefits such as weed control and reduced percolation losses, its long-term effects can be detrimental (Bwire et al., 2024). Over time, repeated puddling can lead to the formation of a hardpan or plough pan, which hinders root penetration and reduces soil aeration (Kalita et al., 2020). This compaction restricts air and water movement within the soil profile, negatively affecting the performance of subsequent wheat crops. Studies have shown that mechanical disruption of soil aggregates during puddling can increase bulk density and decrease porosity, both of which are critical factors for maintaining healthy soil ecosystems (Horn et al., 2021). The destruction of soil structure impairs water infiltration and limits microbial activity, which is essential for nutrient cycling. Consequently, crops planted after rice may experience reduced growth due to inadequate root development and nutrient availability (Muhammad et al., 2024). Furthermore, the long-term reliance on puddled soils can lead to stratification issues, where different soil layers develop distinct physical properties that complicate moisture retention and root access

Yield Stagnation: Yield stagnation in the Rice-Wheat Cropping System has become increasingly evident, particularly concerning the declining wheat yields that follow puddled rice cultivation compared to direct-seeded methods. Puddling involves saturating the soil to facilitate seedling transplantation, but it often leads to detrimental soil conditions for subsequent crops. Research indicates that wheat yields can decline by approximately 8% when sown after puddled, transplanted rice compared to those following direct-seeded rice methods (Xu et al., 2023). This yield reduction is attributed to several factors, including soil compaction and poor aeration caused by the puddling process. It creates a hardpan restricting root growth and nutrient uptake in the succeeding wheat crop. The transition from puddled rice to wheat also presents challenges related to timing. The intensive puddling and the subsequent tillage operations required to prepare a suitable seedbed for wheat result in longer turnaround times between crops. This delay can lead to late wheat planting, which has been shown to significantly impact yields, with reductions of approximately 27.6 kg per hectare for each day planting is postponed beyond mid-November (Chhokar et al., 2023).

Nutrient Deficiencies: Nutrient deficiencies within the Rice-Wheat Cropping System pose a significant challenge to agricultural productivity, primarily due to the soil's depth-wise depletion of essential nutrients. The intensive nature of this double-cropping system, where rice and wheat are cultivated sequentially, leads to substantial nutrient extraction from the soil (Dhanda et al., 2022). For instance, a typical rice-wheat sequence can remove over 300 kg of nitrogen, 30 kg of phosphorus, and 300 kg of potassium per hectare annually. This imbalance has resulted in multi-nutrient deficiencies that hinder crop growth and contribute to declining yields and overall soil health (Vijayakumar et al.,2024). The continuous application of chemical fertilisers without adequate attention to balanced nutrient management exacerbates these deficiencies. Many farmers rely heavily on nitrogen and phosphorus inputs, while neglecting potassium and micronutrients, which can lead to further degradation of soil fertility (Rayne et al., 2020). Studies have shown that soils in key Rice-Wheat Cropping System regions are increasingly deficient in potassium and zinc, which are critical for optimal crop performance. The lack of these nutrients can impair physiological processes in plants, resulting in stunted growth and reduced productivity. Additionally, the phenomenon known as "soil nutrient mining" occurs when essential nutrients are extracted at rates faster than they can be replenished, leading to long-term soil degradation.

4. Current Status of Crop Diversification and Residue Management

Crop Diversification Efforts: Crop diversification efforts within the Rice-Wheat Cropping System have gained momentum to enhance soil health and improve agricultural productivity in South Asia (Kaushal et al., 2020). The introduction of alternative crops, such as maize, soybeans, cotton, and pigeon peas, has been recognised for its potential to break the cycle of nutrient depletion associated with continuous rice and wheat cultivation (Sangma et al., 2020). By incorporating these crops into the cropping system, farmers can achieve several benefits, including improved soil fertility, increased biodiversity, and enhanced resilience against climate variability. For example, legumes like soybeans and pigeon peas provide additional income and contribute to soil nitrogen enrichment through biological fixation, thereby reducing the need for synthetic fertilisers (Kebede et al., 2021). Research has demonstrated that diversifying the Rice-Wheat Cropping System with short-duration crops can significantly improve overall system productivity. Studies indicate that integrating maize into the cropping sequence can enhance water-use efficiency and reduce labour costs while providing a profitable alternative during the summer months (Brar et al., 2022).

Furthermore, innovative cropping patterns that include vegetables or pulses alongside traditional staple crops have been shown to increase land use efficiency and profitability for farmers. For instance, a diversified system incorporating rice, maize, and legumes has been reported to increase net income by over 26% compared to conventional rice-wheat practices (Mishra et al., 2021). The adoption of diversified cropping systems not only addresses the immediate challenges of soil nutrient depletion but also contributes to long-term sustainability by improving soil structure and health. By reducing reliance on single-crop systems, farmers can mitigate risks associated with climate change and market fluctuations.

Residue Management Practices: Effective crop residue management practices are essential for enhancing soil fertility and reducing the environmental impact of the Rice-Wheat Cropping System. Traditionally, farmers have relied on burning crop residues, particularly rice straw, to clear fields quickly after harvest. However, this practice not only contributes to air pollution but also results in the loss of valuable organic matter and nutrients that could otherwise benefit subsequent crops (Dutta et al., 2022). Various strategies have been developed to manage crop residues sustainably to combat these issues. For instance, incorporating residues into the soil can significantly improve soil structure, increase organic carbon content, and enhance nutrient availability (Sarkar et al., 2022). Research indicates that incorporating rice and wheat residues can substantially increase soil organic carbon levels, which are critical for maintaining soil health and promoting microbial activity. Another practical approach is using conservation tillage techniques, such as zero tillage or reduced tillage systems, which allow for the retention of crop residues on the soil surface. These methods help preserve moisture, protect against soil erosion, and improve soil fertility (De Sousa et al., 2024). The Happy Seeder technology has gained popularity in regions like northwestern India, enabling farmers to sow wheat directly into retained rice residues without requiring extensive land preparation. This practice has been shown to enhance wheat yields while improving soil health by increasing organic matter content and nutrient cycling (Kaur et al., 2023). Integrating microbial decomposers into residue management practices has emerged as a promising solution. Studies have demonstrated that the use of microbial inoculants can accelerate the decomposition of crop residues, facilitate the release of nutrients, and enhance soil enzymatic properties (Harindintwali et al., 2020). Such integrated approaches enhance nutrient cycling and contribute to sustainable agricultural practices by minimising reliance on chemical fertilisers. Adopting effective residue management practices is crucial for optimising productivity within the Rice-Wheat Cropping System while mitigating environmental impacts. By transitioning from burning to incorporation and retention strategies, farmers can improve soil health, enhance crop yields, and contribute to a more sustainable agricultural system that addresses both food security and environmental concerns (Korav et al., 2024).

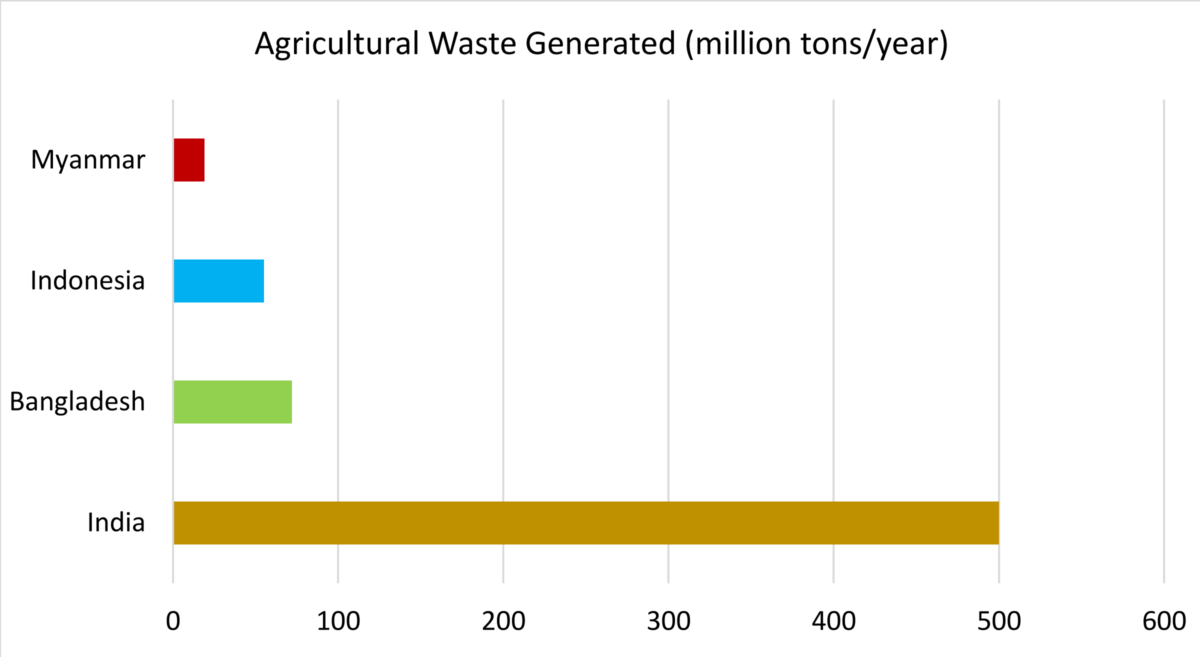


Figure 2.5 The agricultural waste generated in different countries is in metric tons per year. (Source:https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6427124/#B7-ijerph-16-00832)

5. Possible Alternatives to Rice Cultivation

Alternative Cropping Systems: Among the potential replacements, systems such as maize-wheat, cotton-wheat, and pigeon pea-wheat have emerged as promising alternatives that can enhance resource use efficiency and improve farm profitability. For instance, the maize-wheat cropping system has gained traction due to its ability to diversify income sources while reducing the water footprint associated with traditional rice cultivation. Maize, being less water-intensive than rice, allows farmers to conserve groundwater resources while still achieving competitive yields (Shanmugam et al., 2025). Integrating legumes such as pigeon peas into the cropping sequence offers multiple benefits. Pigeon pea enriches soil nitrogen levels through biological fixation but also helps break pest cycles and improve overall soil structure. This crop rotation enhances resilience against climatic stresses and improves nutrient management in subsequent wheat crops. Studies have indicated that incorporating pigeon peas can improve wheat yields compared to continuous rice-wheat systems, highlighting the advantages of diversification in enhancing productivity.

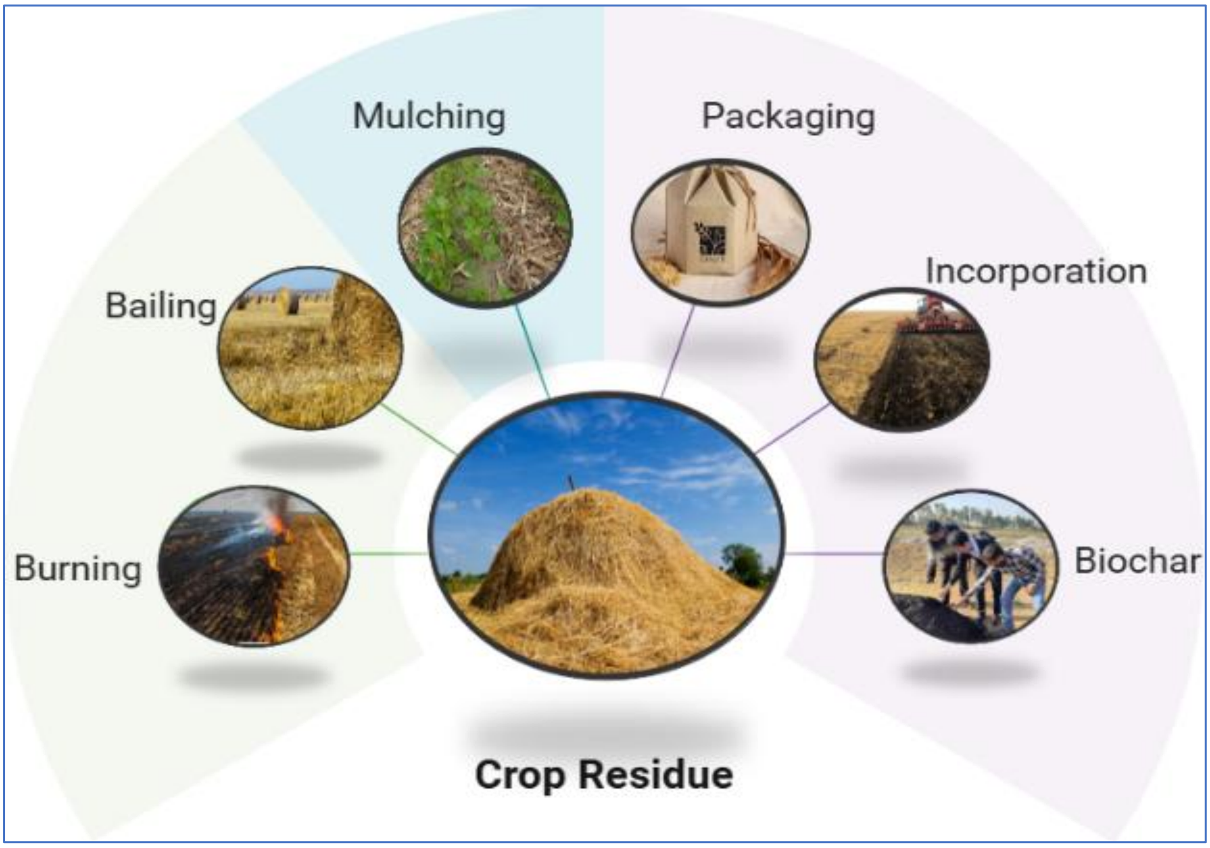


Figure 2.6 Different methods of crop residue management. Approaches include in-situ incorporation, mulching, composting, biochar production, industrial use, and bioenergy utilisation.

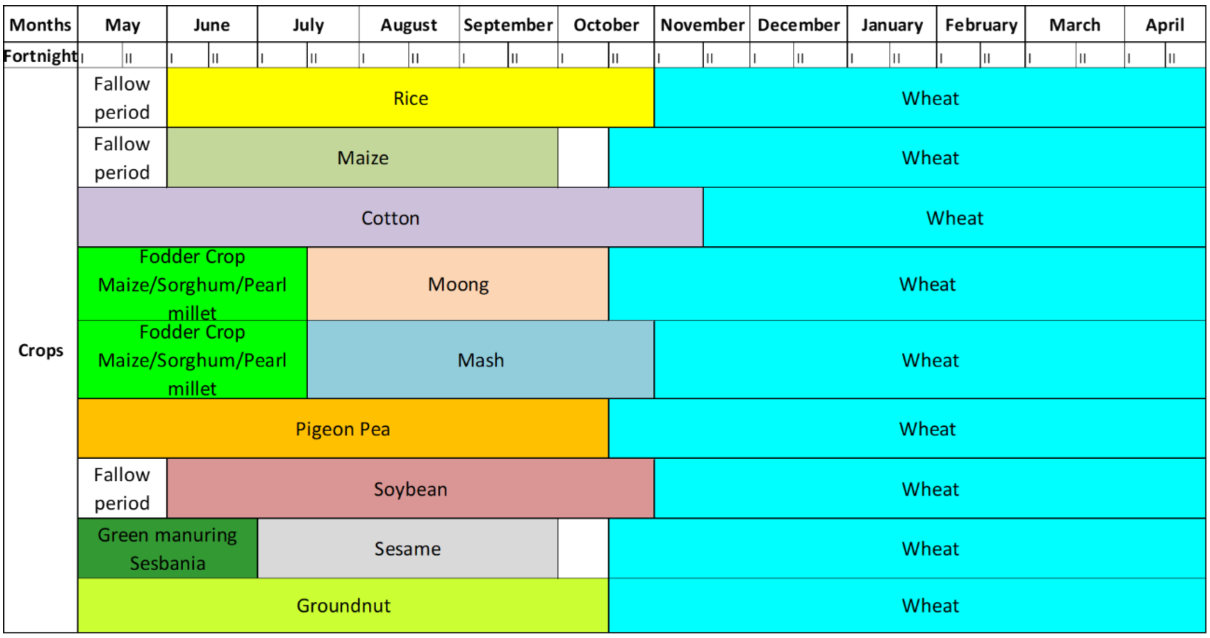


Figure 2.7 Alternative cropping systems to the rice–wheat system in the Indo-Gangetic Plains and other diversified rotations that enhance sustainability and resource-use efficiency.

Furthermore, cotton-wheat systems offer farmers in regions where cotton is a viable cash crop an opportunity. Introducing cotton into the cropping sequence can increase farmers' income while improving soil health through the use of crop rotation practices. This shift diversifies income streams and mitigates the risks associated with monoculture practices inherent in the Rice-Wheat Cropping System. Overall, adopting alternative cropping systems, such as maize-wheat, cotton-wheat, and pigeonpea-wheat, can significantly contribute to sustainable agricultural practices in the Indo-Gangetic Plains.

6. Making Biochar from Crop Residue

Biochar Production Process: The production of biochar from agricultural residues involves several methods that harness the thermal decomposition of biomass in the absence or limited presence of oxygen, a process known as pyrolysis (Seow et al., 2022). This technique converts organic materials, such as rice straw, corn stover, and other agricultural byproducts, into a carbon-rich, stable product that can enhance soil fertility and mitigate environmental impacts. The pyrolysis process typically occurs at temperatures ranging from 400°C to 900°C, with different temperature settings influencing the physical and chemical properties of the resulting biochar (Tomczyk et al., 2020). For instance, lower pyrolysis temperatures tend to yield biochar with higher volatile matter content, while higher temperatures produce a more carbon-dense material with improved structural stability. Various pyrolysis technologies are employed for biochar production, including slow, fast, and hydrothermal carbonisation (Ibitoye et al., 2024). Slow pyrolysis is the most common method used in agricultural settings, allowing for extended heating times that maximise biochar yield while minimising the production of gaseous by-products.

In contrast, fast pyrolysis focuses on rapid heating to produce bio-oil and syngas alongside biochar, making it suitable for energy recovery applications. Additionally, small-scale production units, such as drum kilns or community-scale reactors, can be utilised by farmers to convert their agricultural waste into biochar on-site, thereby reducing waste disposal issues while providing a valuable soil amendment. The choice of feedstock has a significant influence on the characteristics of the produced biochar. Agricultural residues such as rice husks, corn cobs, and sugarcane bagasse provide abundant raw materials and contribute unique properties to the final product (Mrozik et al., 2021). For example, biochar derived from rice straw has been shown to improve soil moisture retention and nutrient availability due to its porous structure and high surface area. Furthermore, soil biochar can enhance microbial activity and promote healthier plant growth by improving nutrient retention and reducing soil compaction. In summary, producing biochar from agricultural residues through various pyrolysis methods offers a sustainable approach to managing agricultural waste while enhancing soil health and contributing to climate change mitigation (Mohammadi et al., 2020).

Benefits of Biochar: The benefits of biochar as a soil amendment are extensive, particularly in enhancing soil health, promoting carbon sequestration, and improving crop productivity. Biochar improves soil properties, including its physical, chemical, and biological characteristics. Its highly porous structure increases soil aeration and water retention, allowing for better root penetration and moisture availability during dry periods (Yadav et al., 2023). This enhanced water-holding capacity is particularly beneficial in regions prone to drought, as it helps mitigate the impacts of water scarcity on crop yields. Additionally, biochar contributes to improved nutrient retention by increasing the cation exchange capacity of the soil, which allows it to hold onto essential nutrients more effectively and reduces nutrient leaching into groundwater. Consequently, this results in higher nutrient availability for plants and can improve fertiliser efficiency, reducing the need for excessive chemical inputs. Moreover, biochar plays a crucial role in carbon sequestration, offering a long-term solution for mitigating climate change. By converting agricultural residues into stable carbon-rich biochar through pyrolysis, carbon that would otherwise be released into the atmosphere as CO_2 during decomposition is stored in the soil for extended periods, potentially thousands of years. This not only helps reduce greenhouse gas emissions but also enhances soil organic carbon levels, thereby contributing to improved soil fertility and health. Regarding crop productivity, numerous studies have demonstrated that applying biochar can lead to significant yield increases across various crops. For instance, experiments have shown that biochar application can enhance crop yields by improving soil structure and nutrient dynamics while promoting beneficial microbial activity (Kumar & Bhattacharya, 2021). The combined effects of improved nutrient retention and enhanced soil conditions create a more favourable environment for plant growth, leading to healthier crops with higher productivity. Overall, the integration of biochar into agricultural practices represents a multifaceted approach to enhancing soil health, promoting sustainable farming practices, and addressing climate change challenges.

Application in wheat-pigeon pea cropping system: Biochar has emerged as a promising strategy to enhance soil health and improve crop productivity. Biochar, produced from agricultural sources, can enhance soil properties, including nutrient retention, water-holding capacity, and microbial activity (Bolan et al., 2023). When integrated into the wheat-pigeon pea cropping system, biochar enriches the soil with essential nutrients and enhances its structural integrity, promoting better root development and overall plant growth. Research indicates that using pigeon pea biochar can significantly improve wheat growth parameters, including increased plant height, tiller numbers, and grain yield (Rahman et al., 2022). For instance, studies have shown that when biochar is applied alongside fertilisers, it can enhance wheat yields by improving nutrient availability and reducing nutrient leaching. Moreover, the synergistic effect of combining biochar with pigeon pea cultivation is particularly noteworthy. Pigeon pea is a leguminous crop that contributes nitrogen to the soil through biological fixation. Paired with biochar application, it creates a more favourable environment for subsequent wheat crops (Huang et al., 2021). This combination boosts soil fertility and helps mitigate the adverse effects of soil degradation commonly associated with continuous cropping systems. In practical applications, farmers have reported increased economic viability through higher yields and reduced fertiliser costs when implementing biochar in their wheat-pigeon pea systems. Integrating biochar into the wheat-pigeon pea cropping system represents a holistic approach to improving agricultural resilience while addressing environmental concerns associated with traditional farming practices.

Numerous studies suggest that biochar can enhance soil quality, promote crop growth, and benefit the environment. However, it does not always have positive effects everywhere. Some research indicates that the use of biochar has made little to no difference, or even caused problems, depending on the soil type, the materials used to produce the biochar, its method of production, and the crops involved. For instance, some studies found no increase in wheat and maize yields after adding biochar, often because the soil was already fertile. In other cases, biochar reduced the amount of nitrogen available to plants, which can slow crop growth. Using excessive amounts of biochar has sometimes raised soil pH or salt levels, which can harm certain crops. These mixed results indicate that the effects of biochar vary depending on the situation. Its success depends on the soil, climate, crops, and land management. Due to these factors, further research and long-term trials in various locations are necessary to determine

CHAPTER -III

MATERIALS AND METHODS

The research objectives were pursued through field experiments conducted during the agricultural seasons of 2022-23 and 2023-24 at the research fields of the School of Agriculture, Lovely Professional University, Phagwara, Punjab. This chapter elaborates on the materials and methods employed in these experiments, organised under specific headings for clarity.

3.1 Geographical Position of the Experiment Location: To understand the effect of biochar combined fertilisers on soil nutrient status, about the growth and yield of the wheat-pigeon pea cropping system, the experiment is conducted at the research fields of Lovely Professional University, Phagwara, Punjab. The coordinates for the location are latitude 31°14'30.5"N and longitude 75°41'52.1" E. The experiment was conducted in an area of 1,200 m^2.

3.2 Climate and weather conditions: The site of the experiment possesses a subtropical climate. The hot winds are observed to flow longer during summers in the daytime, while the nights remain warmer. May, June, and July are noted as the hottest months, with mercury reaching 49°C; however, the temperature falls during the last week of July. October is often considered the start of the winter season, with December and January typically being the coldest months of the year. Rains in the winter season are irregular and erratic. Sometimes, the minimum temperature is recorded to be around the freezing point during the night or early morning. Most months experience humid weather. The meteorological data noted in the 2-year study period are presented in **Figure 3.1** and **Table 3.1**.

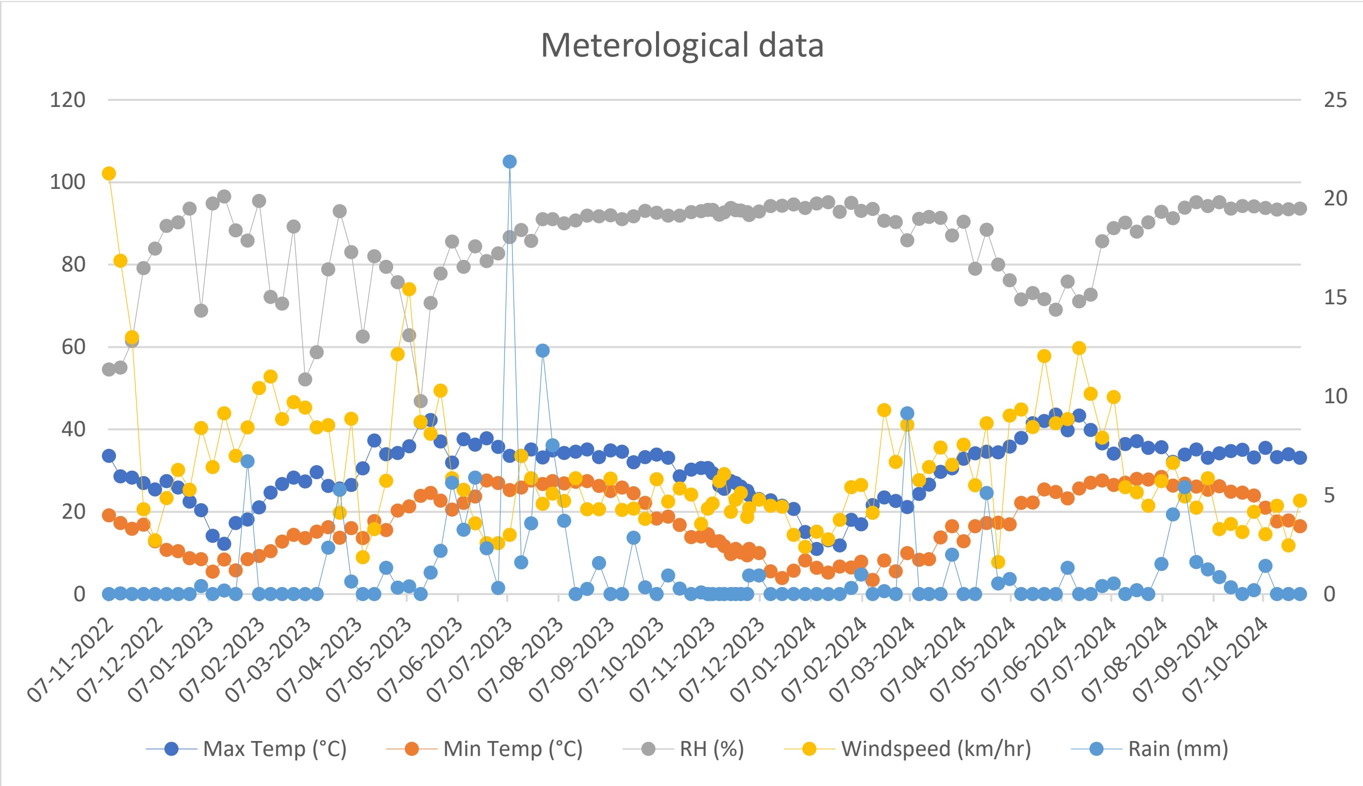


Figure 3.1 The weather and SMW (standard meteorological weeks) average data were collected over two years, from 2022 to 2024. (Source: Lovely Professional University Meteorological weather station)

Table 3.1 presents the weather and monthly average data collected over a two-year period, from 2022 to 2024.

Month	Temperature (°C)						Relative Humidity (%)			Rainfall(mm)		
	Maximum			Minimum								
	2022	2023	2024	2022	2023	2024	2022	2023	2024	2022	2023	2024
Jan.	--	15.6	13.5	--	7.1	6.3	--	91.5	94.4	--	48.3	0.07
Feb.	--	25.4	21.3	--	11.9	6.6	--	81.2	91.0	--	0.00	0.26
Mar.	--	27.5	26.7	--	15.0	11.4	--	73.1	89.8	--	55.6	2.51
Apr.	--	33.1	33.7	--	16.4	15.8	--	74.4	87.7	--	11.5	1.49
May	--	37.9	40.2	--	22.6	22.3	--	68.0	71.9	--	55.2	0.0
Jun.	--	36.4	40.3	--	24.6	25.7	--	82.2	74.5	--	93.4	0.40
Jul.	--	33.9	35.7	--	26.5	27.5	--	88.1	89.5	--	278.2	0.26
Aug.	--	34.5	33.9	--	27.0	26.5	--	91.0	93.2	--	75.0	2.94
Sep.	--	33.7	34.2	--	24.1	25.0	--	92.0	94.3	--	22.3	0.50
Oct.	--	31.1	33.9	--	16.2	18.3	--	92.4	52.9	--	9.2	0.3
Nov.	29.0	26.6	--	17.0	11.5	--	64.0	92.8	--	0.01	6.6	--
Dec.	24.8	21.3	--	10.2	6.3	--	90.2	94.1	--	0.06	0.0	--

3.3 Soil Properties

Table 3.2: Initial Physical and Chemical Properties of Experimental Soil.

Soil characteristics	Values	Soil characteristics	Values
Sand (%)	74.9	Available N (kg/ha)	176
Silt (%)	14.1	Phosphorus (mg/kg)	8.95
Clay (%)	11	Potassium (mg/kg)	41
Textural class	Sandy loam	Sulphur (mg/kg)	10.21
pH	7.4	Calcium (mg/kg)	174.2
EC (dSm^{-1})	0.17	Magnesium (mg/kg)	125.8
Organic carbon (%)	0.49	Iron (mg/kg)	7.14
		Calcium (mg/kg)	174.2
		Magnesium (mg/kg)	125.8
		Iron (mg/kg)	7.14

3.4 Cropping history of the experimental field: A thorough analysis was conducted of the historical crop data from previous years for the experimental area. During the Kharif-Rabi season, the rice-wheat cropping system was observed to be practised, with rice in Kharif and wheat in Rabi sown from 2020-2021 and 2021-2022.

Table 3.3 The Cropping history of the experimental field.

Two-year cropping system (2022-2024)		
Rabi 2022	Wheat crop	November-April 2022
Kharif 2023	Pigeon-pea crop	June-October 2023
Rabi 2023	Wheat crop	November-April 2024
Kharif 2024	Pigeon-pea crop	June-October 2024

3.5 Experimental details: The present study was carried out during the Rabi and Kharif seasons of 2022-2023 and 2023-2024. The experiment was conducted in a randomised block design, with three replications and nine treatments. The total number of plots was 27, the net plot size was 675 m^2, and the gross plot size was 901 m^2. The details of treatments, design, plot size, etc., are shown below in **Table 3.3**

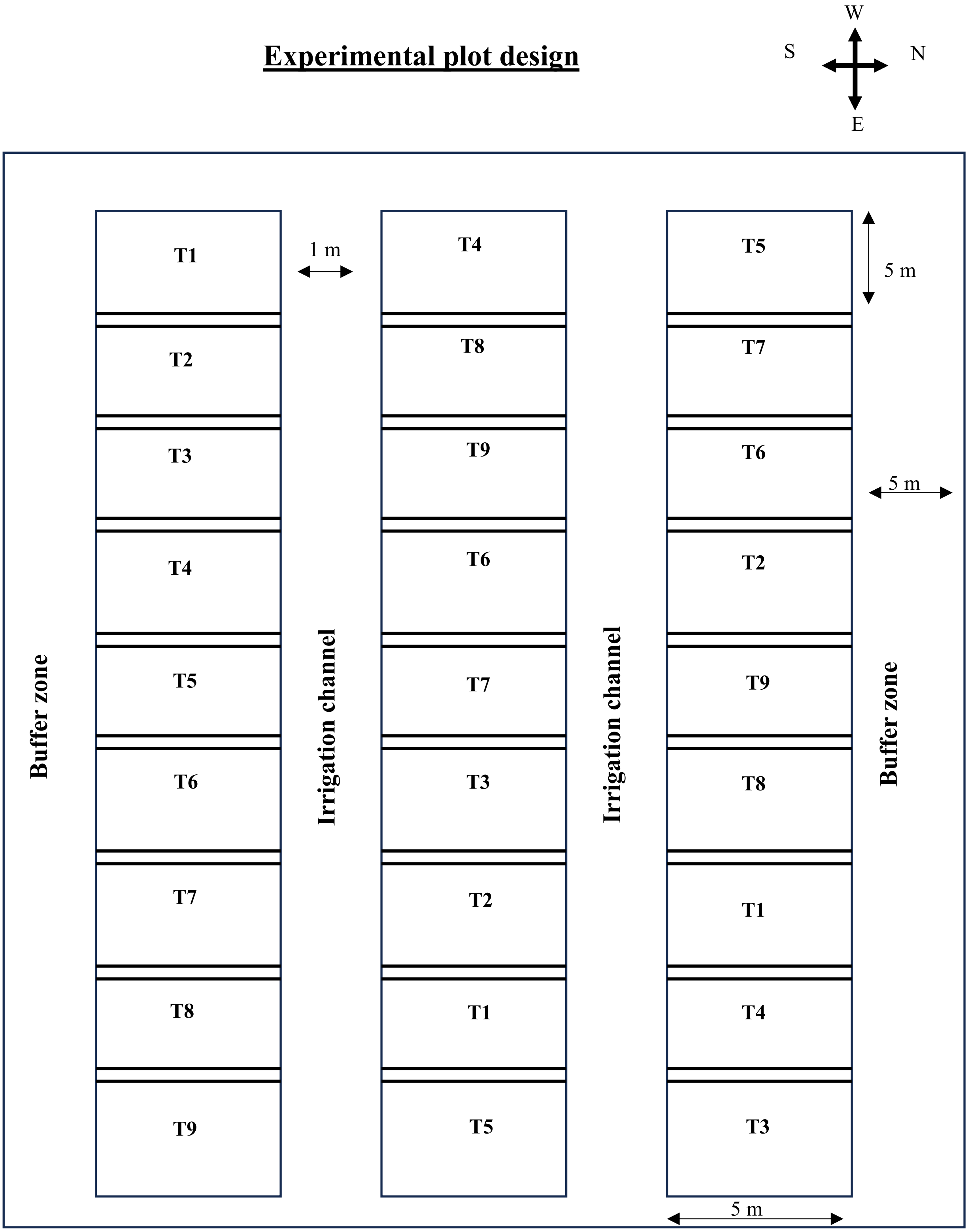
Table 3.4 Experimental details of the research trial.

Design of experiment	Randomised Complete Block Design
Number of treatments	9
Number of replications	3
Number of total plots	27
Plot size	$5*5=25m^2$
Total experimental area	1200 m^2
Cropping system	Wheat-Pigeon pea
Varieties	Wheat PBW 824, Pigeon pea AL 882
Spacing	Wheat 22.5 cm Pigeon pea 50*25 cm

Table 3.5 Treatment details of the research trial.

Treatments	**Treatment details**
T1	Absolute control
T2	100% RDF (N:P: K)
T3	100 % NP
T4	NP + rice husk biochar 5 t/ha
T5	NP + rice husk biochar 10 t/ha
T6	NP + rice husk biochar 15 t/ha
T7	NP rice straw biochar 5 t/ha
T8	NP rice straw biochar 10 t/ha
T9	NP rice straw biochar 15 t/ha

3.2: Field layout of the research trial showing the arrangement of experimental plots under a Randomised Complete Block Design.



3.6 Inputs for the experiments: The certified seeds of Wheat (PBW824) and pigeon pea (AL 882) were purchased from the local market in Phagwara. PBW 824 is a long-duration variety that completes its life cycle in 150 days. The average plant height was observed as 95-105cm. Punjab Agriculture University, Ludhiana, released the PBW 824 variety. The grains are bold and amber in colour. AL 882 is a short-duration (132 days) variety of pigeon pea.

3.6.1 Fertilisers: Urea, DAP, and MOP are nitrogen, phosphorus and potash sources for wheat and pigeon-pea crops. The quantity of fertiliser used was according to the treatments and was uniformly applied in each allotted plot. Phosphorus was applied as basal doses according to recommendations. At the same time, nitrogen was given in split forms, i.e., half as a basal dose and the remaining half top-dressed at critical stages. Soil available potassium reveals a deficiency. This deficiency can be addressed by adding biochar to meet the soil's potassium requirements.

3.6.2 Biochar preparation: Biochar was produced from rice straw and husk; rice straw was dried properly before biochar preparation. Biochar was produced from the carbonisation of rice straw under an open fire in a stainless-steel tub with a height of 48 cm and a diameter of 142 cm. The open fire is an autothermal process that burns a portion of the feedstock material to heat the remainder and convert it into char. The rice straw feedstock was placed inside the open burn tub and ignited. Carbonisation of the feedstocks occurred beneath the flames, where oxygen is absent, because the flames consume all of it, thus creating a pyrolysis zone. The lack of oxygen prevents combustion, so the biomass smoulders but does not release flames or smoke. Instead, much of it is transformed into high-carbon charcoal, oil, and gas. Pyrolysis of the rice straw was performed at temperatures ranging from 400 °C to 600 °C, and the temperature was measured using a heat sensor thermometer. Feedstocks were added continuously until the tub was filled and quenched with water. The biochar yield was approximately 45-50% on a dry weight basis. Biochar was air-dried and ground to pass a 2-mm mesh sieve (Oo, A. Z., & Sudo, 2018).

Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDS) analysis were performed on both rice straw and husk biochar (Figure 1). To prepare the samples for FESEM analysis, they were coated with a thin layer of gold using an ion coater (D II-29030SCTR, Japan). This coating was crucial for enhancing the conductivity of the samples, thereby enabling high-resolution imaging. The FESEM examination was conducted using a JSM-7610 F PLUS microscope (Oxford Instruments X-

Max N, Japan) at an operating voltage of 15–25 kV. This technique enabled detailed observation of the biochar's surface morphology, capturing images that reveal critical structural features, including pore size, shape, and distribution. Concurrently, EDS analysis was performed with an OXFORD X-Max N system (Japan) to determine the elemental composition of the biochar samples. This analysis provided valuable qualitative and quantitative data on the elemental distribution within the biochar, identifying key elements such as carbon, oxygen, and various minerals. The insights gained from both FESEM and EDS analyses not only elucidated the morphological characteristics and elemental composition of the biochar but also informed our understanding of how these materials interact with soil systems upon application.

Table 3.6: The characteristics of rice husk and straw biochar.

Characteristics	Rice husk biochar	Rice straw biochar
pH	10.4	10.2
Carbon (C)	71.2 %	64.6%
Oxygen (O_2)	21.3 %	22.9%
Potassium (K)	1.7 %	2.1%
Silica (Si)	3.1 %	7.4%
Magnesium (Mg)	0.2 %	0.3%

3.7: Cultural operations: All intercultural operations were performed by the recommended package of practices prescribed by Punjab Agricultural University (PAU), Ludhiana, for crop cultivation. Plant protection measures were implemented as needed. The cultural practices carried out during the two-year experiment, along with their details, are summarised below in **Table 3.4.**

3.7.1 Field preparation: Field preparation is a vital process that significantly impacts the crop's yield and overall health. Field preparation was initiated with loosening of the soil; deep ploughing was done to a depth of approximately 15-20 cm during the dry season, followed by a single harrowing to refine the seedbed and minimise competition from weeds. For the prevention of water and fertilisers, bunds were made around each subplot. The layout was prepared, and biochar was added to the plot’s treatment.

3.7.2 Establishment of crop and plant population: The seeds of wheat were sown @ 120 kg/ha by manual seed drill at 3-5 cm depth using 22.5 cm spacing. They were followed by pigeon peas with a 6 kg/ha seed rate, using a spacing of 50 cm x 25 cm.

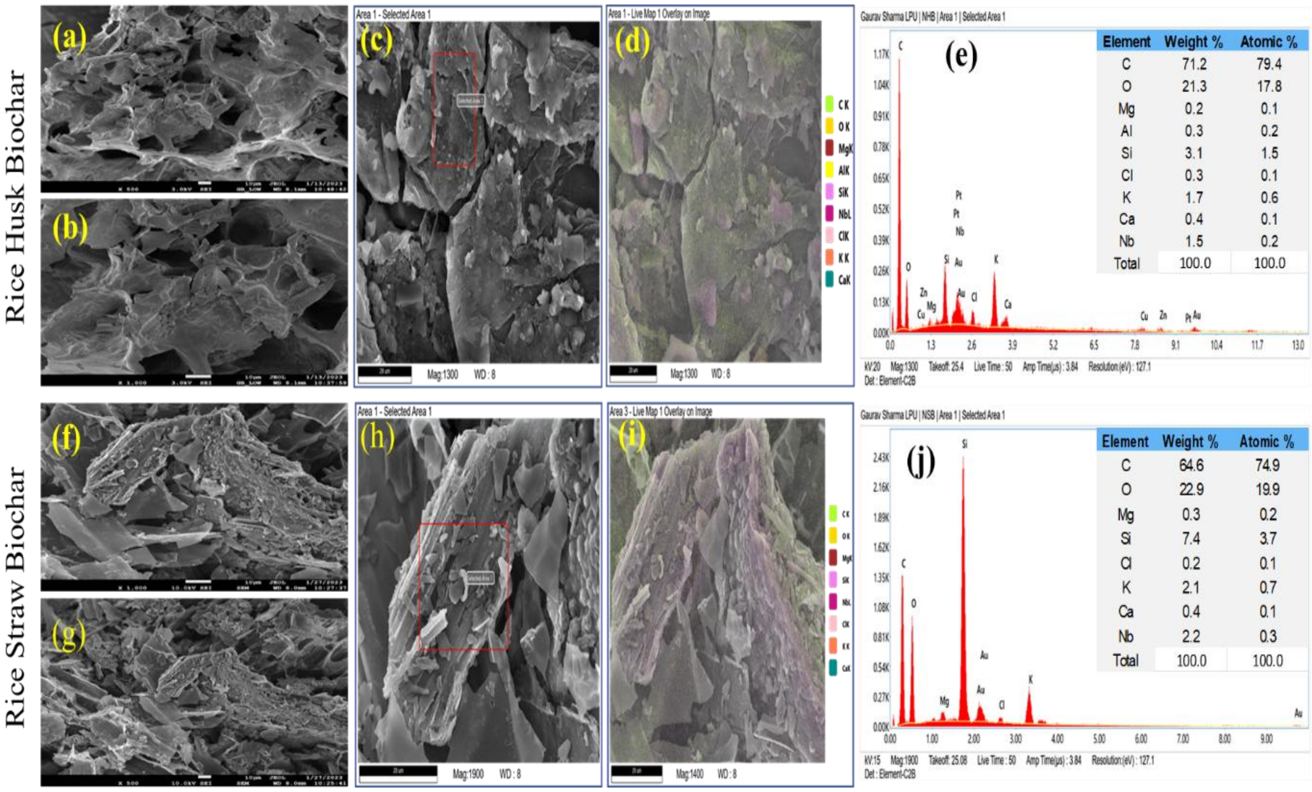


Figure 3.3. FESEM image of rice husk biochar (2a, 2b) and straw biochar (2f, 2g) mapping site rice husk biochar (2c) rice straw biochar (2h), and EDS mapping of rice husk biochar (2d) and rice straw biochar (2i), different colour dotted shad represent different elemental presence (2e, 2j) Elemental concentration of biochar.

3.7.3 Weed and insect pest control: Pendimethalin SC was applied to control weeds in wheat crops, and pendimethalin 36.1 EC was applied to control weeds in pigeon peas. Emamectin benzoate 5% SG insecticides were used based on the incidence of insects.

3.7.4 Harvesting and threshing: Wheat harvesting was performed in the last week of April, when whole plants are observed to turn golden brown. The process of harvesting was manually done with a sickle plot-wise, and threshing was performed by beating the bundles. Pigeon peas were harvested in the last week of November with a sickle when the pods were thoroughly dried. The plant was somewhat green at 25% and threshed at 12-14%.

3.7.5 Observations recorded during field and pot experiment: The following subsections discuss the recorded parameters for Kharif and Rabi crops and soil samples at a specific period:

3.8.1 Soil parameters: Various chemical properties are monitored systematically every 45 days to ensure comprehensive analysis and understanding of the soil's health and nutrient status. The parameters observed include pH, electrical conductivity (dSm^{-1}), and organic carbon %. Additionally, the availability of essential nutrients is evaluated, including nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), and iron (Fe). This regular observation schedule allows for timely adjustments in soil management practices to optimise crop growth and maintain soil fertility.

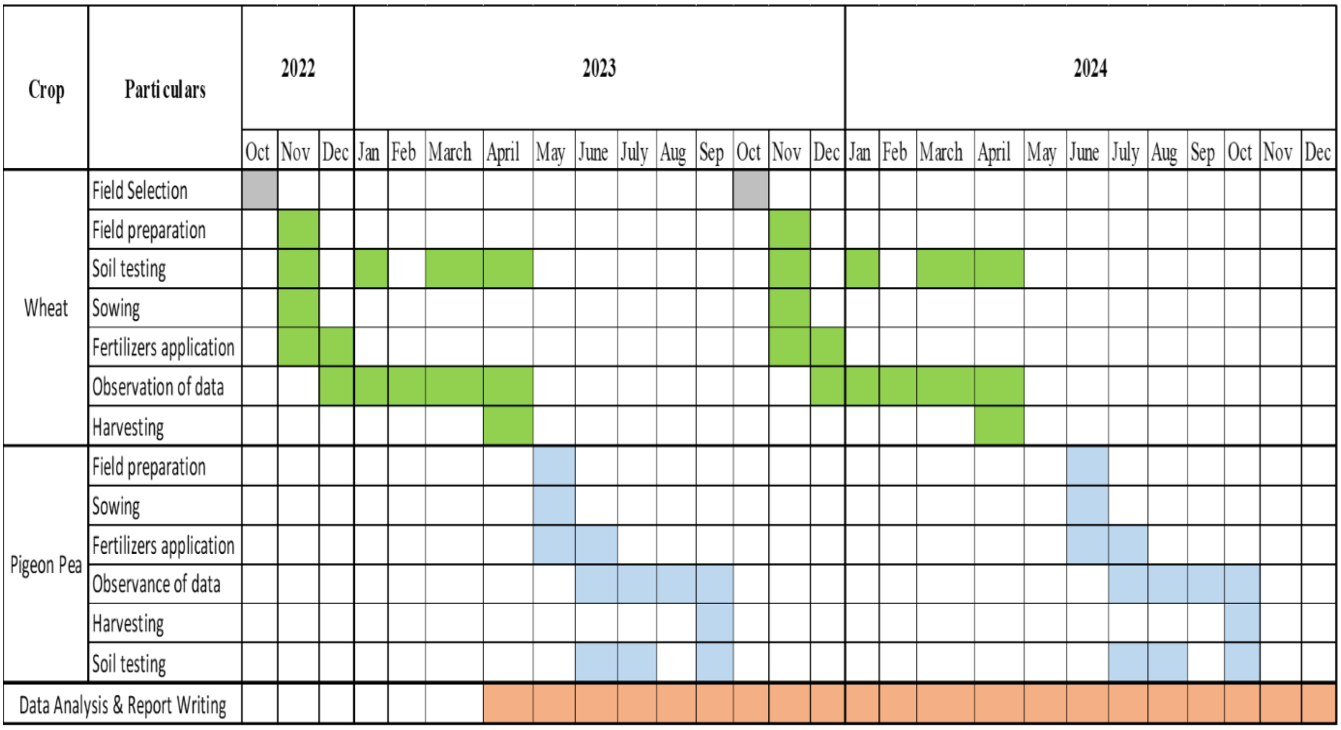


Figure 3.4: Timeline for the cultural operations performed during the research trails

3.8.2 Chemical Properties

3.8.3 Soil pH: pH of soil was recorded with the pH meter as per the procedure performed by Jackson (1973. At pH 7 and pH 9, the two buffer solutions were placed in two beakers and further calibrated with the pH meter. The electrodes were put in the beakers in alternate turns to adjust the pH. In a 100 mL beaker, 10g of the soil sample was taken, followed by the addition of 25 mL of distilled water. The stirring was performed occasionally to equilibrate the soil with water for 30 minutes. pH was recorded by inserting the electrode in the prepared suspension.

3.8.4 Soil Electrical Conductivity: Electrical conductivity estimates the salts dissolved in the solution. The supernatant extract from the soil water suspension used to estimate pH was kept undisturbed overnight and utilised to estimate EC (Jackson, 1973).

3.8.5 Soil Organic Carbon Analysis: The soil organic carbon was estimated by using the Walkley-Black method (Network GSL 2019). In a 500 mL conical flask, 1 g of an air-dried soil sample was kept. In this flask, add 10 mL of 1 N K2Cr2O7 and slowly add 20 mL of concentrated H_2SO_4. Let it stand for 30 minutes, then add 10 mL of orthophosphoric acid (H_3PO_4) and 5-6 drops of diphenylamine indicator to this mixture. The burette was filled with 0.5 N ferrous ammonium sulphate solution. The solution was titrated till the violet colour changed to green colour. Blank samples were also prepared in parallel without the addition of soil. The volume of ferrous ammonium sulphate was noted down, and organic carbon was calculated using the formula.

$$\textbf{\% OC} = \frac{(B-S)\ X\ N\ of\ Ferrous\ amonium\ sulphate\ X\ meq.wt\ of\ C}{Weight\ of\ soil} X\ 100$$

Note: B: Blank reading, S: Sample reading

3.8.6 Available soil Nitrogen analysis: Available soil nitrogen was estimated using the Kjeldahl method (Subbiah & Asija, 1956). Eight gs of air-dried soil and 10 mL of distilled water were added to a distillation flask, followed by 40 mL of 0.32% $KMnO_4$ and 40 mL of 2.5% NaOH. Secondly, 20 mL of 2% boric acid was added to a conical flask and distilled for 6 minutes. The burette was filled with 0.02N H_2SO_4. The boric acid solution was titrated with concentrated H_2SO_4 until a pink colour appeared. The initial and final readings, as well as the available nitrogen levels, were recorded. Blank samples without soil run in parallel without adding soil. Soil available nitrogen was calculated using the following formula:

$$\textbf{Available N (kg/ha)} = \frac{(R-B)\ X\ 14\ X\ 0.01\ X\ 100\ X\ 10000\ X\ 2.24}{1000\ X\ Weight\ of\ soil} X\ 100$$

Note: R: H_2SO_4 used and B: Blank

3.8.9 Available Soil Potassium Analysis: Soil available potassium by using Flame Emission Spectroscopy (Pratt, P.F. 1965). First, soil samples were air-dried, ground, and sieved through a 2 mm mesh to ensure uniformity. From this soil, a 20-g soil sample was added to a 150-ml conical flask, and 50 ml of 1 M ammonium nitrate (NH_4NO_3) was added to it. The mixture was shaken for 30 minutes to extract potassium ions, then filtered through Whatman No. 40 filter paper to obtain the potassium-containing extract. Potassium working standard solutions were prepared with concentrations ranging from 0 to 50 µg/ml using a stock potassium solution (1 mg/ml). The filtered soil extract was then nebulised into the flame photometer, and the corresponding meter reading was recorded. Finally, the potassium concentration in micrograms per millilitre (µg/ml) was determined using the calibration curve, and the extractable potassium in milligrams per litre (mg/l) was calculated based on the difference between the sample and blank readings.

3.8.10 Available Soil Phosphorus and Sulphur Analysis: Soil available phosphorus and sulphur by the colourimetry method (FAO, 2021). First, 0.5 g of the soil sample was placed in a 125 ml conical flask, followed by the addition of 25 ml of 0.5 M sodium bicarbonate solution (pH 8.5). The flask was then shaken for 30 minutes to extract phosphorus. The mixture was filtered through Whatman No. 2 filter paper to obtain the clear extract. The phosphorus concentration was determined using the molybdenum blue method. To a 50 mL aliquot of the filtered extract, 1 mL of concentrated sulfuric acid and 4 mL of ammonium molybdate solution were added, followed by thorough mixing. After standing for 10 minutes, 2 mL of ascorbic acid was added to form a blue-coloured complex, and the absorbance at 650 nm was measured using a spectrophotometer, with the results compared against a calibration curve of known phosphorus standards. For sulphur analysis, 1 g of soil was mixed with 20 ml of calcium phosphate solution in a centrifuge tube and shaken for 30 minutes. The mixture was centrifuged at 2000 rpm for 10 minutes, and the supernatant was collected. The sulphur concentration was analysed calorimetrically using a barium sulphate reagent, with absorbance measured at a wavelength of 760 nm for sulphur detection. Calibration curves were prepared for both nutrients by plotting the absorbance against known concentrations of each nutrient.

3.8.11 Available Soil Iron, Copper, Manganese and Zinc Analysis: The Atomic Absorption Spectroscopy (AAS) method was used to analyse iron, copper, manganese, and zinc in soil. Once dried, the soil was ground to a fine powder using a mortar and pestle or mechanical grinder, and the ground soil was passed through a 2 mm mesh sieve to achieve uniform particle size, which was crucial for consistent digestion and analysis.

For digestion, approximately 1 g of the sieved soil was accurately weighed and placed in a digestion flask. A mixture of concentrated nitric acid (HNO_3) and hydrochloric acid (HCl) was prepared in a 3:1 (v/v) ratio and added to the soil sample in the flask. The flask was covered with aluminium foil to minimise vapour loss during heating, and the mixture was heated on a hot plate at moderate temperatures until the soil was completely digested. After digestion, the solution was allowed to cool to room temperature and then quantitatively transferred to a 100 ml volumetric flask, where it was diluted to the mark with deionised water.

Before sample analysis, the AAS instrument was calibrated using standard solutions of Fe, Cu, Mn, and Zn at known concentrations (e.g., 0, 1, 5, 10, 20 mg/L). Calibration curves for each metal were created by measuring absorbance at specific wavelengths: Fe at 248.3 nm, Cu at 324.7 nm, Mn at 279.5 nm, and Zn at 213.9 nm. The digested and diluted soil samples were then aspirated into the AAS system using a suitable nebuliser. It was essential to avoid cross-contamination between samples by thoroughly cleaning the nebuliser and burner between analyses. The absorbance readings obtained from the instrument were compared with the calibration curves for each metal to determine their concentrations in the soil samples, which can be expressed in milligrams per kilogram (mg/kg).

3.8.12 Crop growth parameters for wheat: At 30, 60, 90, and 120 days after sowing (DAS), key wheat crop growth parameters were recorded, including plant height, number of tillers, leaf area, and leaf area index (LAI). These metrics indicate growth vigour and photosynthetic capacity. Fresh and dry biomass measurements assess overall plant health, while node diameter and stem diameter provide insights into structural integrity. The crop growth rate evaluates biomass accumulation efficiency, and the number of productive tillers helps estimate yield potential. Together, these parameters offer a comprehensive overview of wheat growth dynamics.

3.8.13 Physiological parameters for wheat: At 30, 60, 90, and 120 days after sowing (DAS), key physiological parameters of wheat were measured, including chlorophyll content, relative water content (RWC), membrane stability index (MSI), and membrane integrity index (MII). These metrics assess photosynthetic capacity, hydration status, and membrane integrity, providing insights into the plant's health and resilience to stress throughout its growth stages.

3.8.14 Yield attributes for wheat: Key yield attributes of wheat, including spike length, grains per spike, test weight, biological yield, straw yield, and grain yield, were measured. Additionally, the harvest index and benefit-to-cost (B: C) ratio were calculated. Spike length and grains per spike directly influence grain yield, while test weight indicates grain quality. Biological yield encompasses total biomass, including straw yield, which is essential for understanding resource allocation. The harvest index reflects the biomass conversion efficiency into grain, while the B: C ratio evaluates economic viability. Together, these attributes provide a comprehensive assessment of wheat productivity and profitability.

3.8.15 Crop growth parameters for pigeon pea: Key crop growth parameters for pigeon peas, recorded at 30, 60, 90, and 120 days after sowing (DAS), including plant height, number of primary branches, number of trifoliate leaves, stem girth, fresh biomass, and dry biomass. Plant height and the number of primary branches indicate overall growth vigour, while the count of trifoliate leaves reflects photosynthetic capacity. Stem girth contributes to structural strength, and measurements of both fresh and dry biomass provide insights into plant health and resource allocation. Together, these parameters offer a comprehensive overview of the growth dynamics of pigeon peas throughout their development stages.

3.8.16 Physiological parameters for pigeon pea: Physiological parameters for pigeon pea, recorded at 30, 60, and 90 days after sowing (DAS), including chlorophyll content, relative water content (RWC), membrane stability index (MSI), and membrane integrity index (MII). These metrics are essential for assessing the plant's photosynthetic efficiency and hydration status. Chlorophyll content indicates the capacity for photosynthesis, while RWC reflects the plant's water status and overall health. MSI and MII evaluate the stability and integrity of cell membranes, providing insights into the plant's resilience to stress conditions. Together, these parameters offer a comprehensive understanding of the physiological performance of pigeon peas throughout their growth stages.

3.8.17 Yield attributes for pigeon pea: Key yield attributes for pigeon pea, including pod length, grains per pod, test weight, biological yield, and grain yield, were measured. Additionally, the harvest index and benefit-to-cost (B: C) ratio were calculated. These factors assess productivity and quality, with pod length and grains per pod impacting grain yield, while test weight reflects grain quality. Biological yield refers to the total biomass, while the harvest index measures the conversion efficiency of biomass into grain. The B: C ratio evaluates economic viability, providing a comprehensive overview of pigeon pea yield potential and profitability.

3.9 Procedure used for recording data:

3.9.1 Plant growth parameters

3.9.1 Plant height: With the help of the measuring tape, the height of the highest tiller from the base to the tip of the highest plant part was recorded from 10 tagged plants. For the calculation of the mean plant height, an average of 10 plants was taken.

3.9.2 Number of tillers (m^2): Total shoots and the shoots containing panicles per square m were recorded at various intervals in wheat crops and named total tillers and productive tillers.

3.9.3 Stem girth: The stem girth of wheat and pigeon peas was measured using a digital vernier calliper at consistent heights above the soil surface. Healthy plants were selected at various growth stages, and measurements were taken from 10 plants to ensure accuracy and consistency.

3.9.4 Fresh and dry biomass of plant (g): To observe the fresh and dry biomass at various intervals in both of the crops, plants were cut near the ground from the selected one-meter square area. The fresh biomass from fresh samples was placed in an oven at 65°C until a constant weight was obtained. After drying, the samples were weighed to measure dry weight.

3.9.5 Leaf area: The leaves were collected and further separated from the lamina. Leaf area was recorded at 30, 60, and 90 DAS in wheat via a leaf area meter. The leaf area index was measured by the formula given by Watson, D.J. (1947),

$$LAI = \frac{Groumd\ Area\ m^2}{Leaf\ Area\ m^2}$$

3.9.6 Chlorophyll content: The total chlorophyll content in the leaves was also estimated using the method (Arnon et al., 1949). Chlorophyll was extracted from 100 mg of fresh leaf sample from each treatment using 20 ml of 80% acetone. After centrifugation for 10 minutes at 5000 rpm, the supernatant was transferred to a volumetric flask, and the extraction was repeated until the residue became colourless. The extract's absorbance was measured at 645 and 663 nm using a spectrophotometer, and the chlorophyll content was calculated using a formula:

$$Total\ Chlorophyll\left(\frac{mg}{g}FW\right) = 20.2(A645) + 8.02(A663)\ \mathrm{x}\frac{V}{1000\ \mathrm{x}\ W}$$

Where, V Final volume of the extract, FW Fresh weight of the leaves, A = absorbance at the specific wavelength. The value is expressed as the mg/g fresh weight

3.9.7 Relative water content: To determine RWC, the flag leaves were collected and immediately analysed to minimise water losses due to evaporation. The samples were weighed immediately as fresh weight (FW), then sliced into 2 cm discs and floated on distilled water for four hours. The turgid leaf discs were then rapidly blotted to remove surface water and weighed to obtain turgid weight (TW). The leaf discs were dried in an oven at 60°C for 24 hours, and then the dry weight (DW) was determined. The RWC was calculated by the formula given by Barrs (Barrs, 1968):

$$RWC\% = \frac{FW - DW}{TW - DW}\mathrm{x}100$$

3.9.8 Membrane stability and injury index: The membrane stability index (MSI) and membrane injury index (MII) were evaluated by immersing 200 mg of fresh leaves in 10 mL of double-distilled water, divided into two sets. One set was heated in a water bath at 40°C for 30 minutes and then tested for electrical conductivity (C1). The other set was heated in a water bath at 100°C for 10 minutes before being tested for conductivity (C2). The calculations were based on the following formula given by Premachandran (1990)**:**

$$MSI = 100\text{x}\left(\frac{C1}{C2}\right)$$

$$MII = 100 - \left(\frac{C1}{C2}\right)\text{x}100$$

3.9.9 Crop growth rate (CGR, g day^{-1} m^{-1}): CGR refers to the rate of increase in dry weight of plant material per unit area over a specified period. It was calculated using a formula described initially by Watson in 1952.

$$CGR = \left(\frac{W2 - W1}{T2 - T1}\right)$$

Where W2 is the dry weight of the plant at time T2, and W1 is the dry weight of the plant at time T1.

3.9.10 Yield Attributes:

3.9.11 Spike and pod length (cm): The length of 10 spikes and pods chosen randomly from each plot from each replication was analysed via a measuring scale, and the average value was expressed as panicle and spikelet length

3.9.12 Number of grains per panicle and spikelet: From each treatment plot, ten spikes or pods were randomly chosen, and the number of grains in each was counted.

3.9.13 Test weight (g): A sample of 1,000 grains was selected from the yield of the net plots, and their collective weight was measured in g.

3.9.14 Grain and straw yield (kg/ha): The harvested produce from each plot was gathered into bundles and left in the field for 3-4 days to dry. Afterwards, the bundles were weighed to determine the biological yield. Manual threshing was performed to estimate the grain yield for each plot. The straw yield was calculated by subtracting the grain yield from the biological yield. Finally, the yield for each plot was converted to Kg per hectare (kg/ha).

3.9.15 Harvest index (%): The harvest index represents the ratio of economically usable yield to the total biological yield, calculated using a formula introduced by Donald in 1962:

$$Harvest\ Index = \left(\frac{Economic\ Yield}{Biological\ Yield}\right) \text{x}100$$

3.9.16 Benefit: Cost ratio: The calculation was performed separately for each treatment. The net returns per hectare for each treatment were divided by the corresponding cultivation cost to determine profitability.

3.9.17 Statistical analysis: The data were tabulated treatment-wise across three replications. A one-way ANOVA was performed using R Studio to compare the mean values. Duncan's multiple range test (DMRT) was used to differentiate between means with a significance level of $p < 0.05$. Fisher's LSD test was applied as a post hoc test to evaluate the significance of variance components. Differences among means were considered significant if they exceeded the least significant difference (LSD) at a 5% significance level.

Plate 1: Field visit

Plate 2: Investigate biochar

Plate 3: View at different stages of wheat crop

PIGEON PEA CROP

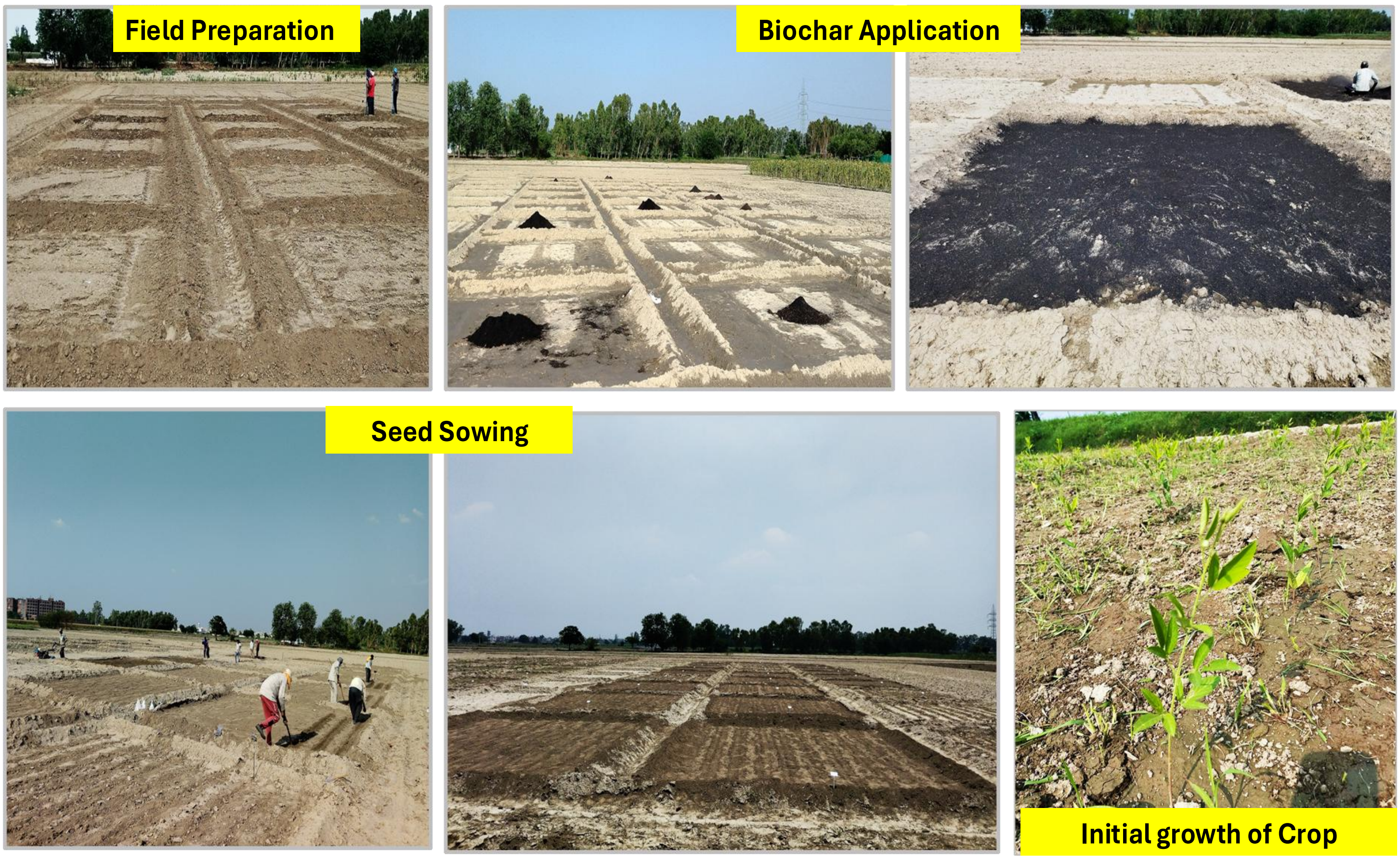


Plate 4: View of application of biochar to sowing of pigeon pea

Plate 5: View of different stages of pigeon pea

Plate 6: Treatments wise Wheat spike

Plate 7: Separation of grains

Plate 8: View of meeting

Plate 9: General view of research field

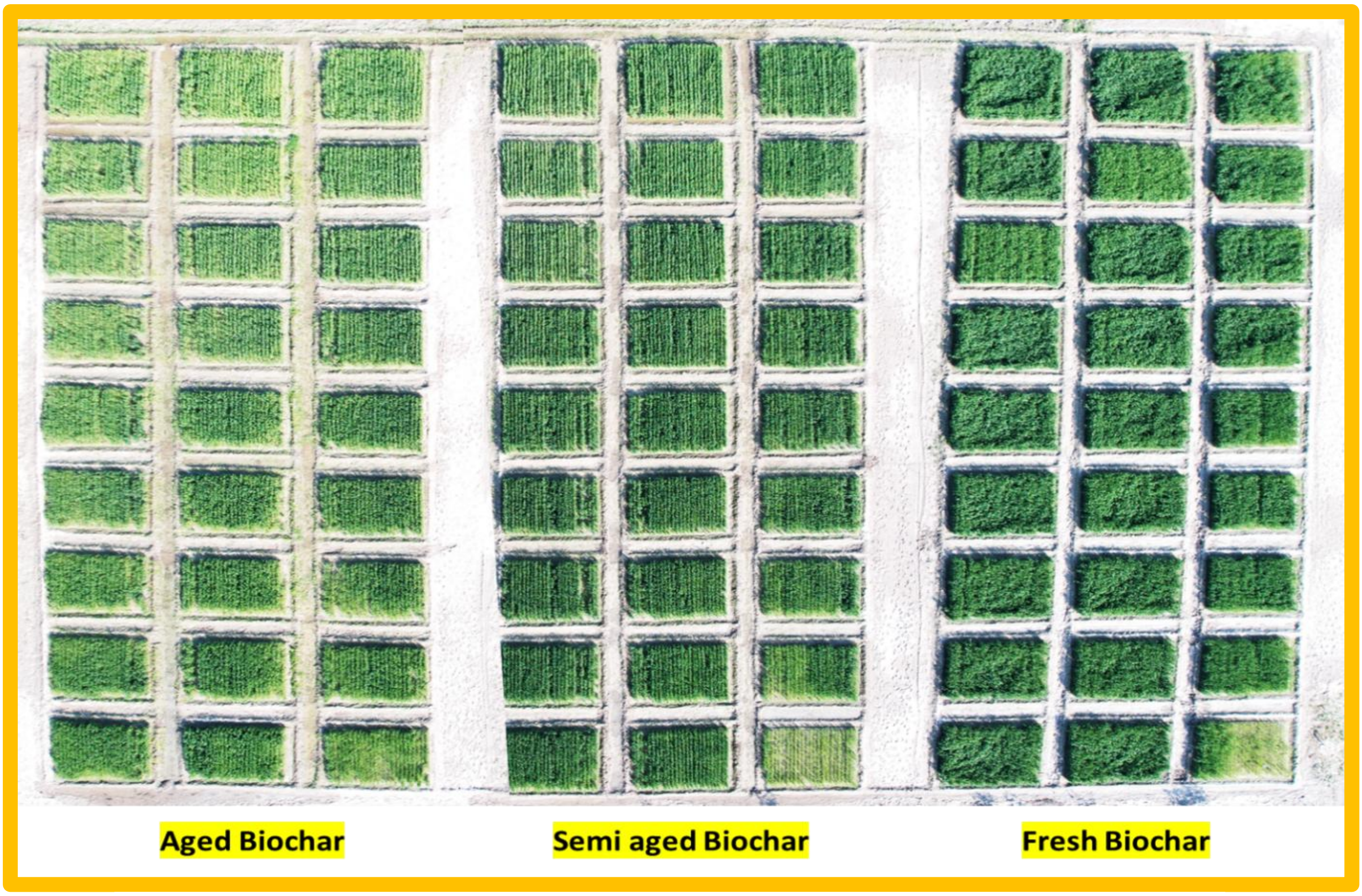


Plate 10: General view of research field with different type of biochar

Plate 11: General view of research field with different type of biochar

Plate 12: Laboratory work

Plate 13: General discussion about the Laboratory work

CHAPTER -IV

RESULTS AND DISCUSSION

4.1 Growth Metrics:

Biochar significantly affected wheat plant height at the various growth stages shown in **Table 4.1** during the 2022–2023 growing season. Among the treatments, T4 and T7 significantly increased plant height compared to other treatments. Treatment T4 recorded maximum plant height at 30 and 60 DAS, i.e. 19.1cm and 43 cm, respectively. At 90 and 120 DAS, treatment T7 (i.e., rice straw biochar at 5 tons/ha) resulted in the maximum plant height, i.e., 91.7 cm and 100 cm, respectively. The maximum plant height at 120 DAS was recorded in T7 (100 cm), followed by T4 (98 cm), T5 (96.5 cm), T8 (96.4 cm), T9 (94.5 cm), T6 (94.5 cm), T2 (92.3 cm), T3 (84.4 cm) and T1 (70 cm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T7 (40.8%), T4 (39.4%), T5 (36%), T8 (34.7%), T6 (32.8%), T9 (30.7%), T2 (26.9%) and T3 (16.1%). Throughout all growth stages, T4 and T7 showed a significant improvement in plant height compared to all other treatments. During the 2023-2024 season, among the treatments, T4 and T7 significantly increased the plant height compared to other treatments. Among all treatments, T7 recorded the maximum plant height at 30 DAS (23.3cm) and 60 DAS, T4 (43 cm). At 90 and 120 DAS, treatment T7 resulted in the maximum plant height, i.e., 91.7 cm and 101 cm, respectively. The maximum plant height at 120 DAS was recorded in T7 (103.1 cm), followed by T4 (100.1 cm), T8 (97.3 cm), T5 (97.2 cm), T9 (95.2 cm), T6 (94.9 cm), T2 (93.3 cm), T3 (84.4 cm) and T1 (72 cm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T7 (38.5%), T4 (37.9%), T8 (34.3%), T5 (34.2%), T9 (31.4%), T6 (30.9%), T2 (28.8%) and T3 (16.5%). Throughout all growth stages, T4 and T7 showed a significant improvement in plant height compared to other treatments.

The mean plant height across both years of crop performance was significantly higher at all growth stages compared to the control. Among the treatments, T4 and T7 significantly increased the plant height compared to other treatments. At 120 DAS, the maximum plant height was recorded in T7 (102.1 cm), followed by T4 (99.5 cm), T5 (96.5 cm), T8 (96.4 cm), T9 (94.5 cm), T6 (94.5 cm), T2 (92.3 cm), T3 (84.4 cm), and T1 (72.4 cm). Compared to the control (T1), a substantial percentage increase in plant height was observed in T7 (38.2%), T4 (37.3%), T5 (33.2%), T8 (33%), T9 (30.5%), T6 (30.5%), T2 (27.5%), and T3 (16.3%).

Table 4.1 Effect of different doses of biochar application on plant height (cm) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2022-23	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**
T_1	12.3^{e}	14.3^{e}	13.3^{e}	27.3^{d}	26.8^{e}	27.1^{e}	64.8^{g}	67.3^{f}	66.0^{f}	70^{e}	72.5^{e}	71.4^{e}
T_2	15.2^{c}	17.5^{d}	16.4^{c}	38.5^{b}	39.2^{c}	38.8^{c}	80.9^{e}	81.3^{d}	81.1^{d}	91.3^{c}	93.3^{c}	92.3^{c}
T_3	13.8^{d}	15.7^{e}	14.7^{d}	32.5^{c}	33.7^{d}	33.1^{d}	76.2^{f}	76.1^{e}	76.2^{e}	84.4^{d}	84.4^{d}	84.4^{d}
T_4	19.1^{a}	22.6^{a}	20.9^{a}	43.0^{a}	44.1^{a}	43.6^{a}	91.2^{a}	89.0^{a}	90.1^{a}	98.0^{a}	100.1^{a}	99.5^{a}
T_5	16.9^{b}	19.9^{bc}	18.4^{b}	39.6^{b}	40.4^{bc}	40.0^{bc}	87.2^{b}	84.8^{b}	86.0^{b}	95.7^{b}	97.2^{b}	96.5^{b}
T_6	15.5^{c}	18.3^{cd}	16.9^{c}	39.8^{b}	39.0^{c}	39.4^{c}	83.7^{de}	83.8^{bc}	83.8^{c}	94.1^{b}	94.9^{c}	94.5^{b}
T_7	18.8^{a}	23.3^{a}	21.0^{a}	42.4^{a}	45.6^{a}	44.0^{a}	91.7^{a}	89.5^{a}	90.6^{a}	100^{a}	103.1^{a}	100.1^{a}
T_8	17.3^{b}	20.6^{b}	18.9^{b}	40.0^{b}	41.8^{b}	40.9^{b}	86.7^{bc}	84.9^{b}	85.8^{b}	95.4^{b}	97.3^{b}	96.4^{b}
T_9	15.7^{c}	18.3^{cd}	17.0^{c}	37.9^{b}	40.3^{bc}	39.1^{c}	84.0^{cd}	82.2^{cd}	83.1^{c}	93.9^{b}	95.2^{bc}	94.5^{b}
CD ($p \leq 0.05$)	0.8	1.8	1.1	2.4	1.7	1.4	2.9	2.1	1.8	2.5	2.2	2.1
SEm (±)	0.3	0.6	0.4	0.8	0.6	0.5	1.0	0.7	0.6	0.8	0.7	0.7

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

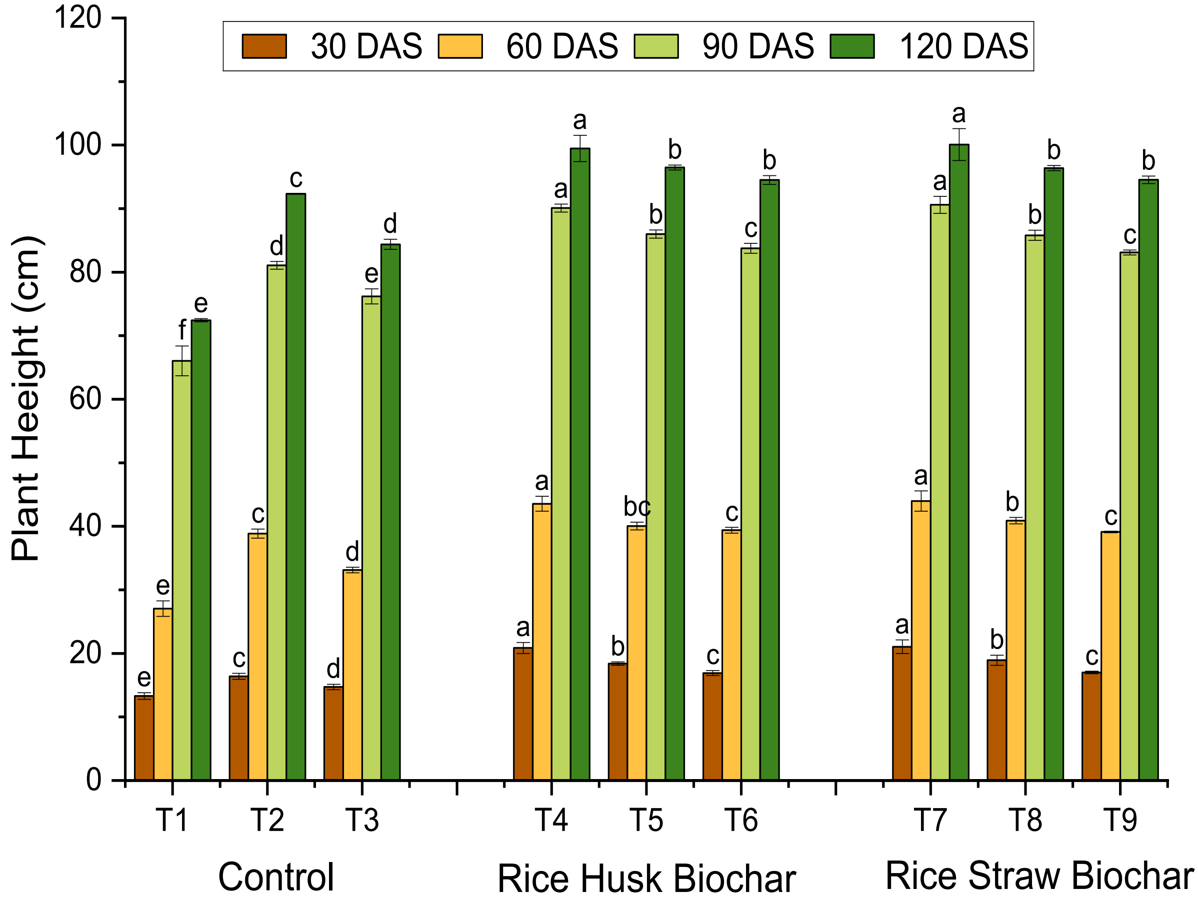


Figure 4.1. Effect of different biochar doses on wheat plant height (cm) at 30, 60, 90, and 120 DAS.

The impact of biochar on the Number of tillers of wheat is presented in **Table 4.2**. A significant result of biochar was observed in the Number of wheat tillers at different growth stages during the 2022-2023 season. Among the treatments, T4 and T7 significantly increased the number of tillers compared to other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum Number of tillers at 60, 90, and 120 DAS, i.e., 127.3, 153, and 155, respectively. The maximum number of tillers at 120 DAS was recorded in T4 (155.3), followed by T7 (152.3), T8 (139.7), T5 (136.3), T6 (124.3), T9 (119.3), T2 (100.7), T3 (86.3) and T1 (68.3). Compared to the control (T1), a substantial percentage increase was recorded in the number of tillers in treatments T4 (127.3%), T7 (122.9%), T8 (104.4%), T5 (99.5%), T6 (82%), T9 (74.6%), T2 (47.3%) and T3 (26.3%). Throughout all growth stages, T4 and T7 showed a significant improvement in the number of tillers compared to all other treatments.

A significant impact of biochar was observed on the Number of tillers of wheat at different growth stages during the 2022-2023 season. Among the treatments, T4 and T7 significantly increased the number of tillers compared to other treatments. Among all treatments, T4 recorded the maximum Number of tillers at 60, 90, and 120 DAS, i.e., 120, 152.7, and 155.3, respectively. The maximum Number of tillers at 120 DAS was recorded in T4 (155.3), followed by T7 (152.7), T5 (147), T8 (138.7), T6 (130.7), T9 (124), T2 (106.7), T3 (88) and T1 (74.7). Compared to the control (T1), a substantial percentage increase was recorded in the Number of tillers in treatments T4 (108%), T7 (104.5%), T5 (96.6%), T8 (85.7%), T6 (75%), T9 (66.1%), T2 (42.9%) and T3 (17.9%). Throughout all growth stages, T4 and T7 showed a significant improvement in the number of tillers compared to all other treatments.

The mean number of tillers was significant at all growth stages. Among the treatments, T4 and T7 significantly increased the number of tillers compared to other treatments. The maximum number of tillers at 120 DAS was recorded in T4 (155.3), followed by T7 (152.5), T5 (141.7), T8 (139.2), T6 (127.5), T9 (121.7), T2 (92.3 cm), T3 (84.4 cm) and T1 (72.4 cm). Compared to the control (T1), a substantial percentage increase was recorded in the number of tillers in treatments T4 (117.2 %), T7 (113.2 %), T5 (98.1 %), T8 (94.6 %), T6 (78.3 %), T9 (70.1%), T2 (44.9 %) and T3 (21.9 %).

Table 4.2 Effect of different doses of biochar application on the number of tillers and productive tillers (m) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS			No. of productive tillers		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	50.7^{f}	57^{f}	53.8^{f}	66.7^{e}	72^{g}	69.3^{f}	68.3^{f}	74.7^{g}	71.5^{f}	60.3^{f}	65.7^{g}	63^{f}
T_2	81.7^{d}	80.3^{d}	81.0^{d}	90.7^{d}	103^{e}	96.8^{d}	100.7^{d}	106.7^{e}	103.7^{d}	92.7^{d}	97.7^{e}	95.2^{d}
T_3	64.3^{e}	67.7^{e}	66.0^{e}	81.7^{d}	85.7^{f}	83.7^{e}	86.3^{e}	88.0^{f}	87.2^{e}	78.3^{e}	79.0^{f}	78.7^{e}
T_4	127.3^{a}	120^{a}	123.7^{a}	153^{a}	152.7^{a}	152.8^{a}	161.3^{a}	155.3^{a}	158.3^{a}	147.3^{a}	146.3^{a}	146.8^{a}
T_5	111.3^{b}	103^{b}	107.2^{b}	132.7^{b}	143.7^{bc}	138.2^{b}	136.3^{b}	147.0^{b}	141.7^{b}	128.3^{b}	138^{b}	133.2^{b}
T_6	92.7^{c}	90^{c}	91.3^{c}	120^{c}	124.3^{d}	122.2^{c}	124.3^{c}	130.7^{cd}	127.5^{c}	116.3^{c}	121.7^{cd}	119^{c}
T_7	122.7^{a}	116.3^{a}	119.5^{a}	147.3^{a}	148.3^{ab}	147.8^{a}	152.3^{a}	152.7^{ab}	152.5^{a}	144.3^{a}	143.7^{ab}	144^{a}
T_8	107.7^{b}	102^{b}	104.8^{b}	136.3^{b}	135.7^{c}	136.0^{b}	139.7^{b}	138.7^{c}	139.2^{b}	131.7^{b}	129.7^{c}	130.7^{b}
T_9	88.7^{cd}	92.3^{c}	90.5^{c}	116.3^{c}	118.7^{d}	117.5^{c}	119.3^{c}	124.0^{d}	121.7^{c}	111.3^{c}	115^{d}	113.2^{c}
CD ($p \leq 0.05$)	8.8	7.8	5.3	9.7	8.6	7.5	9.8	8.2	7.7	9.6	8.2	7.3
SEm (±)	3.0	2.6	1.8	3.2	2.9	2.5	3.3	2.7	2.6	3.3	2.7	2.4

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha**

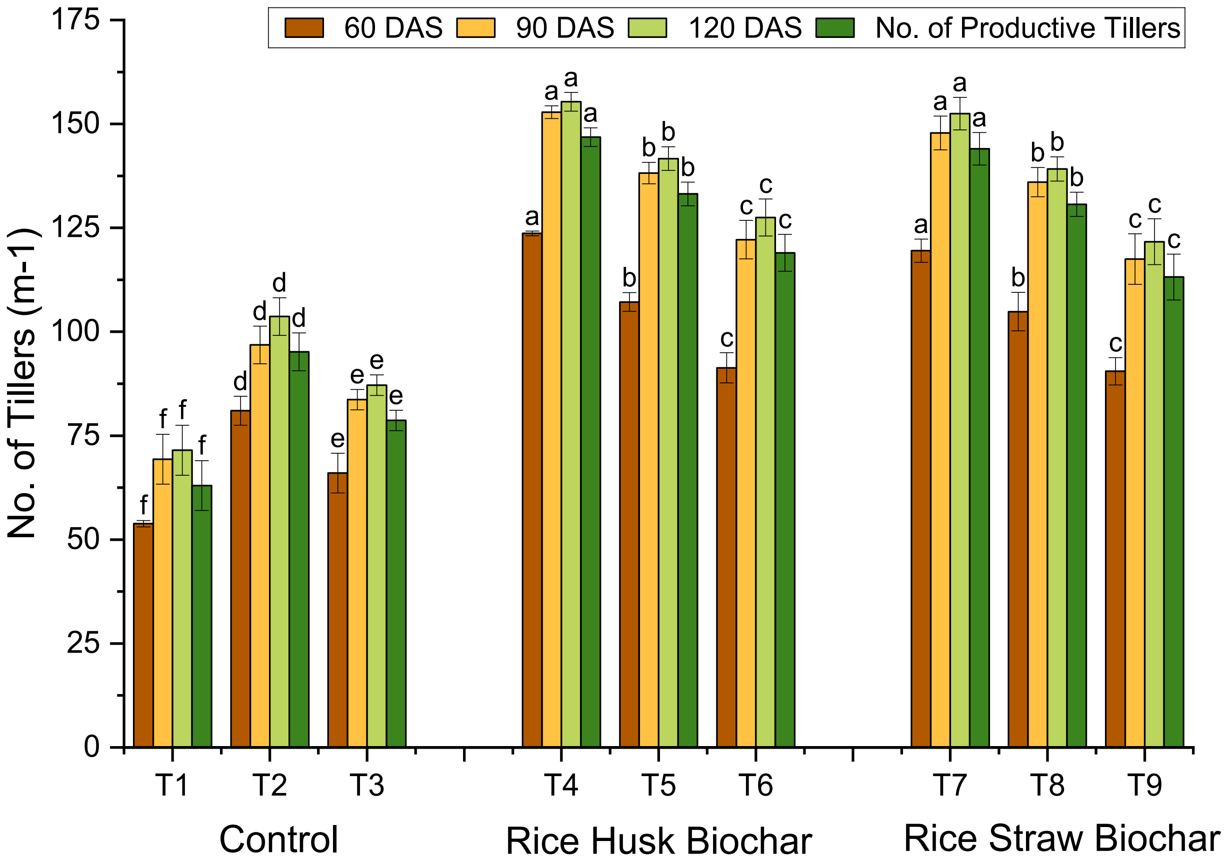


Figure 4.2. Effect of different biochar doses on the number of tillers and productive tillers per unit meter in wheat at 60, 90, and 120 DAS.

Leaf area is a crucial parameter that helps determine crop health. During the 2022-2023 season, a significant impact of biochar was observed on the Leaf area of wheat during different growth stages. The results are presented in **Table 4.3.** Among the treatments, T4 and T7 significantly increased the leaf area compared to other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum Leaf area at 30, 60, 90, and 120 DAS, i.e., 19.6 m^2, 120.4 m^2, 126.1 m^2, and 67.9 m^2, respectively. The maximum Leaf area at 90 DAS was recorded in T7 (126.1 m^2), followed by T4 (123.6 m^2), T5 (81.8 m^2), T8 (81.1 m^2), T9 (106.6 m^2), T6 (101.2 m^2), T2 (84.9 m^2), T3 (71.4 m^2) and T1 (52.8 m^2). Compared to the control (T1), a substantial percentage increase was recorded in Leaf area in treatments T4 (134%), T7 (138.6%), T8 (118.3%), T5 (113.8%), T9 (101.8%), T6 (91.5%), T2 (60.7%) and T3 (35.3%). Throughout all growth stages, T4 and T7 showed a significant improvement in the Leaf area compared to all other treatments.

Biochar application significantly enhanced wheat leaf area during the 2022-2023 growing season, across various growth stages. Among the treatments, T4 and T7 significantly increased the leaf area compared to other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum Leaf area at 30 and 60 DAS, i.e., 18.3 m^2 and 81.9 m^2, respectively. At 90 and 120 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in maximum Leaf area, i.e., 103 m^2 and 57.5 m^2, respectively. The maximum Leaf area at 90 DAS was recorded in T4 (103 m^2), followed by T7 (92.1 m^2), T5 (81.8 m^2), T8 (81.1 m^2), T6 (75.4 m^2), T9 (72.1 m^2), T2 (73.2 m^2), T3 (56.3 m^2) and T1 (47.3 m^2). Compared to the control (T1), a substantial percentage increase was recorded in Leaf area in treatments T4 (117.6 %), T7 (94.5%), T5 (72.2%), T8 (71.2%), T6 (59.2%), T9 (52.3%), T2 (54.6%) and T3 (18.8%). Throughout all growth stages, T4 and T7 showed a significant improvement in Leaf area height compared to all other treatments.

The mean leaf area was found to be significant at all growth stages. Among the treatments, T4 and T7 significantly increased the leaf area compared to other treatments. The maximum leaf area at 90 DAS was recorded in T4 (113.3 m^2), followed by T7 (109.1 m^2), T8 (98.2 m^2), T5 (97.4 m^2), T9 (89.4 m^2), T6 (88.3 m^2), T2 (79.1 m^2), T3 (63.9 m^2) and T1 (50.1 m^2). Compared to the control (T1), a substantial percentage increase was recorded in leaf area in treatments T4 (126.2 %), T7 (117.7 %), T8 (96.1%), T5 (94.4 %), T9 (78.4%), T6 (76.2%), T2 (57.8%) and T3 (27.5%)

Table 4.3 Effect of different doses of biochar application on the leaf area (m^2) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	8.8^{f}	8.7^{e}	8.8^{f}	44.9^{f}	37.4^{g}	41.2^{f}	52.8^{g}	47.3^{g}	50.1^{f}	26.3^{f}	31.5^{e}	28.9^{g}
T_2	13.0^{d}	14.3^{c}	13.7^{d}	82.2^{d}	67.2^{de}	74.7^{d}	84.9^{e}	73.2^{de}	79.1^{d}	50.5^{d}	48.9^{bc}	49.7^{cd}
T_3	10.6^{e}	10.3^{d}	10.5^{e}	63.8^{e}	51.5^{f}	57.6^{e}	71.5^{f}	56.3^{f}	63.9^{e}	37.0^{e}	42.2^{d}	39.6^{f}
T_4	16.6^{b}	18.0^{a}	17.3^{b}	119.4^{a}	79.0^{ab}	99.2^{a}	123.6^{a}	103^{a}	113.3^{a}	64.7^{a}	57.5^{a}	61.1^{a}
T_5	15.3^{c}	15.3^{bc}	15.3^{c}	106.1^{b}	72.6^{cd}	89.4^{b}	113b^{c}	81.8^{c}	97.4^{b}	57.5^{bc}	50.2^{bc}	53.9^{b}
T_6	14.2^{cd}	14.6^{bc}	14.4^{cd}	94.5^{c}	66.3^{e}	80.4^{c}	101.2^{d}	75.4^{cde}	88.3^{c}	49.3^{d}	40.2^{d}	44.8^{e}
T_7	19.6^{a}	18.3^{a}	19.0^{a}	120.4^{a}	81.9^{a}	101.1^{a}	126.1^{a}	92.1^{b}	109.1^{a}	67.9^{a}	53.9^{ab}	60.9^{a}
T_8	17.3^{b}	17.5^{a}	17.4^{b}	109.7^{b}	75.5^{bc}	92.6^{b}	115.4^{b}	81.1^{cd}	98.2^{b}	58.6^{b}	48.3^{c}	53.4^{bc}
T_9	14.7^{c}	15.8^{b}	15.3^{c}	96.0^{c}	69.7^{cde}	82.8^{c}	106.6^{cd}	72.1^{e}	89.4^{c}	53.1^{cd}	40.8^{d}	46.9^{de}
CD ($p \leq 0.05$)	1.3	1.2	1.0	7.1	6.1	3.9	7.8	8.2	6.5	5.1	5.2	3.76
SEm (±)	0.44	0.41	0.32	2.35	2.04	1.29	2.61	2.75	2.16	1.7	1.7	1.3

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

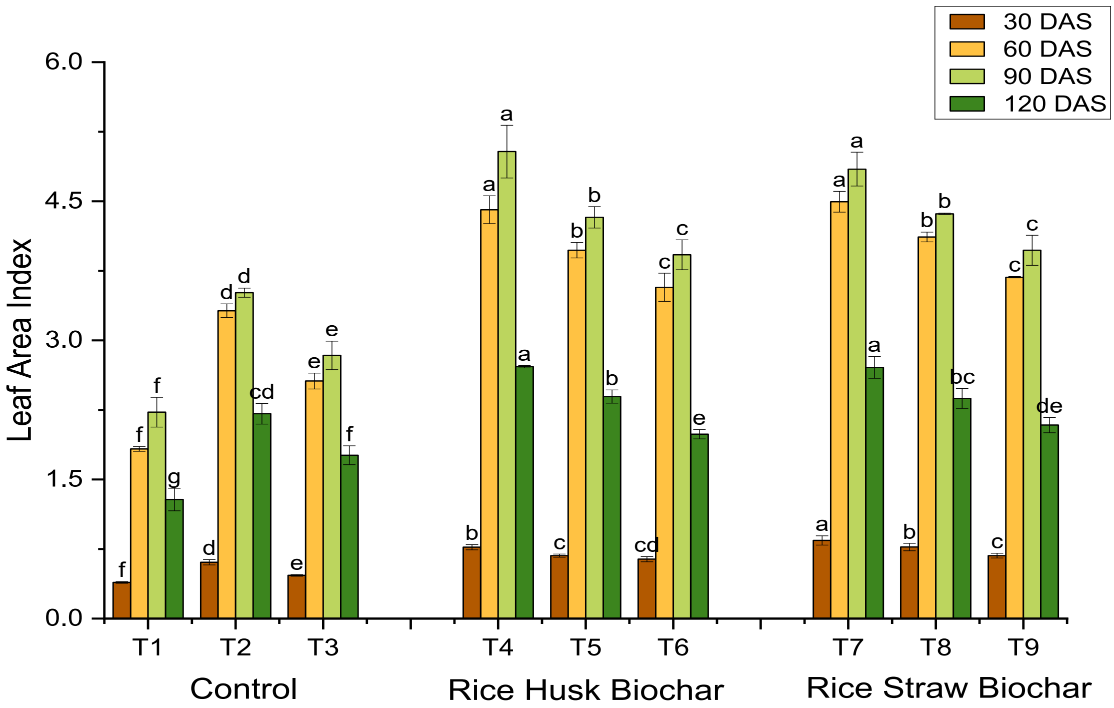


Figure 4.3. Effect of different biochar doses on leaf area Index of wheat at 30, 60, 90, and 120 DAS.

A significant impact of biochar was observed on the leaf area index of wheat during different growth stages during the 2022-2023 season. The results are presented in **Table 4.4.** Among the treatments, T4 and T7 significantly increased the LAI compared to other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum leaf area index at 60, 90, and 120 DAS, i.e., 5.4, 5.6, and 3, respectively. The maximum leaf area index at 90 DAS was recorded in T7 (5.6), followed by T4 (5.5), T8 (5.1), T5 (5), T9 (4.7), T6 (4.5), T2 (3.8), T3 (3.2) and T1 (2.3). Compared to the control (T1), a substantial percentage increase was recorded in leaf area index in treatments T7 (138.6 %), T4 (134 %), T8 (118.3%), T5 (113.8%), T9 (101.8%), T6 (91.5%), T2 (60.7%) and T3 (35.3%). Throughout all growth stages, T4 and T7 showed a significant improvement in leaf area index compared to all other treatments.

Biochar amendment significantly affects the leaf area index of wheat at various growth stages during the 2023-2024 season, with a notable impact of biochar observed. Among the treatments, T4 and T7 significantly increased the LAI compared to other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum leaf area index of 60, corresponding to a value of 3.6. At 90 and 120 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in a maximum leaf area index of 4.6 and 2.6, respectively. The maximum leaf area index at 90 DAS was recorded in T4 (4.6), followed by T7 (4.1), T5 (3.6), T8 (3.6), T6

(3.3), T2 (3.3), T9 (3.3), T3 (2.5) and T1 (2.1). Compared to the control (T1), a substantial percentage increase was recorded in leaf area index in treatments T4 (117.6 %), T7 (94.5 %), T5 (72.8 %), T8 (71.3 %), T6 (59.2%), T9 (52.4%), T2 (54.7%) and T3 (18.9%). Throughout all growth stages, T4 and T7 showed a significant improvement in leaf area index compared to all other treatments.

The mean leaf area index was significant at all growth stages. Among the treatments, T4 and T7 significantly increased the LAI compared to other treatments. The maximum leaf area at 90 DAS was recorded in T4 (5.0), followed by T7 (4.8), T8 (4.4), T5 (4.3), T9 (4.0), T6 (3.9), T2 (3.5), T3 (2.8), and T1 (2.2). Compared to the control (T1), a substantial percentage increase was recorded in leaf area index in treatments T4 (126.2 %), T7 (117.8 %), T8 (96.1 %), T5 (94.4 %), T9 (78.4 %), T6 (76.2 %), T2 (57.9 %) and T3 (27.5 %). Overall, when comparing all growth stages, the impact of T4 and T7 was found to be more significant than all other treatments.

Table 4.4 Effect of different doses of biochar application on leaf area index of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	2.0f	1.7^{g}	1.8f	2.3^{g}	2.1^{g}	2.2^{f}	1.2^{f}	1.4^{e}	1.3^{g}
T_2	3.7^{d}	$3d^{e}$	3.3d	3.8^{e}	3.3^{de}	3.5^{d}	2.2^{d}	2.2^{bc}	2.2^{cd}
T_3	2.8^{e}	2.3^{f}	2.6e	3.2^{f}	2.5^{f}	2.8^{e}	1.6^{e}	1.9^{d}	1.8^{f}
T_4	5.3^{a}	3.5^{ab}	4.4a	5.5^{a}	4.6^{a}	5^{a}	2.9^{a}	2.6^{a}	2.7^{a}
T_5	4.7^{b}	3.2^{cd}	4.0b	5^{bc}	3.6^{c}	4.3^{b}	2.6^{bc}	2.2^{bc}	2.4^{b}
T_6	4.2^{c}	2.9^{e}	3.6c	4.5^{d}	3.3^{cde}	3.9^{c}	2.2^{d}	1.8^{d}	2.0^{e}
T_7	5.4^{a}	3.6^{a}	4.5a	5.6^{a}	4.1^{ab}	4.8^{a}	3.0^{a}	2.4^{ab}	2.7^{a}
T_8	4.9^{b}	3.4^{bc}	4.1b	5.1^{b}	3.6^{cd}	4.4^{b}	2.6^{b}	2.1^{c}	2.4^{bc}
T_9	4.3^{c}	3.1^{cde}	3.7c	4.7^{cd}	3.2^{e}	4^{c}	2.4^{cd}	1.8^{d}	2.1^{de}
CD ($p \leq 0.05$)	0.3	0.3	0.2	0.3	0.4	0.3	0.2	0.2	0.2
SEm (±)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

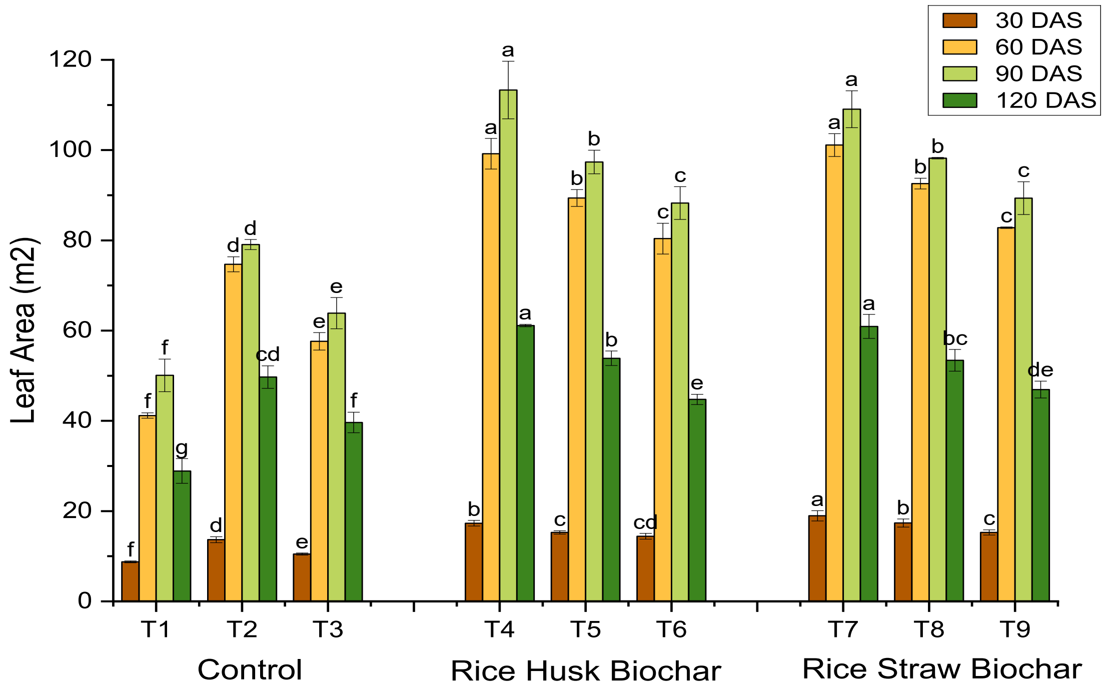


Figure 4.4. Effect of different biochar doses on leaf area (m²) of wheat at 30, 60, 90, and 120 DAS.

Biochar significantly impacted wheat node diameter at different growth stages throughout the 2022-2023 season. The results are presented, rice husk biochar at 5 tons/ha) recorded the maximum node diameter at 60 days, i.e., node diameter compared to other treatments. Among all treatments, T4 (i.e. rice husk biochar @ 5 tons/ha) recorded maximum node diameter at 60, i.e. 4.9 mm. At 90 and 120 DAS, treatment T7 (i.e., rice straw biochar at 5 tons/ha) resulted in the maximum node diameter, i.e., 6 mm and 5.5 mm, respectively. The maximum node diameter at 90 DAS was recorded in T7 (6 mm), followed by T4 (5.6 mm), T8 (6.6 mm), T9 (5.5 mm), T5 (5.3 mm), T6 (5.1 mm), T2 (4.9 mm), T3 (4.1 mm) and T1 (3.6 mm). Compared to the control (T1), a substantial percentage increase was recorded in node diameter in treatments T7 (64.1%), T8 (55.5%), T4 (53.1%), T9 (50.5%), T5 (47%), T6 (41.6 %), T2 (35.3 %) and T3 (12.9 %). However, at 60 and 120 DAS, T4 and T7 showed a significant improvement in node diameter compared to all other treatments.

Biochar treatment significantly increases the node diameter across all growth phases from 20 23 to 2023. Among the treatments, T4 and T7 significantly increased the node diameter compared to other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum node diameter at 60, 90, and 120 DAS, i.e., 4.9 mm, 6 mm, and 5.6 mm, respectively. The maximum node diameter at 90 DAS was recorded in T7 (6 mm), followed by T8 (5.8 mm), T4 (5.6 mm), T9 (5.5 mm), T5 (5.3 mm), T6 (5 mm), T2 (5 mm), T3 (4.3 mm) and T1 (3.8 mm). Compared to the control (T1), a substantial percentage increase was recorded in node diameter in treatments T7 (58.9%), T8 (52.7%), T4 (46.5%), T9 (45.7%), T6 (32.6%), T5 (39.8%), T2 (31.3%) and T3 (14.7%). However, during 60 DAS, T4 and T7 showed a significant improvement in node diameter compared to all other treatments.

The mean node diameter was found to be significant at all growth stages. Among the treatments, T4 and T7 significantly increased plant height compared to other treatments. The maximum leaf area at 90 DAS was recorded in T7 (6 mm), followed by T8 (5.7 mm), T4 (5.6 mm), T9 (5.5 mm), T5 (5.3 mm), T6 (5.1 mm), T2 (4.9 mm), T3 (4.2 mm) and T1 (3.7 mm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T7 (61.4%), T8 (54 %), T4 (49.7%), 95 (48.1%), T5 (43.3%), T6 (37%), T2 (33.2%) and T3 (13.8%). However, at 60 DAS, both T4 and T7 were found to be more significant than all other treatments.

Table 4.5 Effect of different doses of biochar application on node diameter (mm) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 & 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	3.2^{h}	3^{h}	3.1^{f}	3.6^{g}	3.8^{g}	3.7^{h}	3.4^{g}	3.4^{f}	3.4^{f}
T_2	3.7^{f}	3.7^{f}	3.7^{d}	4.9^{e}	5.0^{e}	4.9^{f}	4.7^{e}	4.8^{d}	4.7^{d}
T_3	3.5^{g}	3.5^{g}	3.5^{e}	4.1^{f}	4.3^{f}	4.2^{g}	3.8^{f}	4.1^{e}	4^{e}
T_4	4.9^{a}	4.8^{ab}	4.8^{a}	5.6^{b}	5.6^{c}	5.6^{c}	5.3^{abc}	5.3^{b}	5.3^{b}
T_5	4.7^{bc}	4.7^{cd}	4.7^{b}	5.3^{cd}	5.3^{d}	5.3^{d}	5.1^{cd}	5.0^{c}	5.1^{c}
T_6	4.5^{de}	4.5^{de}	4.5^{c}	5.1^{d}	5.0^{e}	5.1^{e}	4.9^{de}	4.9^{d}	4.9^{d}
T_7	4.8^{ab}	4.9^{a}	4.9^{a}	6.0^{a}	6.0^{a}	6.0^{a}	5.5^{a}	5.6^{a}	5.5^{a}
T_8	4.6^{cd}	4.7^{bc}	4.7^{b}	5.6^{b}	5.8^{b}	5.7^{b}	5.4^{ab}	5.4^{b}	5.4^{b}
T_9	4.4^{e}	4.5^{e}	4.5^{c}	5.5^{bc}	5.5^{c}	5.5^{c}	5.2^{bc}	5.0^{c}	5.1^{c}
CD ($p \leq 0.05$)	0.1	0.0	0.1	0.2	0.1	0.1	0.2	0.1	0.2
SEm (±)	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

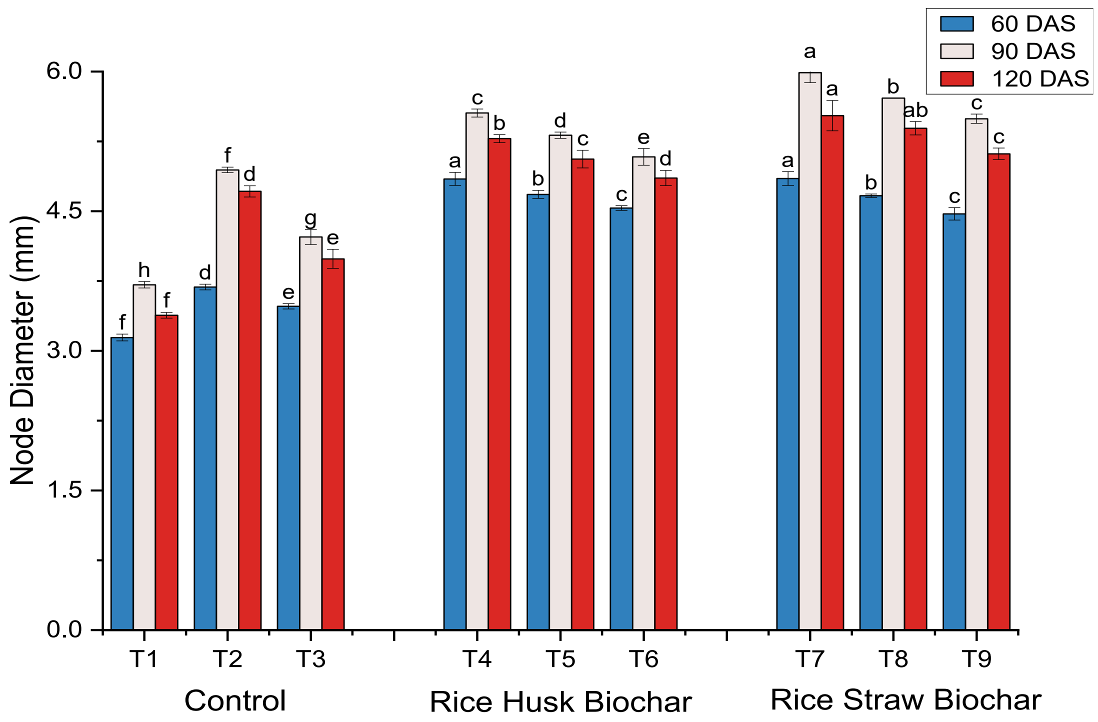


Figure 4.5. Effect of different biochar doses on node diameter (mm) of wheat at 60, 90, and 120 DAS.

Internode length is a crucial agronomic trait that influences plant architecture and crop yield. During the 2022-2023 season, a significant impact of biochar on the internode diameter of wheat was observed at different growth stages. The results are presented in **Table 4.6.** Among the treatments, T4 and T7 significantly increased the internode length compared to other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum internode diameter at 60 days, i.e., 4.3 mm. At 90 and 120 DAS, treatment T7 (i.e., rice straw biochar at 5 tons/ha) resulted in maximum internode diameters of 5 mm and 4.7 mm, respectively. The maximum internode diameter at 90 DAS was recorded in T7 (5 mm), followed by T8 (4.7 mm), T4 (4.6 mm), T9 (4.5 mm), T5 (4.4 mm), T6 (4.2 mm), T2 (4 mm), T3 (3.3 mm) and T1 (2.7 mm). Compared to the control (T1), a substantial percentage increase was recorded in internode diameter in treatments T7 (81.1%), T8 (70.6%), T4 (69.5%), T9 (65%), T5 (60.5%), T6 (53.3%), T2 (47%) and T3 (19.2%). However, at 60 DAS, T4 and T7 showed a significant improvement in internode diameter compared to all other treatments.

A significant impact of biochar was observed on the node diameter of wheat during different growth stages during the 2023-2024 season. Among the treatments, T4 and T7 significantly increased the internode length compared to other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum node diameter at 60, 90, and 120 DAS, i.e., 4.4 mm, 5.1 mm, and 4.7 mm, respectively. The maximum internode diameter at 90 DAS was recorded in T7 (5.1 mm), followed by T4 (4.8 mm), T8 (4.8 mm), T5 (4.5 mm), T9 (4.4 mm), T6 (4.3 mm), T2 (4 mm), T3 (3.3 mm) and T1 (2.8 mm). Compared to the control (T1), a substantial percentage increase was recorded in node diameter in treatments T8 (78.2%), T4 (67%), T8 (67%), T5 (56.6%), T9 (55.9 %), T6 (49.6%), T2 (39.5%) and T3 (14.3%). However, at 60 and 120 DAS, T4 and T7 showed a significant improvement in internode diameter compared to all other treatments.

The mean stem diameter was found to be significant at all growth stages. However, at 60 days after surgery (DAS), both T4 and T7 were found to be more significant than all other treatments. The maximum leaf area at 90 DAS was recorded in T7 (5 mm), followed by T8 (4.7 mm), T4 (4.7 mm), T9 (4.5 mm), T5 (4.4 mm), T6 (4.2 mm), T2 (4 mm), T3 (3.3 mm) and T1 (2.8 mm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T7 (79.7%), T8 (68.7%), T4 (68.2%), T9 (60.3%), T5 (58.5%), T6 (51.4%), T2 (43.1%) and T3 (16.7%).

Table 4.6 Effect of different doses of biochar application on stem diameter (mm) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 & 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	2.5^{e}	2.6^{h}	2.5^{f}	2.7^{f}	2.8^{g}	2.8^{g}	2.6^{h}	2.7^{g}	2.6^{f}
T_2	3.1^{d}	3.1^{f}	3.1^{d}	4.0^{d}	4^{e}	4.0^{e}	3.9^{f}	4.0^{e}	4.0^{d}
T_3	2.9^{d}	2.9^{g}	2.9^{e}	3.3^{e}	3.3^{f}	3.3^{f}	3.2^{g}	3.3^{f}	3.2^{e}
T_4	4.3^{a}	4.3^{ab}	4.3^{a}	4.6^{b}	4.8^{b}	4.7^{b}	4.6^{bc}	4.6^{ab}	4.6^{b}
T_5	4.1^{ab}	4.1^{cd}	4.1^{b}	4.4^{c}	4.5^{c}	4.4^{c}	4.3^{d}	4.4^{c}	4.3^{c}
T_6	3.9^{c}	3.9^{e}	3.9^{c}	4.2^{d}	4.3^{d}	4.2^{d}	4.1^{e}	4.0^{de}	4.1^{d}
T_7	4.1^{ab}	4.4^{a}	4.3^{a}	5^{a}	5.1^{a}	5^{a}	4.9^{a}	4.7^{a}	4.8^{a}
T_8	4.0^{bc}	4.3^{bc}	4.1^{b}	4.7^{b}	4.8^{b}	4.7^{b}	4.7^{b}	4.5^{bc}	4.6^{b}
T_9	3.8^{c}	4.0^{de}	3.9^{c}	4.5^{bc}	4.4^{cd}	4.5^{c}	4.5^{c}	4.2^{d}	4.3^{c}
CD ($p \leq 0.05$)	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.1
SEm (±)	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

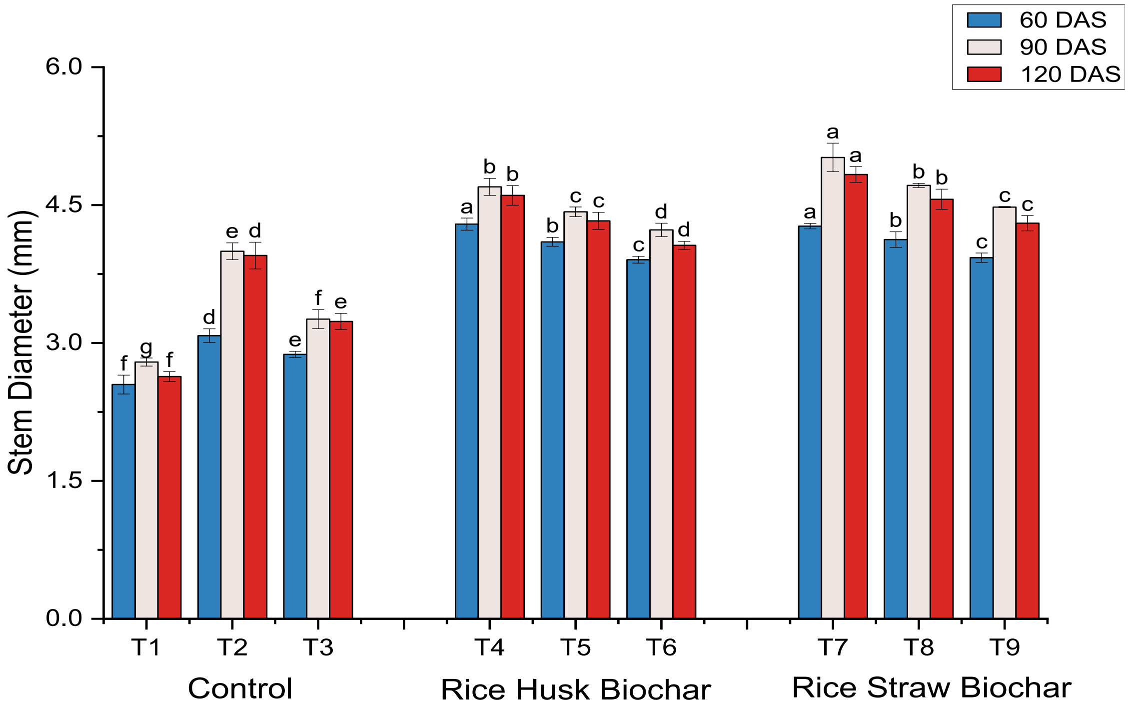


Figure 4.6. Effect of different biochar doses on Stem diameter (mm) of wheat at 60, 90, and 120 DAS.

Fresh biomass is a key indicator of plant growth and productivity. During the 2022-2023 season, a significant impact of biochar was observed on the fresh biomass of wheat during different growth stages. The results are presented in **Table 4.7.** Throughout all growth stages, T4 and T7 showed a significant improvement in stem diameter compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum fresh biomass at 60, 90, and 120 DAS, specifically 155.7 g, 467.1 g, and 630.5 g, respectively. The maximum fresh biomass at 120 DAS was recorded in T7 (630.5 g), followed by T4 (612.5 g), T8 (589.8 g), T5 (577.3 g), T9 (572.8 g), T6 (555.2 g), T2 (518.4 g), T3 (482.5 g) and T1 (458.4 g). As compared to control (T1), there was a significant percentage increase of fresh biomass in treatments T7 (37.5%), T4 (33.6%), T8 (28.7%), T5 (25.9%), T9 (24.9%), T6 (21.1%), T2 (13.1%) and T3 (5.3%).

The mean fresh biomass was found to be significant at all growth stages. Overall, when comparing all growth stages, the impact of T4 and T7 was found to be more significant than all other treatments. The maximum fresh biomass at 120 DAS was recorded in T7 (616.3 g), followed by T4 (613.8 g), T8 (592.9 g), T5 (588 g), T9 (568.4 g), T6 (561.9 g), T2 (521 g), T3 (494 g) and T1 (467.6 g). As compared to control (T1), there was a significant percentage increase of fresh biomass in treatments T7 (31.8 %), T4 (31.3%), T8 (26.8%), T5 (25.7%), T9 (21.6%), T6 (20.2%), T2 (11.4%) and T3 (5.8%).

Table 4.7 Effect of different doses of biochar application on fresh biomass (g) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	69.9^{f}	62.4^{g}	66.2^{h}	295^{h}	284.9^{d}	289.9^{f}	458.4^{f}	476.8^{e}	467.6^{g}
T_2	103.4^{d}	95.6^{e}	99.5^{f}	354.2^{f}	335.0^{c}	344.6^{d}	518.4^{d}	523.6^{cd}	521^{e}
T_3	81.9^{e}	74.6^{f}	78.2^{g}	327.3^{g}	317.6^{cd}	322.5^{e}	482.5^{e}	507.1^{de}	494.8^{f}
T_4	151.4^{a}	145.0^{ab}	148.2^{ab}	453.1^{ab}	436.4^{a}	444.8^{a}	612.5^{a}	615.1^{a}	613.8^{a}
T_5	137.6^{b}	127.8^{cd}	132.7^{cd}	427.1^{cd}	413.8^{b}	420.4^{b}	577.3^{b}	598.7^{b}	588.0^{bc}
T_6	125.1^{c}	121.7^{d}	123.4^{e}	395.2^{e}	380.8^{b}	388.0^{c}	555.2^{c}	568.6^{b}	561.9^{d}
T_7	155.7^{a}	147.2^{a}	151.5^{a}	467.1^{a}	423.2^{a}	445.1^{a}	630.5^{a}	602.2^{ab}	616.3^{a}
T_8	142.6^{b}	136.9^{bc}	139.8^{bc}	437.6^{bc}	409.7^{b}	423.7^{b}	589.8^{b}	595.9^{b}	592.9^{b}
T_9	125.9^{c}	126.1^{d}	126.1^{de}	411.8^{de}	381^{b}	396.4^{c}	572.8^{bc}	564.1^{bc}	568.4^{cd}
CD ($p \leq 0.05$)	7.78	10.1	8.6	18.7	36.3	18.2	20	40.7	20.3
SEm (±)	2.59	3.37	2.87	6.25	12.2	6.07	6.68	13.6	6.8

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

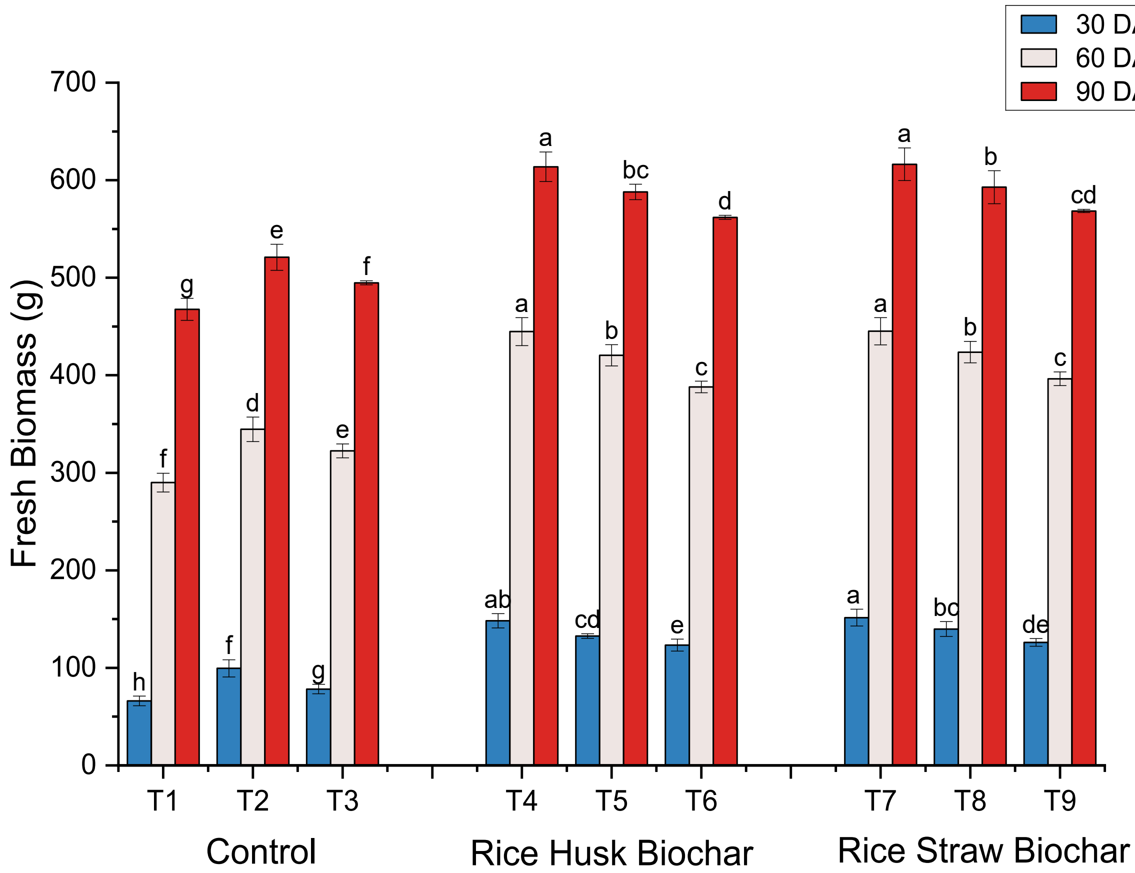


Figure 4.7. Effect of different biochar doses on fresh biomass (g) of wheat at 30, 60, and 90 DAS.

Dry wheat biomass throughout all growth stages during the 2022-2023 season, a significant impact of biochar was observed. The results are shown in **Table 4.8.** However, during 60 DAS, T4, T7, and T8, while T4 and T7 at 120 DAS, showed a significant improvement in dry biomass compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum dry biomass at 60, 90, and 120 DAS, specifically 16.3 g, 68.7 g, and 109.7 g, respectively. The maximum dry biomass at 120 DAS was recorded in T4 (109.7 g), followed by T7 (102.9 g), T8 (98 g), T5 (97.9 g), T9 (91.4 g), T6 (89.6 g), T2 (75.1 g), T3 (65.6 g) and T1 (57.7 g). As compared to control (T1), there was a significant percentage increase of fresh biomass in treatments T4 (90%), T7 (78.4%), T8 (69.9%), T5 (69.8%), T9 (58.4%), T6 (55.4%), T2 (30.2%) and T3 (13.8%).

Biochar had a considerable effect on dry biomass accumulation. During the 2023-2024 season, a significant impact of biochar on wheat was observed at various growth stages. However, at 60, DAS T4 and T7, while at 90 and 120, DAS T4, T7 and T8 showed a significant improvement in dry biomass compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum fresh biomass at 60 and 120 DAS, i.e., 16.2 g and 101.4 g, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum fresh biomass, i.e., 61.5 g. The maximum fresh biomass at 90 DAS was recorded in T7 (101.4 g), followed by T4 (101.1 g), T8 (95.8 g), T5 (95.3 g), T9 (91 g), T6 (89.3 g), T2 (523.6 g), T3 (74.4 g) and T1 (62 g). As compared to control (T1), there was a significant percentage increase of fresh biomass in treatments T7 (63.5%), T4 (63%), T8 (54.5%), T5 (53.8%), T9 (46.7%), T6 (44%), T2 (34.6%) and T3 (20%).

The mean dry biomass was found to be significant at all growth stages. However, at 60 DAS, T4, T7, and T8 were found to be more significant than all other treatments. At 120 DAS, T4 and T7 were found to be more significant than all other treatments. The maximum dry biomass at 120 DAS was recorded in T4 (105.4 g), followed by T7 (102.1 g), T8 (96.9 g), T5 (96.6 g), T9 (91.2 g), T6 (89.4 g), T2 (79.3 g), T3 (70 g) and T1 (59.8 g). As compared to control (T1), there was a significant percentage increase of dry biomass in treatments T4 (76.2%), T7 (70.7%), T8 (61.9%), T5 (61.5%), T9 (52.4%), T6 (49.5%), T2 (32.5%) and T3 (17%).

Table 4.8 Effect of different doses of biochar application on dry biomass (g) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 and 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	7.3^{f}	6.3^{f}	6.8^{f}	34.7^{f}	38^{e}	36.4^{f}	57.7^{g}	62^{f}	59.8^{f}
T_2	11.5^{d}	10.2^{d}	10.8^{d}	49^{d}	50.7^{c}	49.9^{d}	75.1^{e}	83.4^{d}	79.3^{d}
T_3	9.2^{e}	8.1^{e}	8.7^{e}	41.6^{e}	44.5^{d}	43^{e}	65.6^{f}	74.4^{e}	70.0^{e}
T_4	16.3^{a}	15.9^{ab}	16.1^{a}	68.7^{a}	61.5^{a}	65.1^{a}	109.7^{a}	101.1^{a}	105.4^{a}
T_5	14.2^{b}	14.1^{c}	14.1^{b}	61^{b}	57.9^{ab}	59.5^{b}	97.9^{bc}	95.3^{b}	96.6^{b}
T_6	13.2^{c}	13.4^{c}	13.3^{c}	55^{c}	54.4^{bc}	54.7^{c}	89.6^{d}	89.3^{c}	89.4^{c}
T_7	15.8^{a}	16.2^{a}	16.0^{a}	63.3^{b}	59.2^{ab}	61.3^{b}	102.9^{ab}	101.4^{a}	102.1^{a}
T_8	15.7^{a}	15.1^{b}	15.4^{a}	61.2^{b}	57.4^{ab}	59.3^{b}	98.0^{bc}	95.8^{ab}	96.9^{b}
T_9	13.8^{bc}	13.9^{c}	13.8^{bc}	56.2^{c}	54.4^{bc}	55.3^{c}	91.4^{cd}	91.0^{bc}	91.2^{c}
CD ($p\leq0.05$)	0.94	1.0	0.7	4.7	4.8	3.1	6.87	5.7	5.14
SEm (±)	0.31	0.33	0.24	1.55	1.6	1.04	2.29	1.9	1.71

***** Means denoted by different letters are significantly different at $p\leq0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

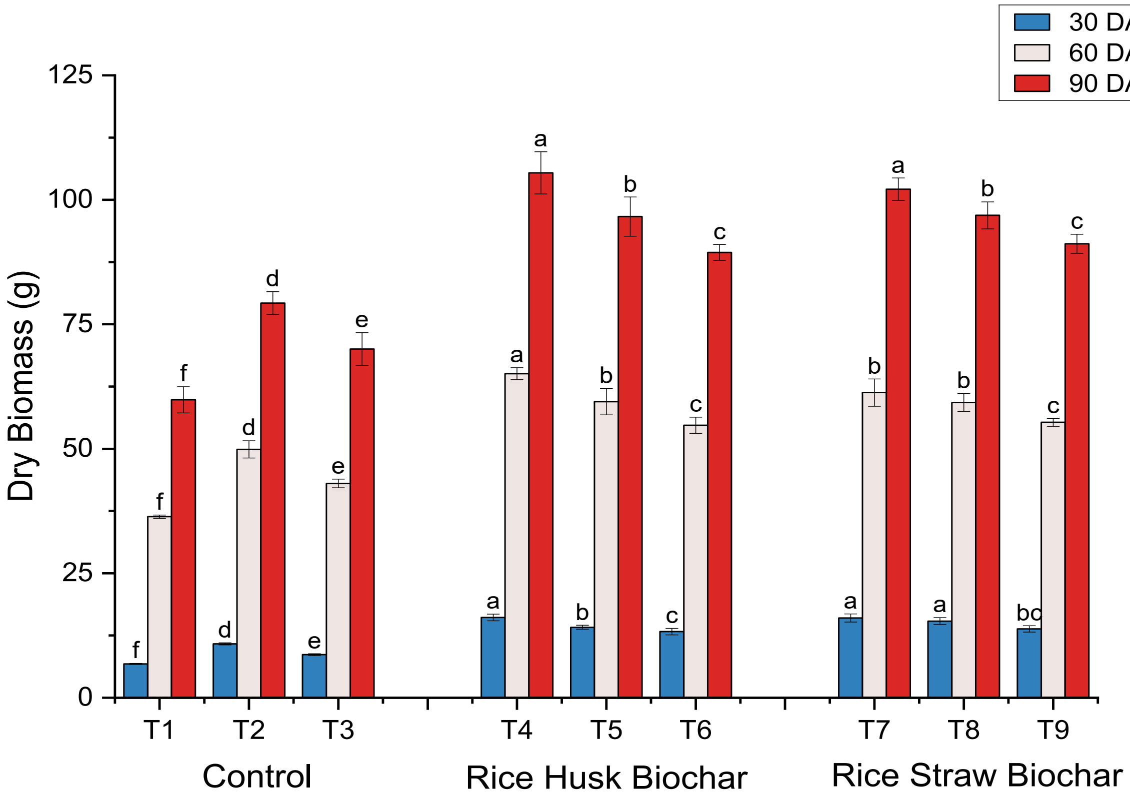


Figure 4.8. Effect of various biochar doses on dry biomass (g) of wheat at 30, 60, and 90 DAS.

A significant impact of biochar was observed on the growth rate of wheat throughout its various growth stages during the 2022-2023 season. The results are presented in **Table 4.9.** However, at 60 DAS, T4, T7, and T8 showed a significant improvement in crop growth rate, while at 120 DAS, T4, T5, T6, T7, T8, and T9 showed a significant improvement in crop growth rate compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum crop growth rate at 60, 90, and 120 DAS, i.e., 2.4, 7.8, and 6.1, respectively. The maximum crop growth rate at 120 DAS was recorded in T4 (6.1), followed by T7 (5.9), T5 (5.5), T8 (5.4), T9 (5.2), T6 (5.1), T2 (3.9), T3 (3.6) and T1 (3.4). Compared to the control (T1), a substantial percentage increase was recorded in crop growth rate in treatments T8 (78.8%), T7 (72.1%), T5 (60.8%), T6 (59.9%), T9 (53.1%), T6 (50.5%), T2 (13.6%) and T3 (4.6%).

The inclusion of biochar influences crop growth rate. During the 2023-2024 season, a significant impact of biochar on wheat crop growth rates was observed at various growth stages. However, at 60 DAS (T4 and T7), at 90 DAS (T4, T5, T6, T7, and T8), and at 120 DAS (T4, T5, T7, T8, and T9), significant improvements in crop growth rate were observed compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum crop growth rate at 60 and 120 DAS, i.e., 2.4 and 6.2, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in a maximum crop growth rate of 6.7. The maximum crop growth rate at 120 DAS was recorded in T7 (6.2), followed by T4 (5.9), T8 (5.7), T5 (5.5), T9 (5.4), T6 (5.2), T2 (4.8), T3 (4.4) and T1 (3.6). Compared to the control (T1), a substantial percentage increase was recorded in crop growth rate in treatments T7 (75.7%), T4 (65%), T8 (60.3%), T5 (56%), T9 (52.3%), T6 (45.2%), T2 (36.3%) and T3 (24.8%).

The mean crop growth rate was found to be significant at all growth stages. However, at 60 DAS, T4, T7 and T8 were found to be more significant than all other treatments. At 120 DAS, T4, T5, T6, T7 and T8 were found to be more significant than all other treatments. The maximum crop growth rate at 120 DAS was recorded in T7 (6.1), followed by T4 (6.0), T8 (5.6), T5 (5.5), T9 (5.3), T6 (5.1), T2 (4.4), T3 (4.0), and T1 (3.5). Compared to the control (T1), a substantial percentage increase was recorded in CGR in treatments T7 (74%), T4 (71.7%), T8 (60.1%), T5 (58.3%), T9 (52.7%), T6 (47.8%), T2 (25.2%) and T3 (14.9%).

Table 4.9 Effect of different doses of biochar application on crop growth rate (CGR) of wheat at 30, 60, 90 and 120 DAS during 2022-2023 and 2023-2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	1^{f}	0.9^{f}	1.0^{f}	4.1^{g}	4.7^{d}	4.4^{f}	3.4^{b}	3.6^{d}	3.5^{d}
T_2	1^{d}	1.5^{d}	1.6^{d}	5.6^{e}	6.0^{bc}	5.8^{d}	3.9^{b}	4.8^{bc}	$4.4b^{bc}$
T_3	1.3^{e}	1.2^{e}	1.3^{e}	4.8^{f}	5.4^{cd}	5.1^{e}	3.6^{b}	4.4^{cd}	4.0^{cd}
T_4	2.4^{a}	2.4^{ab}	2.4^{a}	7.8^{a}	6.7^{a}	7.3^{a}	6.1^{a}	5.9^{ab}	6.0^{ab}
T_5	2.1^{b}	2.1^{c}	2.1^{b}	6.9^{bc}	6.5^{ab}	6.7^{b}	5.5^{a}	5.5^{ab}	5.5^{ab}
T_6	1.9^{c}	2.0^{c}	2.0^{c}	6.2^{de}	6.1^{abc}	6.1^{cd}	5.1^{a}	5.2^{bc}	5.1^{bc}
T_7	2.3^{a}	2.4^{a}	2.4^{a}	7.0^{b}	6.4^{ab}	6.7^{b}	5.9^{a}	6.2^{a}	6.1^{a}
T_8	2.3^{a}	2.2^{b}	2.3^{a}	6.7^{bcd}	6.3^{ab}	6.5^{bc}	5.4^{a}	5.7^{ab}	5.6^{ab}
T_9	2.0^{bc}	2.1^{c}	2.0^{bc}	6.3^{cd}	6.0^{bc}	6.1^{cd}	5.2^{a}	5.4^{abc}	5.3^{abc}
CD ($p \leq 0.05$)	0.14	0.14	0.11	0.7	0.7	0.5	1.19	1.04	0.91
SEm (±)	0.04	0.04	0.036	0.21	0.24	0.15	0.39	0.34	0.3

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

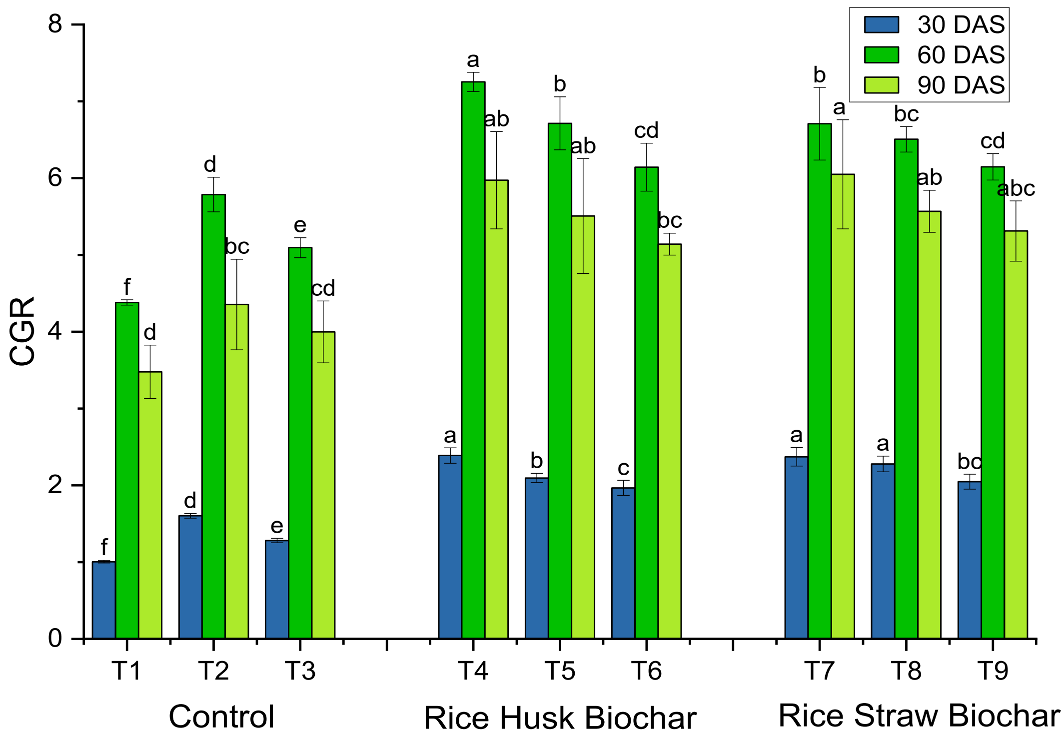


Figure 4.9. Effect of different biochar doses on CGR of wheat at 30, 60, and 90 DAS.

Biochar application has been widely recognised as an effective agronomic strategy to improve plant growth, including the plant height, number of tillers, leaf area, leaf area index (LAI), node diameter, stem diameter, fresh biomass, dry biomass, and crop growth rate (CGR) of wheat plants. Increasing wheat production is directly related to optimising growth characteristics such as plant height, number of tillers, leaf area, leaf area index (LAI), node diameter, stem diameter, fresh biomass, dry biomass, and crop growth rate. Increased plant height and tiller numbers enhance the photosynthetic surface area, thereby boosting light collection and biomass accumulation, which are crucial for achieving higher grain yields. Optimal LAI increases dry matter production, particularly during blooming, when photosynthesis is at its peak. Furthermore, larger stem and node widths improve structural integrity and nutrient delivery, whilst increased fresh and dry biomass indicates improved utilisation of resources. Ultimately, a higher CGR indicates improved growth efficiency, underscoring the importance of these metrics in enhancing wheat production. Our finding aligns with those of Murtaza et al. (2021) and Zulfiqar et al. (2022). Research has shown that biochar can lead to substantial increases in leaf area, with some studies reporting improvements of up to 73% compared to control treatments. One study reported a 23% increase in maize LAI when using finely ground biochar compared to larger particle sizes. (Xu et al., 2023; Wang et al., 2022).

The physiological enhancements lead to higher photosynthetic rates and improved plant metabolism, resulting in increased plant height and fresh and dry biomass of wheat plants. For instance, Research indicates that biochar can lead to substantial increases in wheat biomass when applied at a rate of 20 t ha–1, compared to control treatments. Improved stomatal conductance and transpiration rates associated with biochar application further support increased fresh biomass by optimising photosynthesis and nutrient transport within the plant. Furthermore, biochar has been shown to reduce oxidative stress in plants by enhancing the activities of antioxidant enzymes, which help maintain cellular health and promote growth under stress conditions. (Iqbal et al., 2022 Ali et al., 2022) Including biochar significantly improved the xylem and phloem at the maximum total chlorophyll content at 30, 60, 90, and 120 DAS, i.e., 0.70 mg/g, 1.50 mg/g, and 1.68 mg/g chlorophyll, hence improving rice stalk bending resistance. Our research also found that biochar treatment enhances node, internode diameter, and internode spacing in wheat plants. Furthermore, Miao et al. (2023) found that applying 30 t ha−1 of rice husk biochar increases stem thickness and wall density in rice cultivars by 18-21% and 28-32%, respectively. This enhancement is attributed to the co-deposition of silica, hemicellulose, and lignin in the cell walls, contributing to improved lodging resistance and yield. Overall, biochar enhances biological yield-biochar functions as both a sink and a source of most available nutrients for plant development and productivity. Similar results confirmed that Biochar treatment resulted in considerably enhanced leaf lengths, shoot length, leaf number, leaf breadth, and dry weight. This finding aligns with the observations of those who noted that using rice husk biochar enhanced the final biomass compared to non-biochar treatments. The 2% and 3% biochar applications significantly enhanced plant height, leaf length, shoot breadth, and dry weight compared to the control group. Several researchers have noted that biochar improves plant growth, increases shoot dry matter, and boosts the yield of various crops (Major et al., 2010). Biochar enhances soil properties and nutrient availability by modifying the soil's physical, chemical, and biological properties, which in turn influence the levels of nutrients in the soil and crop development (Murtaza et al., 2021). Biochar serves as a substrate for beneficial microbial communities, thereby enhancing soil enzyme activities and organic matter decomposition, which in turn contributes to nutrient cycling and uptake. For example, Lehmann et al. (2015) highlighted the role of biochar in promoting soil microbial activity, which directly impacts plant growth and biomass production. Research indicates that biochar application can increase fertile tiller counts by up to 17.14% compared to control treatments.

4.2 Physiological attributes

A significant impact of biochar was observed on the relative water content of wheat at different growth stages during the 2022-2023 season. The results are presented in **Table 4.10.** However, during 90 and 120 DAS, T4 and T7 showed a significant improvement in relative water content compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum relative water content at 30, 60, and 120 DAS, i.e., 92.6 %, 82.7%, and 66.2%, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum relative water content, i.e., 73.5%. The maximum relative water content at 120 DAS was recorded in T7 (66.2 %), followed by T4 (65.4%), T8 (63.6 %), T5 (63 %), T6 (61.7 %), T9 (61.3 %), T2 (58.2 %), T3 (53.8 %) and T1 (50.5 %). Compared to the control (T1), a substantial percentage increase was recorded in relative water content in treatments T7 (31.2%), T4 (29.5%), T8 (26.1%), T5 (24.8%), T6 (22.3%), T9 (21.5%), T2 (15.4%) and T3 (6.5%).

During the 2023-2024 season, a significant impact of biochar was observed on the relative water content of wheat during different growth stages. However, during 90 and 120 DAS, T4 and T7 showed a significant improvement in relative water content compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum relative water content at 30, 60, and 90 DAS, i.e., 91.2 %, 83.3%, and 72%, respectively. While at 120 DAS, treatment T7 (i.e. rice straw biochar @ 5 tons/ha) resulted in maximum relative water content, i.e. 68.3 %. The maximum relative water content at 120 DAS was recorded in T7 (68.3 %), followed by T4 (67.3 %), T8 (66.1 %), T5 (65.1 %), T6 (63.8 %), T9 (62.8 %), T2 (60.7 %), T3 (58.6 %) and T1 (56.4 %). Compared to the control (T1), a substantial percentage increase was recorded in relative water content in treatments T7 (21.2%), T4 (19.4%), T8 (17.2%), T5 (15.6%), T6 (13.2%), T9 (11.4%), T2 (7.6%) and T3 (4%).

The mean relative water content was found to be significant at all growth stages. Overall, when comparing all growth stages, the impact of T4 and T7 was found to be more significant than all other treatments. The maximum relative water content at 90 DAS was recorded in T7 (67.3 %), followed by T4 (66.3 %), T8 (64.9 %), T5 (64.1 %), T6 (62.8 %), T9 (62.1 %), T2 (59.5%), T3 (56.2 %) and T1 (53.4 %). Compared to the control (T1), a substantial percentage increase was recorded in relative water content in treatments T7 (25.9%), T4 (24.2%), T8 (21.4%), T5 (19.9%), T6 (17.5%), T9 (16.2%), T2 (11.3%) and T3 (5.2%). %).

Table 4.10 Effect of different doses of biochar application at relative water content (%) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	81.5^{f}	83.7^{g}	82.6^{e}	69.6^{g}	73.2^{h}	71.4^{f}	57.1^{f}	62.3^{f}	59.7^{f}	50.5^{g}	56.4^{h}	53.4^{f}
T_2	85.7^{d}	86.9^{e}	86.3^{c}	73.9^{e}	76.3^{f}	75.1^{d}	63.5^{d}	65.7^{d}	64.6^{d}	58.2^{e}	60.7^{f}	59.5^{d}
T_3	83.6^{e}	85.3^{f}	84.5^{d}	71.9^{f}	74.7^{g}	73.3^{e}	61.0^{e}	64.3^{e}	62.6^{e}	53.8^{f}	58.6^{g}	56.2^{e}
T_4	90.1^{b}	91.2^{a}	90.7^{a}	81.0^{b}	83.3^{a}	82.1^{a}	73.5^{a}	72.0^{a}	72.7^{a}	65.4^{ab}	67.3^{ab}	66.3^{a}
T_5	87.9^{c}	88.8^{bc}	88.4^{b}	79.4^{c}	79.8^{bc}	79.6^{b}	69.4^{b}	69.9^{b}	69.7^{b}	63.0^{cd}	65.1^{cd}	64.1^{b}
T_6	85.8^{d}	87.2^{de}	86.5^{c}	76.3^{d}	77.9^{de}	77.1^{c}	66.4^{c}	66.8^{cd}	66.6^{c}	61.7^{cd}	63.8^{de}	62.8^{c}
T_7	92.6^{a}	89.4^{b}	91.0^{a}	82.7^{a}	80.9^{b}	81.8^{a}	72.8^{a}	70.9^{ab}	71.9^{a}	66.2^{a}	68.3^{a}	67.3^{a}
T_8	89.4^{b}	88.0^{cd}	88.7^{b}	79.5^{bc}	78.7^{cd}	79.1^{b}	70.6^{b}	68.1^{c}	69.4^{b}	63.6^{bc}	66.1^{bc}	64.9^{b}
T_9	86.4^{d}	86.8^{e}	86.6^{c}	76.5^{d}	76.9^{ef}	76.7^{c}	65.8^{c}	67^{c}	66.4^{c}	61.3^{d}	62.8^{e}	62.1^{c}
CD ($p \leq 0.05$)	1.2	0.9	0.9	1.6	1.2	0.9	1.7	1.3	0.9	2.3	1.6	1.1
SEm (±)	0.4	0.3	0.3	0.5	0.4	0.3	0.6	0.4	0.3	0.8	0.5	0.4

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tonper centT6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

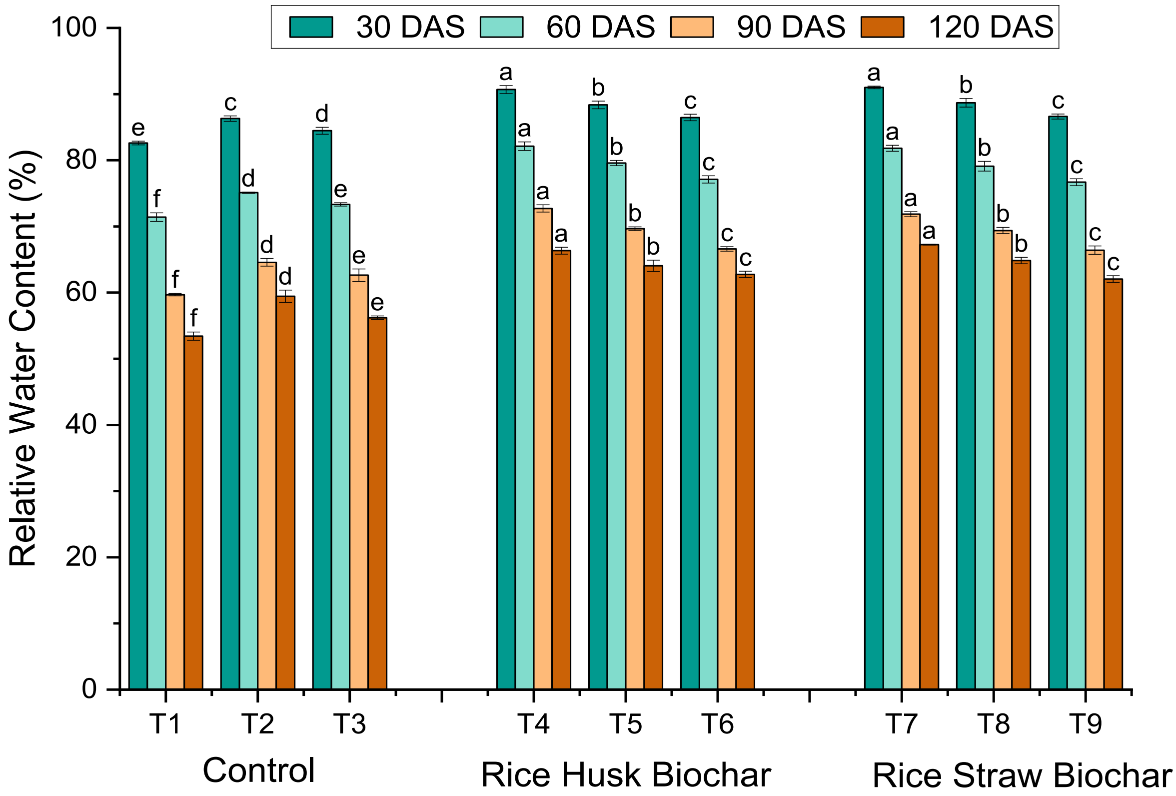


Figure 4.10. Effect of different biochar doses on RWC of wheat at 30, 60, 90, and 120 DAS.

The chlorophyll content of wheat was significantly altered by biochar at different growth stages during the 2022-2023 season. The results are shown in **Table 4.11.** However, during the 30-day assessment (T4, T5, T6, T7, T8, and T9) at 60 and 90 days after surgery (T4 and T7) and at 120 days after surgery (T4, T5, T6, T7, and T8), a significant improvement was observed compared to all other treatments. Among all treatments, T6 recorded the maximum total chlorophyll content at 30, 60, 90, and 120 DAS, i.e., 0.70 mg/g, 1.50 mg/g, 1.68 mg/g, and 1.71 mg/g, respectively. The maximum chlorophyll content at 90 DAS was recorded in T7 (1.68 mg/g) followed by T4 (1.62 mg/g), T8 (1.57 mg/g), T5 (1.52 mg/g), T9 (1.47 mg/g), T9 (1.43 mg/g), T2 (1.24 mg/g), T3 (1.08 mg/g) and T1 (0.84 mg/g). As compared to control (T1), there was a significant percent increase of chlorophyll content in treatments T7 (98.3%), T4 (90.6%), T8 (84.4%), T5 (79%), T9 (73.5%), T6 (68.6%), T2 (45.6%) and T3 (25.9%).

Subsequently, during the 2023-2024 season, however, both T4 and T7 showed a significant improvement in total chlorophyll compared to all other treatments at 30, 60, and 120 DAS. T4 recorded maximum total chlorophyll content at 30 and 60 DAS—i.e. 0.81 mg/g and 1.57 mg/g, respectively. At 90 and 120 DAS, treatment T7 resulted in the maximum total chlorophyll content, i.e., 1.74 mg/g and 0.47 mg/g, respectively. The maximum chlorophyll content at 90 DAS was recorded in T7 (1.74 mg/g) followed by T4 (1.66 mg/g), T8 (1.58 mg/g), T5 (1.57

mg/g), T6 (1.46 mg/g), T9 (1.45 mg/g), T2 (1.28 mg/g), T3 (1.07 mg/g) and T1 (0.84 mg/g). As compared to control (T1), there was a significant percentage increase of chlorophyll content in treatments T7 (107.5%), T4 (97.6%), T8 (87.7%), T5 (86.9%), T6 (73.8%), T9 (73%), T2 (52%) and T3 (28.2%).

The mean total chlorophyll content was found to be significant at all growth stages. Overall, at 30 DAS, T4, T5, T6 and T7 were found to be more significant than all other treatments. At 60 and 120 DAS, T4 and T7 were found to be more significant than all other treatments. The maximum total chlorophyll content at 90 DAS was recorded in T7 (1.71 mg/g) followed by T4 (1.64 mg/g), T8 (1.57 mg/g), T5 (1.54 mg/g), T9 (1.46 mg/g), T6 (1.45 mg/g), T2 (1.26 mg/g), T3 (1.07 mg/g) and T1 (0.84 mg/g). Compared to the control (T1), a substantial percentage increase was recorded in total chlorophyll content in treatments T7 (102.9%), T4 (94.1%), T8 (86.1%), T5 (82.9%), T9 (73.3%), T6 (71.2%), T2 (48.8%) and T3 (27%).

Table 4.11 Effect of different doses of biochar application on chlorophyll content (mg/g) of wheat at 30, 60, 90 and 120 DAS, during 2022-2023 & 2023-2024.

Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	0.41^{d}	0.43^{f}	0.42^{f}	0.69^{g}	0.61^{g}	0.65^{g}	0.85^{g}	0.84^{g}	0.84^{g}	0.10^{e}	0.16^{f}	0.13^{f}
T_2	0.56^{b}	0.69^{cd}	0.63^{d}	0.97^{e}	1.07^{e}	1.02^{e}	1.24^{e}	1.28^{e}	1.26^{e}	0.17^{bcd}	0.28^{d}	0.22^{d}
T_3	0.49^{c}	0.55^{e}	0.52^{e}	0.85^{f}	0.83^{f}	0.84^{f}	1.07^{f}	1.08^{f}	1.07^{f}	0.13^{de}	0.21^{e}	0.17^{e}
T_4	0.67^{a}	0.81^{a}	0.74^{a}	1.48^{a}	1.57^{a}	1.53^{a}	1.62^{ab}	1.66^{b}	1.64^{b}	0.20^{ab}	0.46^{a}	0.33^{a}
T_5	0.64^{a}	0.75^{b}	0.7^{abc}	1.38^{b}	1.36^{c}	1.37^{b}	1.52^{cd}	1.57^{c}	1.54^{c}	0.18^{abc}	0.40^{b}	0.29^{b}
T_6	0.70^{a}	0.73^{bc}	0.72^{ab}	1.20^{d}	1.24^{d}	1.22^{d}	1.43^{d}	1.46^{d}	1.45^{d}	0.21^{a}	0.35^{c}	0.28^{b}
T_7	0.65^{a}	0.77^{ab}	0.71^{abc}	1.50^{a}	1.54^{a}	1.52^{a}	1.68^{a}	1.74^{a}	1.71^{a}	0.19^{ab}	0.47^{a}	0.32^{a}
T_8	0.69^{a}	0.69^{cd}	0.69^{bc}	1.37^{b}	1.42^{b}	1.39^{b}	1.57^{bc}	1.58^{c}	1.57^{bc}	0.19^{ab}	0.39^{b}	0.29^{b}
T_9	0.66^{a}	0.67^{d}	0.67^{cd}	1.27^{c}	1.32^{c}	1.30^{c}	1.47^{cd}	1.45^{d}	1.46^{d}	0.15^{cd}	0.36^{c}	0.25^{c}
CD ($p \leq 0.05$)	0.07	0.06	0.05	0.06	0.05	0.04	0.10	0.07	0.07	0.04	0.03	0.03
SEm (±)	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.02	0.01	0.01	0.01

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

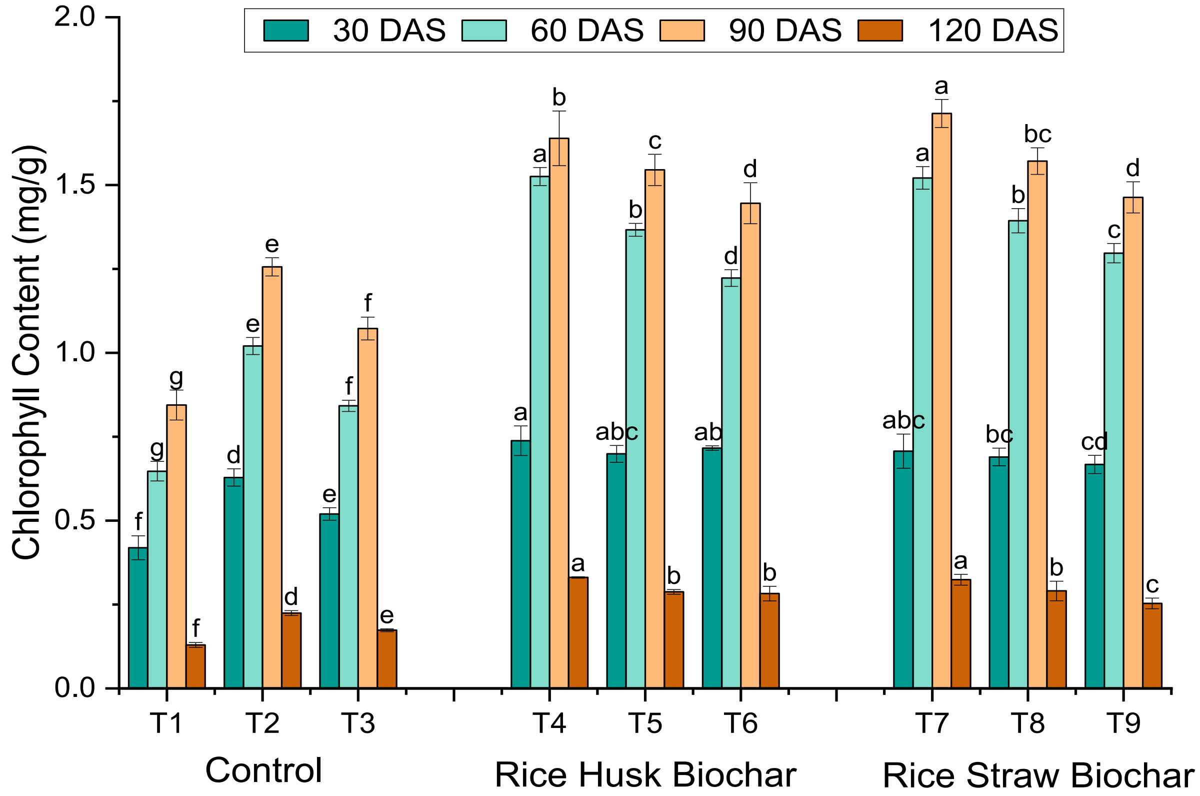


Figure 4.11. Effect of various biochar doses on chlorophyll (mg/g) of wheat at 30, 60, 90, & 120 DAS.

Membrane stability index of wheat during different growth stages. During the 2022-2023 season, a significant impact of biochar was observed on the s. The results are presented in **Table 4.12.** Throughout all growth stages, T4 and T7 showed a significant improvement in the membrane stability index compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum membrane stability index at 30 and 60 DAS, i.e., 77.4 and 84.7, respectively. At 90 and 120 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum membrane stability index, i.e., 86.9 and 70.6, respectively. The maximum membrane stability index was recorded at 120 DAS in T4 (70.6), followed by T7 (68.4), T5 (67.9), T8 (65.4), T6 (64.8), T9 (63.4), T2 (58.9), T3 (55.5), and T1 (52.2). Compared to the control (T1), a substantial percentage increase was recorded in membrane stability index in treatments T4 (35.1%), T7 (31%), T5 (30.1%), T8 (25.3%), T9 (24%), T6 (21.3%), T2 (12.7%) and T3 (6.3%).

In the 2023-2024 season, biochar had a considerable impact on the wheat membrane stability index. Throughout all growth stages, T4 and T7 showed a significant improvement in the membrane stability index compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum membrane stability index at 30 and 60 DAS, i.e., 75.5 and 80.7, respectively. At 90 and 120 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum membrane stability index, i.e., 85.4 and 69.6, respectively. The maximum membrane stability index was recorded at 120 DAS in T4 (69.6), followed by T7 (68.9), T5 (64.7), T8 (62.5), T6 (60.7), T9 (59.4), T2 (61.1), T3 (57.8), and T1 (54.9). Compared to the control (T1), a substantial percentage increase was recorded in membrane stability index in treatments T4 (26.9%), T7 (25.5%), T5 (17.9%), T8 (13.9%), T6 (10.7%), T9 (8.2%), T2 (11.4%) and T3 (5.3%).

The mean membrane stability index was significant at all growth stages. Overall, when comparing all growth stages, the impact of T4 and T7 was found to be more significant than all other treatments. The maximum total chlorophyll content was recorded at 120 DAS in T4 (70.1), followed by T7 (68.7), T5 (66.3), T8 (64.0), T6 (62.8), T9 (61.4), T2 (60.0), T3 (56.6), and T1 (53.6). Compared to the control (T1), a substantial percentage increase was recorded in total chlorophyll content in treatments T4 (30.9%), T7 (28.2%), T5 (23.8%), T8 (19.5%), T6 (17.2%), T9 (14.6%), T2 (12%) and T3 (5.8%).

Table 4.12: Effect of different doses of biochar application on the membrane stability index (%) of wheat at 30, 60, 90, and 120 DAS during 2022-2023 & 2023-2024.

Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	64.0^{e}	59.1^{e}	61.6^{f}	68.3^{e}	64.1^{e}	66.2^{g}	77^{e}	73.2^{e}	75.1^{f}	52.2^{g}	54.9^{e}	53.6^{g}
T_2	69.0^{cd}	66.2^{cd}	67.6^{d}	79.0^{c}	72^{cd}	75.6^{e}	81.2^{cd}	79^{cd}	80.1^{cd}	58.9^{e}	61.1^{bc}	60.0^{e}
T_3	67.0^{d}	63.6^{d}	65.3^{e}	72.9^{d}	66.8^{d}	69.9^{f}	78.5^{de}	76.5^{d}	77.5^{e}	55.5^{f}	57.8^{d}	56.6^{f}
T_4	76.9^{a}	73.2^{a}	75.0^{a}	82.7^{ab}	79.1a	80.9^{ab}	86.9^{a}	85.4^{a}	86.2^{a}	70.6^{a}	69.6^{a}	70.1^{a}
T_5	73.2^{b}	71.5^{b}	72.4^{b}	78.8^{c}	77.2^{b}	78.0^{cd}	84.4^{b}	83.7^{b}	84.1^{b}	67.9^{bc}	64.7^{b}	66.3^{b}
T_6	71^{c}	68.8^{c}	69.9^{c}	78.7^{c}	76.3^{c}	77.5^{cde}	81.4^{cd}	80.9^{c}	81.2^{cd}	64.8^{d}	60.7^{c}	62.8^{cd}
T_7	77.4^{a}	75.5^{a}	76.5^{a}	84.7^{a}	80.7^{a}	82.7^{a}	84.9^{ab}	83.7^{b}	84.3^{ab}	68.4^{ab}	68.9^{a}	68.7^{a}
T_8	73.8^{b}	72.1^{b}	73.0^{b}	80.9^{bc}	78.3^{b}	79.6^{bc}	82.6^{bc}	81.8^{c}	82.2^{bc}	65.4^{cd}	62.5^{b}	64.0^{c}
T_9	70.7^{c}	68.7^{c}	69.7^{c}	77.7^{c}	75.5^{c}	76.6^{de}	79.1^{de}	80.2^{bc}	79.6^{de}	63.4^{d}	59.4^{c}	61.4^{de}
CD ($p \leq 0.05$)	2	3.56	1.9	3.40	2.7	2.1	3.00	2.5	2.3	2.6	2.61	1.85
SEm (±)	0.67	1.18	0.62	1.14	0.91	0.71	1	0.81	0.75	0.86	0.87	0.61

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

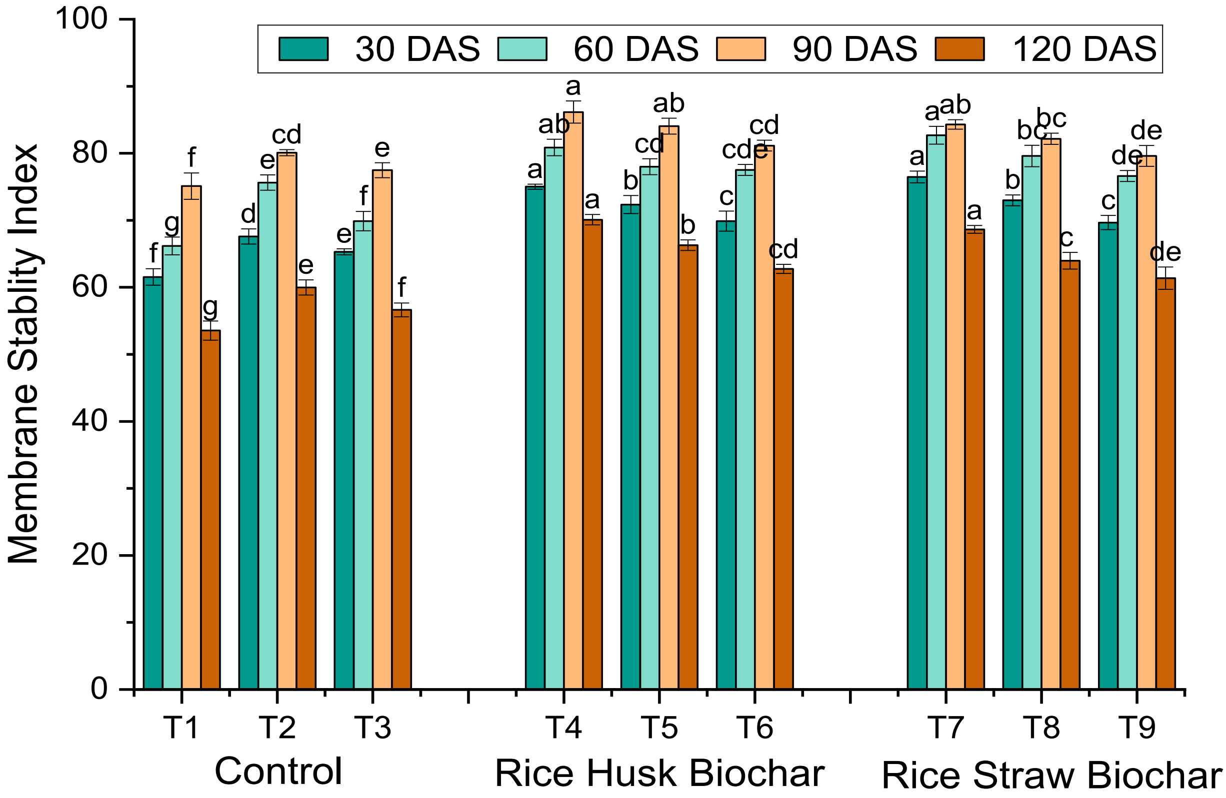


Figure 4.12. Effect of different biochar doses of biochar on MSI (%) of wheat at 30, 60, 90, and 120 DAS.

Characteristics such as relative water content (RWC), chlorophyll content, membrane stability index (MSI), and membrane injury index (MII) have a significant influence on wheat production. Increased RWC suggests improved water retention, which promotes photosynthesis and development, resulting in greater grain yields. Increased chlorophyll concentration is associated with higher photosynthetic efficiency, which directly influences biomass accumulation and yield potential. A greater MSI shows cellular integrity and tolerance to environmental stresses, enabling long-term development under bad conditions. In contrast, a lower MII indicates less cellular damage, which contributes to overall plant health. Optimising these physiological features can boost wheat output by enhancing stress tolerance and maximising resource utilisation throughout the development cycle. Applying biochar significantly increases the RWC, chlorophyll content, MSI and MII in wheat leaves through several physiological and biochemical mechanisms. Compared to the control group that did not receive biochar, Biochar additions increased wheat physiological parameters, including chlorophyll content. Similar results were confirmed by other authors (Laird et al., 2010; Agegnehu et al., 2016; Trupiano et al., 2017). The use of biochar enhances plant photosynthesis, increases the quantity of chlorophyll, and reduces the transpiration rate. Biochar application significantly boosted chlorophyll a, b, and total chlorophyll concentrations. A similar result was reported by Liu et al. (2024). Biochar can help mitigate the effects of environmental stresses, such as drought and salinity, which can negatively impact chlorophyll levels. By improving water use efficiency and reducing oxidative stress in plants, the application of biochar helps maintain higher chlorophyll content even under stressful conditions. Overall, the incorporation of biochar into wheat cultivation practices effectively enhances chlorophyll content, contributing to improved photosynthetic efficiency and overall plant productivity (Iqbal et al., 2022; Liu et al., 2024). The increased water availability helps maintain turgor pressure in plant cells, contributing to greater membrane integrity and stability. Furthermore, biochar has been shown to reduce oxidative stress in plants by decreasing the accumulation of reactive oxygen species (ROS) and enhancing the activities of antioxidant enzymes. This reduction in oxidative stress helps protect cellular membranes from damage, thereby improving MSI. Studies have demonstrated that applying biochar can lead to significant increases in MSI, with improvements reported under drought and salinity stress conditions. For instance, one study noted that biochar application resulted in a 22% increase in MSI under high-salinity conditions, highlighting its role in mitigating the stress effects on plant membranes.

This increased water availability directly contributes to higher RWC in leaves. Research has shown that biochar can improve the water-holding capacity of soils, allowing plants to maintain higher moisture levels even under drought conditions, which is crucial for sustaining leaf turgor and overall plant health. Moreover, biochar promotes beneficial microbial activity in the soil; Biochar can also affect microbes. It serves as a habitat, enhancing nutrient cycling and improving plant health. This microbial enhancement can lead to increased production of root exudates, which help retain moisture in the rhizosphere, thereby further supporting leaf hydration. By improving nutrient availability and reducing oxidative stress in plants, biochar application helps maintain cellular integrity and function, contributing to enhanced RWC. Biochar facilitates better root development and nutrient uptake, particularly nitrogen and phosphorus, key nutrients for chlorophyll synthesis. Studies have shown that biochar can significantly boost chlorophyll a and b levels, with increases of up to 19% for chlorophyll a and 22% for chlorophyll b under drought conditions compared to control treatments. The increased microbial activity supports chlorophyll production.

4.3 Yield attributes

Biochar considerably impacted wheat spike length during the 2022-2023 season, as shown in **Table 4.13**. Among the treatments, T4 and T7 significantly increased the spike length compared to other treatments. Among all treatments, T4 (i.e. rice husk biochar @ 5 tons/ha) recorded the maximum spike length. i.e. 16.7 cm. However, T4 and T7 showed a significant improvement in spike length compared to all other treatments. The maximum spike length was recorded in T4 (16.7 cm), followed by T7 (16.1 cm), T5 (15.7 cm), T8 (14.3 cm), T6 (13.7 cm), T9 (13.7 cm), T2 (13.3 cm), T3 (10.7 cm) and T1 (8.5 cm). Compared to the control (T1), a substantial percentage increase was recorded in spike length in treatments T4 (96.8%), T7 (89.8%), T5 (84.3%), T8 (68.6%), T6 (61.5%), T9 (61.5%), T2 (56.5%) and T3 (25.5%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar on wheat spike length was observed. Among the treatments, T4 and T7 significantly increased the spike length compared to other treatments. Among all treatments, T4 (i.e. rice husk biochar @ 5 tons/ha) recorded the maximum spike length. i.e. 17.1 cm. However, T4 and T7 showed a significant improvement in spike length compared to all other treatments. The maximum spike length was recorded in T4 (17.1 cm), followed by T7 (16.6 cm), T5 (15.9 cm), T8 (15.6 cm), T9 (15.1 cm), T6 (14.3cm), T2 (12.8 cm), T3 (10.9 cm) and T1 (8.8 cm). Compared to the control (T1), a substantial percentage increase was recorded in spike length in treatments T4 (93.9%), T7 (88.3%), T5 (80.3%), T8 (76.6%), T9 (71.3%), T6 (61.5%), T2 (44.5%) and T3 (23.4%). **Subsequently,** the mean spike length was significantly affected by the application of biochar. Among the treatments, T4 and T7 significantly increased the spike length compared to other treatments. The maximum spike length was recorded in T4 (16.9 cm), followed by T7 (16.4 cm), T5 (15.8 cm), T8 (15 cm), T9 (14.4 cm), T6 (14 cm), T2 (13 cm), T3 (10.8 cm) and T1 (8.7 cm). Compared to the control (T1), a substantial percentage increase was recorded in spike length in treatments T4 (95.4%), T7 (89%), T5 (82.3%), T8 (72.7%), T9 (66.5%), T6 (61.3%), T2 (50.3%) and T3 (24.4%).

Throughout the 2022-2023 season, biochar treatment had a considerable impact on wheat grain per spike. However, T4 and T7 showed a significant improvement in grain per spike compared to all other treatments. Among all treatments, T4 recorded the maximum grain per spike. i.e. (84.3) followed by T7 (80.5), T5 (78), T8 (70.7), T6 (68.7), T9 (63.4), T2 (61), T3 (54.9) and T1 (43.6). As compared to control (T1), there was a significant percentage increase of grain per spike in treatments T4 (93.3%), T7 (84.7%), T5 (78.8%), T8 (62.1%), T6 (57.5%), T9 (45.3%), T2 (39.8%) and T3 (26%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar was observed on the grain per spike of wheat. However, T4 and T7 showed a significant improvement in grain per spike compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum grain per spike. i.e. (81.1) followed by T7 (79.2), T5 (74.5), T8 (72.7), T6 (65.4), T9 (65.4), T2 (56.6), T3 (49.3) and T1 (33.3). As compared to control (T1), there was a significant percentage increase of grain per spike in treatments T4 (143.2%), T7 (137.6%), T5 (123.5%), T8 (118.1%), T6 (96.5%), T9 (96.3%), T2 (69.9%) and T3 (48%). **Subsequently,** the mean grain per spike was found to be significant at all growth stages. However, T4 and T7 showed a significant improvement in grain per spike compared to all other treatments. The maximum grain per spike was recorded in T4 (82.7 cm), followed by T7 (79.9cm), T5 (76.2 cm), T8 (71.7 cm), T6 (67.1 cm), T9 (64.4 cm), T2 (58.8 cm), T3 (52.1 cm) and T1 (38.5 cm). As compared to control (T1), there was a significant percentage increase of grain per spike in treatments T4 (114.9%), T7 (107.6%), T5 (98.2%), T8 (86.4%), T6 (74.4%), T9 (67.4%), T2 (52.9%) and T3 (35.5%).

A significant impact of biochar was observed on test weight during the 2022-2023 season. However, T4 and T7 showed a significant improvement in test weight compared to all other treatments. T4 (i.e., rice husk biochar @ 5 tons/ha) recorded the maximum test weight among all treatments. i.e. (49.3 g) followed by T7 (49 g), T5 (48.9 g), T8 (47.2 g), T6 (46.7 g), T9 (46.3 g), T2 (44.7 g), T3 (42.9 g) and T1 (40.8 g). Compared to the control (T1), a substantial percentage increase was recorded in test weight in treatments T4 (20.7%), T7 (20.1%), T5 (19.8%), T8 (15.6%), T6 (14.4%), T9 (13.5%), T2 (9.6%) and T3 (5.2%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar on test weight was observed. However, T4 and T7 showed a significant improvement in test weight compared to all other treatments. T4 (i.e., rice husk biochar @ 5 tons/ha) recorded the maximum test weight among all treatments. i.e. (49.4 g) followed by T7 (48.8 g), T8 (47.8 g), T5 (47.2 g), T6 (45.9 g), T9 (45.8 g), T2 (45.3 g), T3 (43.5 g) and T1 (41.7 g). Compared to the control (T1), a substantial percentage increase was recorded in test weight in treatments T4 (18.5%), T7 (17.1%), T8 (14.6%), T5 (13.3%), T6 (10.2%), T9 (10%), T2 (8.6%) and T3 (4.4%). **Subsequently,** the mean test weight was found to be significant at all growth stages. However, T4 and T7 showed a significant improvement in test weight compared to all other treatments. The maximum test weight was recorded in T4 (49.3 g), followed by T7 (48.9 g), T5 (48 g), T8 (47.5 g), T6 (46.3 g), T9 (46.1 g), T2 (45 g), T3 (43.2 g) and T1 (41.2 g). Compared to the control (T1), a substantial percentage increase was recorded in test weight in treatments T4 (19.6%), T7 (18.6%), T5 (16.5%), T8 (15.1%), T6 (12.2%), T9 (11.7%), T2 (9.1%) and T3 (4.8%).

Table 4.13 Effect of different doses of biochar application on spike length (cm), grain per spike and test weight (g) of wheat during 2022-2023 and 2023-2024.

Treatments	SPIKE LENGTH			GRAIN PER SPIKE			TEST WEIGHT		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	8.5^{f}	8.8^{h}	8.7^{h}	43.6^{g}	33.3^{g}	38.5^{g}	40.8^{e}	41.7^{e}	41.2^{f}
T_2	13.3^{d}	12.8^{f}	13.0^{f}	61.0^{e}	56.6^{e}	58.8^{e}	44.7^{c}	45.3^{c}	45.0^{d}
T_3	10.7^{e}	10.9^{g}	10.8^{g}	54.9^{f}	49.3^{f}	52.1^{f}	42.9^{d}	43.5^{d}	43.2^{e}
T_4	16.7^{a}	17.1^{a}	16.9^{a}	84.3^{a}	81.1^{a}	82.7^{a}	49.3^{a}	49.4^{a}	49.3^{a}
T_5	15.7^{b}	15.9^{bc}	15.8^{c}	78.0^{b}	74.5^{bc}	76.2^{b}	48.9^{a}	47.2^{b}	48.0^{b}
T_6	13.7^{cd}	14.3^{e}	14.0^{e}	68.7^{cd}	65.5^{d}	67.1^{d}	46.7^{b}	45.9^{c}	46.3^{c}
T_7	16.1^{ab}	16.6^{ab}	16.4^{b}	80.5^{ab}	79.2^{ab}	79.9^{ab}	49.0^{a}	48.8^{a}	48.9^{a}
T_8	14.3^{c}	15.6^{cd}	15.0^{d}	70.7^{c}	72.7^{c}	71.7^{c}	47.2^{b}	47.8^{b}	47.5^{b}
T_9	13.7^{cd}	15.1^{d}	14.4^{e}	63.4d^{e}	65.4^{d}	64.4^{d}	46.3^{b}	45.8^{c}	46.1^{c}
CD ($p\leq0.05$)	0.93	0.75	0.51	5.85	5.76	4.0	1.23	0.9	0.75
SEm (±)	0.31	0.25	0.17	1.95	1.92	1.36	0.4	0.3	0.25

***** Means denoted by different letters are significantly different at $p\leq0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

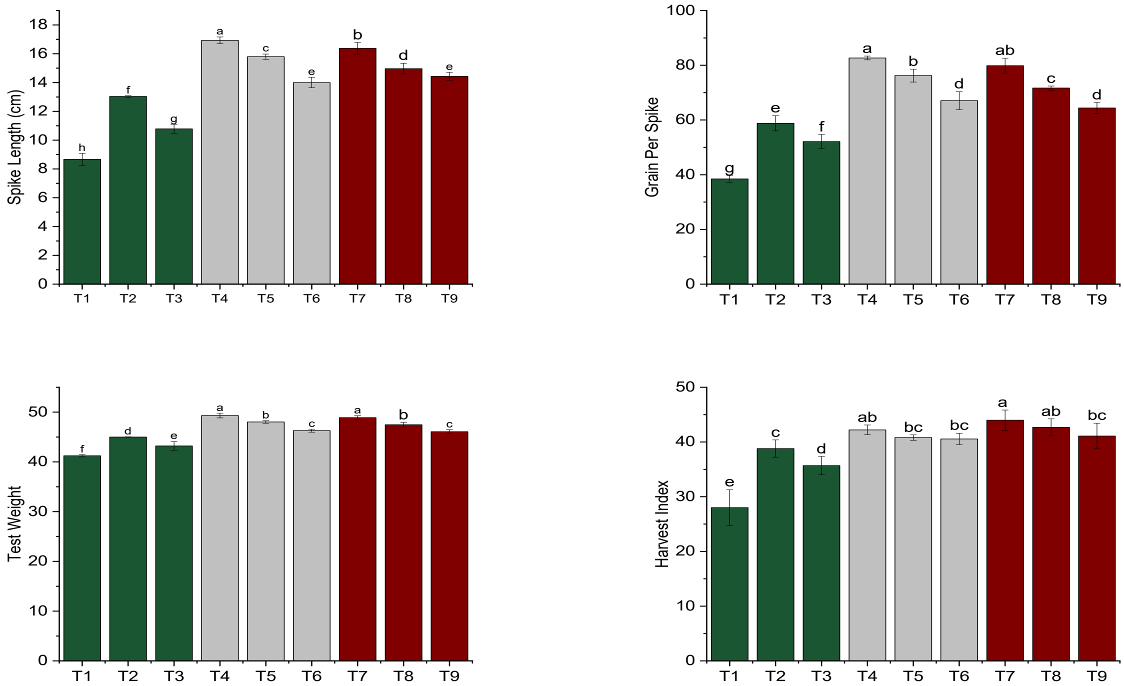


Figure 4.13: Effect of different biochar doses on yield traits of wheat crop

Biological yield was significantly affected by biochar treatment during the 2022-2023 season. The results are presented in **Table 4.14**. However, T4 and T7 showed a significant improvement in biological yield compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the highest biological yield. i.e. (157.8 q/ha) followed by T7 (156.3 q/ha), T5 (152 q/ha), T8 (149.4 q/ha), T6 (149.5 q/ha), T9 (143 q/ha), T2 (135.5 q/ha), T3 (125.4 q/ha) and T1 (94.4 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in biological yield in treatments T4 (67.1%), T7 (65.5%), T5 (60.9%), T6 (58.3%), T8 (58.2%), T9 (51.4%), T2 (43.4%) and T3 (32.7%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar on biological yield was observed. However, T4 and T7 showed a significant improvement in biological yield compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the highest biological yield. i.e. (160.6 q/ha) followed by T4 (156.2 q/ha), T5 (151.5 q/ha), T8 (151.4 q/ha), T6 (150.8 q/ha), T9 (144.5 q/ha), T2 (135 q/ha), T3 (123.6 q/ha) and T1 (96.5 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in biological yield in treatments T7 (66.4%), T4 (61.8%), T5 (57%), T8 (56.9%), T6 (56.2%), T9 (49.7%), T2 (39.9%) and T3 (28%). **Subsequently**, the mean biological yield was found to be significant at all growth stages. However, T4 and T7 showed a significant improvement in biological yield compared to all other treatments. The maximum biological yield was recorded in T7 (158.5 q/ha), followed by T4 (157 q/ha), T5 (151.8 q/ha), T8 (150.4 q/ha), T6 (150.2 q/ha), T9 (143.71 q/ha), T2 (135.3 q/ha), T3 (124.5 q/ha) and T1 (95.5 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in biological yield in treatments T7 (65.9%), T4 (64.5%), T5 (58.9%), T8 (57.5%), T6 (57.3%), T9 (50.5%), T2 (41.7%) and T3 (30.4%).

A significant impact of biochar was observed on grain yield during the 2022-2023 season. However, T4 and T7 showed a significant improvement in biological yield compared to all other treatments. Among all treatments, T7 (i.e., rice husk biochar at 5 tons/ha) recorded the highest grain yield. i.e. (70 q/ha) followed by T4 (66.8 q/ha), T8 (64.4 q/ha), T5 (62.4 q/ha), T6 (60.7 q/ha), T9 (58.2 q/ha), T2 (51.8 q/ha), T3 (43 q/ha) and T1 (27.1 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in grain yield in treatments T7 (158.6%), T4 (146.7%), T8 (137.8%), T5 (130.4%), T6 (124.3%), T9 (115.1%), T2 (91.5%) and T3 (58.7%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar on grain yield was observed. However, T4 and T7 showed a significant improvement in biological yield compared to all other treatments. Among all treatments, T7 (i.e., rice husk biochar at 5 tons/ha) recorded the highest grain yield. i.e. (69.3 q/ha) followed by T4 (65.8 q/ha), T8 (64 q/ha), T5

(61.5 q/ha), T6 (60.9 q/ha), T9 (59.8 q/ha), T2 (53.1 q/ha), T3 (45.8 q/ha) and T1 (26.1 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in grain yield in treatments T7 (165.3%), T4 (151.6%), T8 (144.7%), T5 (135.2%), T6 (133.5%), T9 (128.7%), T2 (103.2%) and T3 (75.2%). **Subsequently,** the mean grain yield was found to be significant at all growth stages. Among the treatments, T4 and T7 significantly increased the grain yield compared to other treatments. The maximum grain yield was recorded in T7 (69.7 q/ha), followed by T4 (66.3 q/ha), T8 (64.2 q/ha), T5 (61.9 q/ha), T6 (60.9 q/ha), T9 (59.8 q/ha), T2 (52.5 q/ha), T3 (44.4 q/ha) and T1 (26.6 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in grain yield in treatments T7 (191.9%), T4 (149.1%), T8 (141.2%), T5 (132.7%), T6 (128.8%), T9 (121.8%), T2 (97.2%) and T3 (66.8%).

Throughout the 2022-2023 season, a significant impact of biochar on straw yield was observed. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in straw yield compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the highest straw yield. i.e. (91.1 q/ha) followed by T5 (89.6 q/ha), T6 (88.8 q/ha), T7 (86.3 q/ha), T8 (85 q/ha), T9 (84.7 q/ha), T2 (83.6 q/ha), T3 (82.4 q/ha) and T1 (67.4 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in straw yield in treatments T4 (35.2%), T5 (33%), T6 (31.8%), T7 (28.1%), T8 (26.2%), T9 (25.8%), T2 (24.1%) and T3 (22.3%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar on straw yield was observed. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in straw yield compared to all other treatments. Among all treatments, T7 (i.e., rice husk biochar at 5 tons/ha) recorded the highest straw yield. i.e. (91.3 q/ha) followed by T4 (90.4 q/ha), T5 (90.1 q/ha), T6 (89.8 q/ha), T8 (87.4 q/ha), T9 (84.9 q/ha), T2 (81.9 q/ha), T3 (77.8 q/ha) and T1 (70.4 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in straw yield in treatments T7 (29.7%), T4 (28.5%), T5 (28%), T6 (27.6%), T8 (24.3%), T9 (20.4%), T2 (16.4%) and T3 (10.6%). **Subsequently,** the mean straw yield was significant at all growth stages. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in straw yield compared to all other treatments. The maximum straw yield was recorded in T4 (90.8 q/ha), followed by T5 (89.8 q/ha), T6 (89.3 q/ha), T7 (88.8 q/ha), T8 (86.2 q/ha), T9 (84.7 q/ha), T2 (82.8 q/ha), T3 (80.1 q/ha) and T1 (68.9 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in straw yield in treatments T4 (31.8%), T5 (30.4%), T6 (29.6%), T7 (28.9%), T8 (25.2%), T9 (23%), T2 (20.2%) and T3 (16.3%). Throughout the 2022-2023 season, a significant impact of biochar was observed on the harvest index. However, both T4, T7 and T8 showed a significant improvement in harvest index compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the highest harvest index. i.e. (44.8) followed by T8 (43.1), T4 (42.3), T9 (40.8), T6 (40.6), T2 (38.3), T3 (34.3) and T1 (28.7). Compared to the control (T1), a substantial percentage increase was recorded in harvest index in treatments T7 (56.2%), T8 (50.2%), T4 (47.6%), T5 (43.1%), T9 (42.2%), T6 (41.6%), T2 (33.5%) and T3 (19.4%). **Subsequently,** during the 2023-2024 season, a significant impact of biochar on the harvest index was observed. However, both T4, T5, T6, T7, T8 and T9 showed a significant improvement in harvest index compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the highest harvest index. i.e. (43.2) followed by T8 (42.3), T4 (42.1), T9 (41.4), T5 (40.6), T9 (40.5), T2 (39.3), T3 (37.1) and T1 (27.3). Compared to the control (T1), a substantial percentage increase was recorded in harvest index in treatments T7 (58%), T8 (54.6%), T4 (54%), T9 (51.4%), T5 (48.3%), T6 (48.1%), T2 (43.9%) and T3 (35.7%). **Subsequently,** the mean harvest index was found to be significant. However, T4, T7, and T8 showed a significant improvement in harvest index yield compared to all other treatments. The maximum harvest index was recorded in T7 (44), followed by T8 (42.7), T4 (42.2), T9 (41.1), T5 (40.8), T6 (40.6), T2 (38.8), T3 (35.7) and T1 (28). Compared to the control (T1), a substantial percentage increase was recorded in harvest index in treatments T7 (57.1%), T8 (52.4%), T4 (50.7%), T9 (46.7%), T5 (45.7%), T6 (44.8%), T2 (38.5%) and T3 (27.4%).

Several key parameters, including spike length, grains per spike, test weight, biological yield, grain yield, straw yield, and harvest index, heavily influence wheat productivity. Increasing the spike length increases the number of grains per spike, resulting in higher overall grain production. A higher test weight implies superior grain quality and density, which is critical for market value and storage stability. Improvements in biological yield represent the whole biomass generated, whereas grain yield measures only the harvested component, with straw yield providing significant biomass for soil health and livestock feed. The harvest index, which represents the ratio of grain yield to biological yield, measures resource allocation efficiency; optimising these factors together increases wheat production potential by improving photosynthetic efficiency and nutrient utilisation. Biochar application significantly affects these parameters. Our finding aligns with those of Ali et al. (2022). Research has demonstrated that biochar can substantially increase spike length; for instance, one study reported a 16.61% increase in spike length under drought conditions when biochar was applied compared to control treatments. Other studies have shown significant increases in grains per spike up to 13.89% when biochar is applied, especially under drought conditions. Studies indicate that biochar can increase grain yield by up to 15.7% and straw yield by 16.5%, demonstrating its effectiveness in boosting overall productivity.

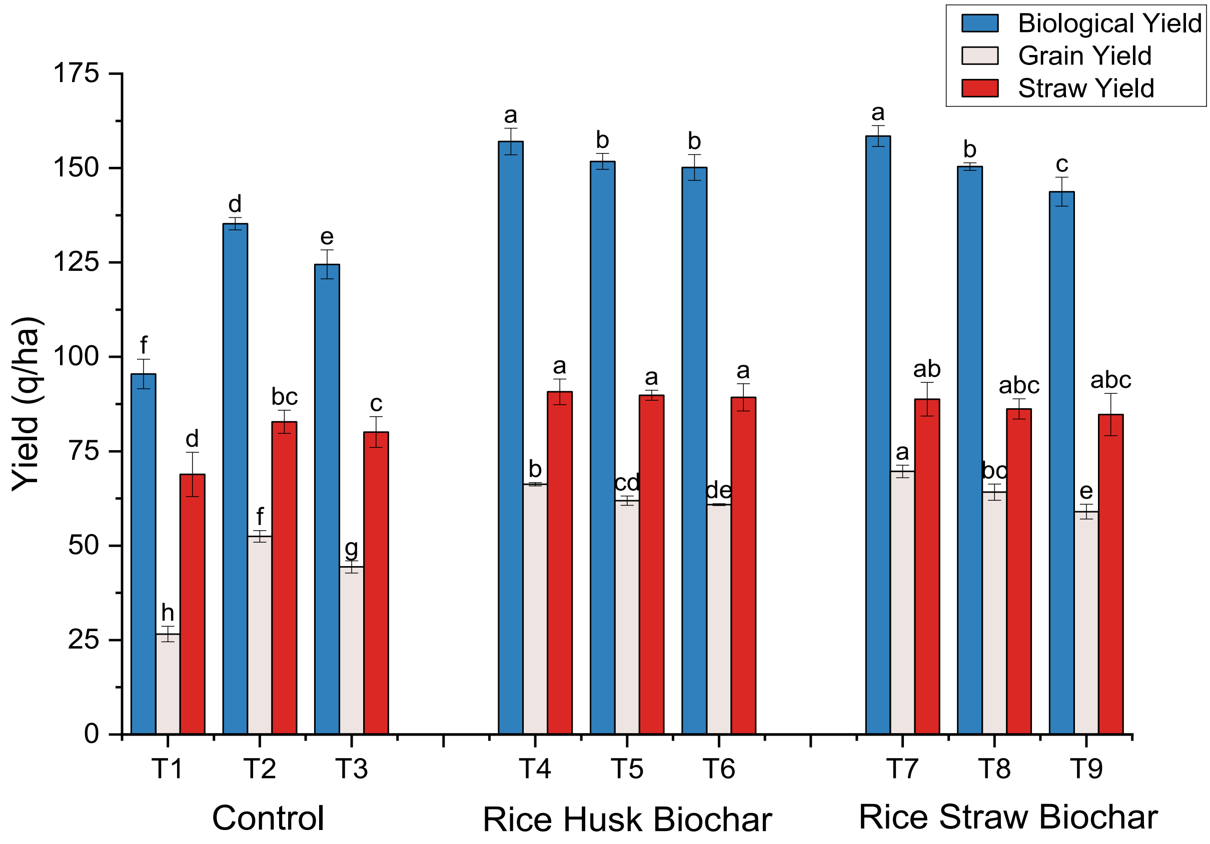


Figure 4.14. Effect of different biochar doses on biological, grain, and straw yield.

Moreover, biochar has been shown to mitigate the effects of environmental stresses, such as drought and salinity, allowing wheat plants to maintain their growth potential even under adverse conditions. By improving physiological parameters such as photosynthesis and transpiration rates, the application of biochar contributes to enhanced energy availability for spike formation. Biochar application enhances the number of grains per spike and test weight in wheat through several key mechanisms. Firstly, it improves soil fertility by increasing nutrient retention and availability, particularly for essential nutrients like nitrogen, phosphorus, and potassium, which support better spike development and grain filling. Collectively, these benefits contribute to higher grain yield attributes in wheat. The application of biochar significantly enhances biological yield, grain yield, straw yield, and harvest index in wheat through several interrelated mechanisms. Enhanced chlorophyll content and photosynthetic efficiency, resulting from biochar application, led to greater energy production, supporting robust growth and higher grain yields. Finally, the harvest index is defined as the ratio of grain yield to total biological yield, which is positively influenced by biochar as it encourages greater resource allocation towards grain production rather than vegetative growth. Overall, incorporating biochar into wheat cultivation practices effectively enhances biological yield, grain yield, straw yield, and harvest index through improved nutrient availability, water retention, root development, stress mitigation, and photosynthetic efficiency (Major et al., 2022).

Table 4.14 Effect of different doses of biochar application on biological yield (q/ha), grain yield (q/ha), straw yield (q/ha) and harvest index of wheat at harvest, during 2022-2023 and 2023-2024.

Treatments	BIOLOGICAL YIELD			GRAIN YIELD			STRAW YIELD			HARVEST INDEX		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T$_1$	94.4^{g}	96.5^{f}	95.5^{f}	27.1^{h}	26.1^{g}	26.6^{h}	67.4^{c}	70.4^{d}	68.9^{d}	28.7^{e}	27.3^{c}	28^{e}
T$_2$	135.5^{e}	135.0^{d}	135.3^{d}	51.8^{f}	53.1^{e}	52.5^{f}	83.6^{b}	81.9^{bc}	82.8^{bc}	38.3^{c}	39.3^{ab}	38.8^{c}
T$_3$	125.4^{f}	123.6^{e}	124.5^{e}	43.0^{g}	45.8^{f}	44.4^{g}	82.4^{b}	77.8^{cd}	80.1^{c}	34.3^{d}	37.1^{b}	35.7^{d}
T$_4$	157.8^{a}	156.2^{ab}	157^{a}	66.8^{ab}	65.8^{ab}	66.3^{b}	91.1^{a}	90.4^{a}	90.8^{a}	42.3^{ab}	42.1^{a}	42.2^{ab}
T$_5$	152^{bc}	151.5^{b}	151.8^{b}	62.4^{cd}	61.5^{cd}	61.9^{cd}	89.6^{ab}	90.1^{a}	89.8^{a}	41.1^{bc}	40.6^{ab}	40.8^{bc}
T$_6$	149.5^{c}	150.8^{b}	150.2^{b}	60.7^{de}	61.0^{cd}	60.9^{de}	88.8^{ab}	89.8^{ab}	89.3^{a}	40.6^{bc}	40.5^{ab}	40.6^{bc}
T$_7$	156.3^{ab}	160.6^{a}	158.5^{a}	70.0^{a}	69.3^{a}	69.7^{a}	86.3^{ab}	91.3^{a}	88.8^{ab}	44.8^{a}	43.2^{a}	44.0^{a}
T$_8$	149.4^{c}	151.4^{b}	150.4^{b}	64.4^{bc}	64.0^{bc}	64.2^{bc}	85^{ab}	87.4^{ab}	86.2^{abc}	43.1^{ab}	42.3^{a}	42.7^{ab}
T$_9$	143.0^{d}	144.5^{c}	143.7^{c}	58.2^{e}	59.8^{d}	59^{e}	84.7^{ab}	84.7^{abc}	84.7^{abc}	40.8^{bc}	41.4^{a}	41.1^{bc}
CD ($p \leq 0.05$)	5.57	6.11	4.7	3.4	3.7	2.6	7.26	8.025	6.41	3.12	3.87	2.9
SEm (±)	1.85	2.04	1.6	1.13	1.23	0.8	2.42	2.67	2.14	1.04	1.29	0.96

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

The benefit-cost ratio expresses the extent of benefit or profit earned by applying a particular treatment in relation to its cost. The calculations were performed for the different treatment combinations in both seasons, as presented in Table 4.15. During the 2022-2023 season, the highest benefit-cost ratio was recorded under treatment T7 (3.2), followed by T8 (2.7), T2 (2.6), T3 (2.2), T9 (2.2), T4 (2.0), T1 (1.6), T5 (1.3) and T6 (1.0). During the 2023-2024 season, the highest benefit-cost ratio was recorded under T7 (rice straw biochar @ 5 t/ha) (3.4), T2 (2.9), T8 (2.8), T2 (2.5), T9 (2.4), T4 (2.1), T1 (1.7), T5 (1.4) and T6 (1.1).

The maximum B: C ratio was achieved with rice straw biochar at 5 t ha^{-1} (T7), mainly because straw biochar has lower production and application costs than husk biochar, while also improving soil fertility and crop productivity. This balance of reduced input cost and increased yield response explains its economic advantage. T2 and 10 t ha^{-1} straw biochar (T8) also showed positive returns, indicating that balanced fertilisation and the intermediary use of biochar help maintain profitability. Conversely, higher levels of husk biochar (T5 and T6) were not economical due to increased cultivation costs, which offset the yield benefits. Medium-husk biochar (T4) and larger amounts of straw biochar (T9) provided only modest gains, again demonstrating that cost-effectiveness depends on both biochar type and quantity. In summary, the results suggest that rice straw biochar at a rate of 5 t ha^{-1} is most profitable for wheat production (Blackwell et al., 2010)

4.15 Effect of different doses of biochar application on Benefit-Cost Ratio (B: C ratio) of wheat.

Treatments	Cost of cultivation	2022-2023 season			2023-24 season		
		Gross return	Net return	B: C	Gross return	Net return	B: C
T_1	35910	57517	21607	1.6	57785	21875	1.7
T_2	42383	110146	67763	2.6	120120	77737	2.9
T_3	41083	91304	50221	2.2	100327.5	59244.5	2.5
T_4	71083	141879	70796	2.0	155155	84072	2.1
T_5	101083	132529	31446	1.3	137410	36327	1.4
T_6	131083	128988	-2095	1.0	141732.5	10649.5	1.1
T_7	46083	148750	102667	3.2	153562.5	107479.5	3.4
T_8	51083	136779	85696	2.7	143097.5	92014.5	2.8
T_9	56083	123746	67663	2.2	136272.5	80189.5	2.4

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

4.4 Soil attributes

Soil pH is a crucial characteristic that significantly influences crop development and production, as it regulates nutrient absorption, microbial activity, and overall soil health. During the 2022-2023 season, a significant impact of biochar on the soil pH was observed at various stages. The results are presented in **Table 4.16.** Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the highest pH. At 45 DAS, 90 DAS and at harvest, i.e. 8.3, 8.1 and 8.1, respectively. However, at 45 DAS (T4, T5, T6, T7, T8 & T9), at 90 DAS (T4, T5, T6 & T9), and at harvest (T5, T6, and T9), the soil pH showed a significant improvement compared to all other treatments. The maximum pH at harvest was recorded in T6 (8.1), followed by T5 (8), T8 (7.9), T9 (7.8), T7 (7.8), T4 (7.8), T2 (7.5), T3 (7.4) and T1 (7.3). As compared to control (T1), there was a significant percentage increase of pH in treatments T6 (10%), T8 (9.1%), T9 (7.7%), T4 (6.8%), T7 (6.4%), T9 (6.4%), T2 (1.8%) and T3 (0.9%). Throughout the 2023-2024 season, a significant impact of biochar on the soil pH was observed at various stages. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum pH at 45 DAS, 90 DAS, and the harvesting treatment T6 (i.e., rice husk biochar at 15 tons/ha) resulted in maximum pH levels of 8.4, 8.1, and 7.9, respectively. However, at 45 DAS (T5, T6, T7, T8, T9), at 90 DAS (T4, T5, T6, T7, T9) and at harvest (T4, T5, T6, T7, T8, T9) showed a significant improvement in soil pH compared to all other treatments. The maximum pH at harvest was recorded in T6 (7.9), followed by T5 (7.9), T9 (7.9), T4 (7.8), T7 (7.7), T8 (7.7), T2 (7.3), T3 (7.3) and T1 (7.2). As compared to control (T1), there was a significant percentage increase of pH in treatments T6 (9.7%), T5 (9.3%), T4 (7.9%), T9 (7.9%), T8 (6.9%), T7 (6.5%), T2 (1.9%) and T3 (1.4%).

The mean pH of the soil was found to be significant at all stages. However, at 45 DAS (T5, T6, T8, T9), at 90 DAS (T4, T5, T6 & T9), and at harvest (T4, T5, T6, T7, T8, T9), a significant improvement in soil pH was observed compared to all other treatments. The maximum pH of soil was recorded at harvest in T6 (8), followed by T5 (7.9), T4 (7.8), T9 (7.8), T8 (7.8), T7 (7.7), T2 (7.4), T3 (7.4) and T1 (7.3). Compared to the control (T1), a substantial percentage increase was recorded in the pH of the soil in treatments T6 (9.9%), T5 (9.2%), T8 (7.3%), T4 (7.3%), T9 (7.1%), T7 (6.4%), T2 (1.8%) and T3 (1.1%).

Maintaining ideal pH levels enhances the solubility of essential macronutrients and micronutrients necessary for plant physiological processes. Furthermore, soil pH affects the activity of beneficial soil microbes involved in nutrient cycling and the decomposition of organic matter, which are essential for sustaining soil fertility. As a result, maintaining soil pH within an acceptable range is critical for increasing agricultural output and supporting sustainable farming techniques. According to the results, biochar enhances soil pH through several processes that help neutralise soil acidity. One of the key reasons is the alkaline nature of biochar, which contains numerous basic cations, including calcium, magnesium, and potassium. (Kammann & Flessa, 2012). Adding biochar to acidic soils reduces acidity and raises soil pH by reacting with hydrogen ions (H^+) and aluminium ions (Al^{3+}). Biochar has been shown to dramatically alter the pH of acidic soils, with some studies indicating increases of 0.5 to 1 unit following application. Furthermore, during the pyrolysis process utilised for making biochar, alkaline minerals, such as carbonates and oxides, are produced, which enhances their potential to elevate soil pH. (Lehmann & Joseph, 2015).

Table 4.16: Effect of different doses of biochar application on soil pH at 45 DAS, 90 DAS, and harvest during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	7.2^b	7.2^c	7.2^c	7.4^c	7.2^c	7.3^c	7.3^d	7.2^b	7.3c
T_2	7.4^b	7.2^c	7.3^c	7.4^c	7.4^c	7.4^c	7.5^d	7.3^b	7.4b
T_3	7.3^b	7.5^c	7.4^c	7.5^c	7.4^c	7.4^c	7.4^d	7.3^b	7.4b
T_4	8.1^a	8.0^b	8.1^b	8.0^{ab}	8.1^a	8.0^{ab}	7.8^{bc}	7.8^a	7.8a
T_5	8.2^a	8.2^{ab}	8.2^{ab}	8.1^{ab}	7.9^{ab}	8.0^{ab}	8.0^{ab}	7.9^a	7.9a
T_6	8.3^a	8.4^a	8.4^a	8.1^a	8.1^a	8.1^a	8.1^a	7.9^a	8.0a
T_7	8.1^a	8.1^{ab}	8.1^b	7.8^b	8.0^{ab}	7.9^b	7.8^c	7.7^a	7.7ab
T_8	8.2^a	8.3^{ab}	8.3^{ab}	8.1^{ab}	7.7^b	7.9^b	7.9^{abc}	7.7^a	7.8a
T_9	8.1^a	8.2^{ab}	8.2^{ab}	8.0^{ab}	8.1^a	8.0^{ab}	7.8^c	7.8^a	7.8a
CD ($p \leq 0.05$)	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.2
SEm (±)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Initial value	7.4								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

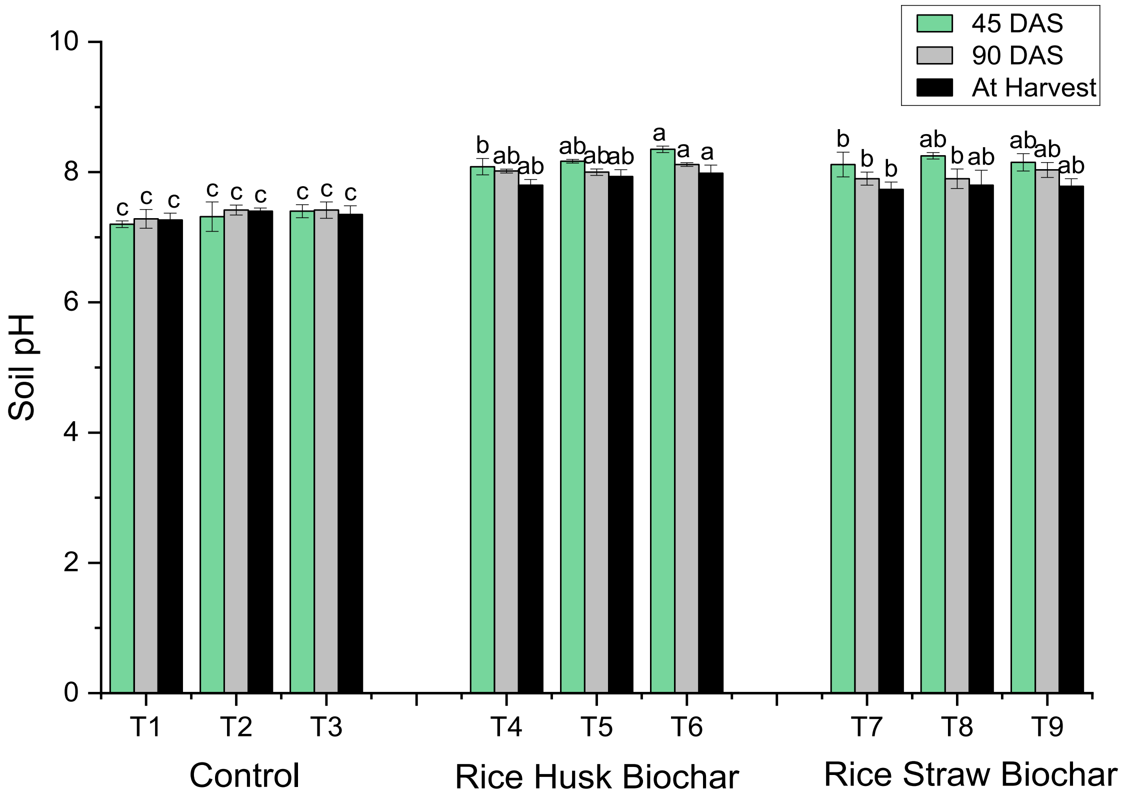


Figure 4.15. Effect of different biochar doses on soil pH under wheat at 45, 90 DAS and at harvest.

The electrical conductivity of the soil was significantly affected by biochar throughout various stages of the 2022-2023 season, as presented in **Table 4.17.** However, during the 45-day assessment (T4, T5, T8) and at 90 days after sowing (T4, T5, T6, T7, T8, T9), a significant improvement in soil electrical conductivity was observed compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum Electrical conductivity at 45 DAS and harvest, i.e., 0.37 and 0.28, respectively. While at 90 DAS treatment, T9 (i.e. rice straw biochar @ 15 tons/ha) resulted in maximum Electrical conductivity, i.e. 0.25 and at harvest, T6 revealed maximum EC (0.26). The maximum electrical conductivity at harvest was recorded in T5 (0.26), followed by T9 (0.24), T4 (0.22), T6 (0.21), T2 (0.21), T7 (0.20), T8 (0.20), T3 (0.16) and T1 (0.17). As compared to control (T1), there was a significant percentage increase of electrical conductivity in treatments T5 (51%), T9 (43.1%), T4 (29.4%), T2 (23.5%), T6 (23.5%), T7 (15.7%), T8 (15.7%) and T3 (9.8%).

Biochar considerably affected soil electrical conductivity at different stages during the 2023-2024 season. However, during 45 DAS (T4, T5, T6 & T7), at 90 DAS (T4, T5, T6 & T9) and at harvest (T5, T6, T7, T8 & T9) showed a significant improvement in electrical conductivity compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum Electrical conductivity at 45 DAS and 90 DAS, i.e., 0.29 and 0.24, respectively. During harvest, treatment with T9 (i.e., rice straw biochar at 15 tons/ha) resulted in the maximum Electrical conductivity, i.e., 0.25. The maximum Electrical conductivity at harvest was recorded in T9 (0.25), followed by T8 (0.24), T7 (0.24), T5 (0.22), T6 (0.21), T4 (0.20), T2 (0.19), T3 (0.16) and T1 (0.15). Compared to the control (T1), a substantial percentage increase was recorded in electrical conductivity in treatments T9 (64.4%), T7 (62.2%), T8 (60%), T5 (48.9%), T6 (42.2%), T4 (33.3%), T2 (24.4%) and T3 (8.9%).

The mean electrical conductivity of soil was found to be significant at all stages. However, during 45 DAS T4, T5, T6 and T7, at 90 DAS T4, T5, T6, T8 and T9, at harvest, T5, T6, T7, T8 and T9 showed a significant improvement in soil electrical conductivity compared to all other treatments. The maximum electrical conductivity of soil was recorded at harvest in T9 (0.25), followed by T5 (0.24), T7 (0.22), T8 (0.22), T4 (0.21), T6 (0.21), T2 (0.20), T3 (0.18) and T1 (0.16). Compared to the control (T1), a substantial percentage increase was recorded in the pH of the soil in treatments T9 (53.1%), T5 (50%), T7 (37.5%), T8 (36.5%), T6 (32.3%), T4 (31.3%), T2 (24%) and T3 (9.4%).

Soil electrical conductivity (EC) is crucial for evaluating soil health and its influence on crop yield. High EC values may indicate increased nutrient availability, promoting optimal plant development. Biochar application improves soil EC through a variety of processes. One necessary explanation is the inherent electrical conductivity of biochar itself, which can vary greatly depending on its feedstock and manufacturing circumstances. (Mia et al., 2014). When biochar is introduced to the soil, it contributes soluble salts and organic compounds that dissolve in water, increasing the soil solution's total EC level. Studies indicate that applying biochar at high rates (e.g., 120 t ha^{-1}) can raise soil EC by up to 14 times, owing to the release of soluble chemicals into the soil matrix. (Haq Nawaz et al., 2018). Furthermore, biochar enhances soil porosity and water retention, thereby improving the transport and availability of ions within the soil. The increased surface area and porosity promote more significant interaction between water and dissolved salts, contributing to higher EC levels.

Table 4.17 Effect of different doses of biochar application on soil electrical conductivity (mmhos/cm) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	0.13^{c}	0.15^{b}	0.14^{e}	0.15^{c}	0.16^{c}	0.16^{e}	0.17^{d}	0.15^{e}	0.16^{e}
T_2	0.16^{c}	0.19^{b}	0.18^{d}	0.19^{b}	0.18^{c}	0.18^{cd}	0.21^{bcd}	0.19^{cde}	0.20^{cd}
T_3	0.15^{c}	0.17^{b}	0.16^{de}	0.17^{bc}	0.17^{c}	0.17^{de}	0.19^{cd}	0.16^{de}	0.18^{de}
T_4	0.28^{a}	0.29^{a}	0.29^{a}	0.24^{a}	0.24^{a}	0.24^{a}	0.22^{bc}	0.20^{bcd}	0.21^{bc}
T_5	0.26^{ab}	0.31^{a}	0.28^{ab}	0.23^{a}	0.22^{ab}	0.23^{ab}	0.26^{a}	0.22^{abc}	0.24^{ab}
T_6	0.24^{b}	0.28^{a}	0.26^{abc}	0.25^{a}	0.20^{abc}	0.22^{ab}	0.21^{bcd}	0.21^{abc}	0.21^{bc}
T_7	0.23^{b}	0.28^{a}	0.26^{abc}	0.22^{a}	0.18^{bc}	0.20^{bc}	0.20^{cd}	0.24^{a}	0.22^{abc}
T_8	0.25^{ab}	0.25^{a}	0.25^{bc}	0.24^{a}	0.20^{abc}	0.22^{ab}	0.20^{cd}	0.24^{ab}	0.22^{abc}
T_9	0.23^{b}	0.26^{a}	0.24^{c}	0.25^{a}	0.18^{bc}	0.22^{ab}	0.24^{cd}	0.25^{a}	0.25^{a}
CD ($p \leq 0.05$)	0.03	0.06	0.03	0.03	0.05	0.03	0.05	0.04	0.03
SEm (±)	0.01	0.02	0.01	0.01	0.02	0.00	0.02	0.01	0.01
Initial value	0.17								

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

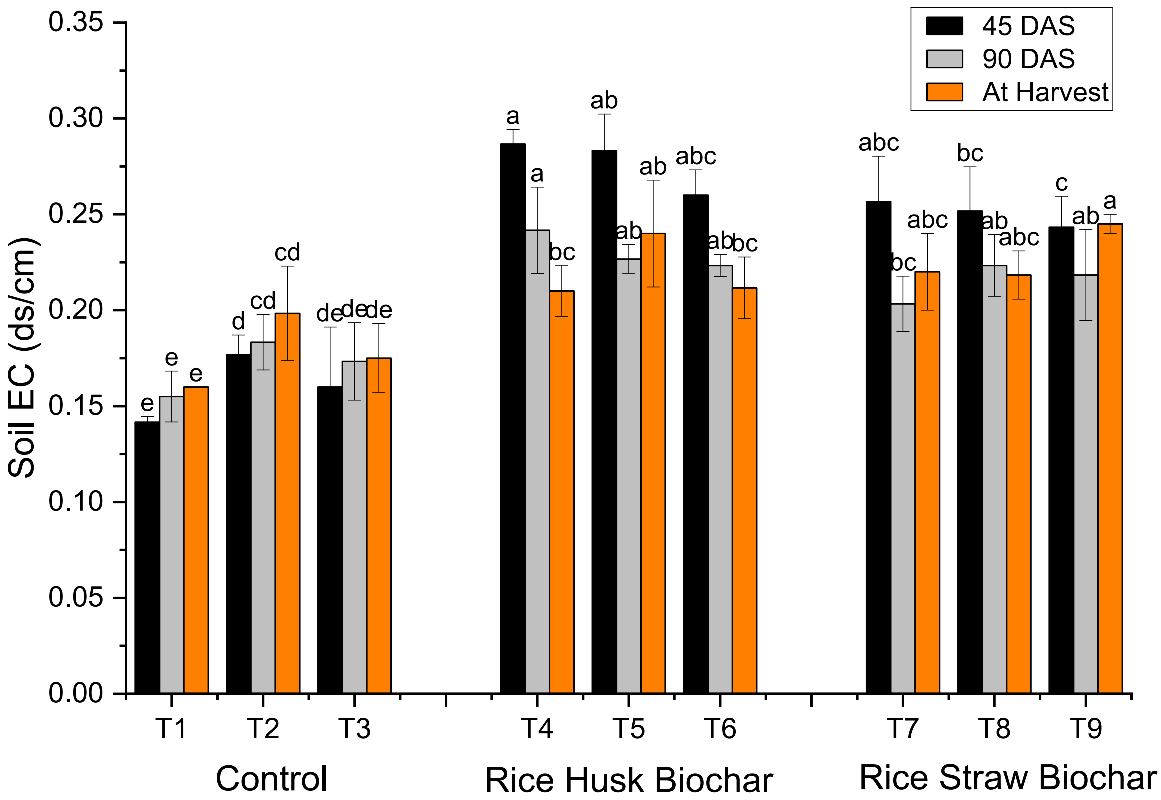


Figure 4.16. Effect of different biochar doses on soil EC (ds/cm) at 45 and 90 DAS and at harvest.

Soil organic carbon (SOC) promotes plant development and production by improving soil fertility and structure. During the 2022-2023 season, a significant impact of biochar on soil organic carbon was observed at different stages. The results are presented in **Table 4.18.** However, at 45 DAS (T5 & T6), at 90 DAS (T4 & T6), and at harvest (T2, T4, T5, T6, T7, T8 & T9), significant improvements in soil organic carbon were observed compared to all other treatments. Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the maximum organic carbon at 45 DAS, 90 DAS, and at harvest, i.e., 0.65, 0.58, and 0.54, respectively. The maximum organic carbon content at harvest was recorded in T6 (0.54), followed by T9 (0.53), T4 (0.53), T8 (0.51), T5 (0.51), T7 (0.49), T2 (0.50), T3 (0.42), and T1 (0.39). As compared to control (T1), there was a significant percentage increase of organic carbon in treatments T6 (38.8%), T4 (37.9%), T9 (36.2%), T8 (31%), T5 (31%), T7 (27.6%), T2 (29.3%) and T3 (8.6%).

Throughout the 2023-2024 season, a significant impact of biochar on soil organic carbon was observed at various stages of development. However, at 45 DAS (T4, T5, T6, T7, T8 & T9), at 90 DAS (T4, T6, T7, T8 & T9) and at Harvest (T4, T5, T6, T7, T8 & T9) showed a significant improvement in soil organic carbon compared to all other treatments. Among all treatments, T5 (45 DAS), T4 (90 DAS), and T9 (at harvest) recorded the highest organic carbon levels, i.e., 0.66, 0.54, and 0.56, respectively. The maximum organic carbon at harvest was recorded in T9 (0.56), followed by T5 (0.55), T6 (0.55), T8 (0.54), T4 (0.52), T7 (0.51), T2 (0.47), T3 (0.44) and T1 (0.44). As compared to control (T1), there was a significant percentage increase of organic carbon in treatments T9 (29%), T5 (26.7%), T6 (25.2%), T8 (22.9%), T4 (19.8%), T7 (16%), T2 (6.9%) and T3 (1.5%).

The mean electrical conductivity of soil was found to be significant at all stages. However, at 45 DAS (T4, T5, T6, T7, T8 & T9), at 90 DAS (T4, T6, T7, T8 & T9) and at Harvest (T4, T5, T6, T7, T8 & T9) showed a significant improvement in soil organic carbon compared to all other treatments. The maximum electrical conductivity of soil was recorded at harvest in T9 (0.55), followed by T6 (0.54), T4 (0.53), T5 (0.53), T8 (0.52), T7 (0.50), T2 (0.48), T3 (0.43) and T1 (0.41). As compared to control (T1), there was a significant percentage increase of soil organic carbon in treatments T9 (32.4%), T6 (31.6%), T5 (28.7%), T4 (28.3%), T8 (26.7%), T7 (21.5%), T2 (17.4%) and T3 (4.9%).

Organic carbon serves as a reservoir for critical nutrients, thereby increasing their availability while reducing leaching losses. SOC also enhances water retention and aeration, creating an ideal environment for root growth. It promotes the activity of beneficial soil microorganisms involved in nutrient cycling and the breakdown of organic matter. Overall, higher levels of soil organic carbon lead to healthier soils and increased agricultural yields. According to the data, biochar application enhances soil organic carbon through various processes. Initially, biochar is high in carbon, and its addition to soil increases the overall organic carbon content of the soil. Biochar treatment may significantly raise SOC levels, with one research indicating an average increase of 13.0 Mg ha^{-1}, resulting in a 29% increase in SOC stocks. (Mia et al., 2024). Additionally, biochar increases soil structure and porosity, thereby enhancing the habitat for soil microorganisms. The microbial activity promotes the decomposition of organic matter and the formation of stable organic compounds, thereby contributing to an increase in the percentage of organic carbon. A similar result was revealed by Ibrahim et al. (2024). Furthermore, biochar can influence nutrient cycling by enhancing the availability of key nutrients, particularly nitrogen and phosphorus.

Table 4.18 Effect of different doses of biochar application on soil organic carbon (%) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	0.44^{d}	0.48^{c}	0.46^{c}	0.41^{e}	0.33^{e}	0.37^{d}	0.39^{b}	0.44^{c}	0.41^{c}
T_2	0.48^{d}	0.53^{bc}	0.51^{c}	0.46^{cde}	0.43^{bcd}	0.45^{bc}	0.50^{a}	0.47^{bc}	0.48^{b}
T_3	0.47^{d}	0.50^{c}	0.49^{c}	0.44^{de}	0.35^{de}	0.40^{cd}	0.42^{b}	0.44^{c}	0.43^{c}
T_4	0.59^{bc}	0.61^{a}	0.60^{ab}	0.54^{ab}	0.54^{a}	0.54^{a}	0.53^{a}	0.52^{ab}	0.53^{ab}
T_5	0.62^{ab}	0.66^{a}	0.64^{a}	0.51^{bc}	0.51^{cde}	0.51^{bc}	0.51^{a}	0.55^{a}	0.53^{a}
T_6	0.65^{a}	0.63^{a}	0.64^{a}	0.58^{a}	0.48^{abc}	0.53^{a}	0.54^{a}	0.55^{a}	0.54^{a}
T_7	0.55^{c}	0.59^{ab}	0.57^{b}	0.49^{bcd}	0.47^{abc}	0.48^{ab}	0.49^{a}	0.51^{ab}	0.50^{ab}
T_8	0.57^{bc}	0.58^{ab}	0.58^{b}	0.52^{bc}	0.52^{ab}	0.52^{a}	0.51^{a}	0.54^{a}	0.52^{ab}
T_9	0.60^{bc}	0.65^{a}	0.63^{a}	0.50^{bcd}	0.53^{a}	0.52^{a}	0.53^{a}	0.56^{a}	0.55^{a}
CD ($p \leq 0.05$)	0.06	0.08	0.05	0.06	0.10	0.06	0.06	0.06	0.05
SEm (±)	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.02

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biocon the soil's available nitrogen was observed at variousa), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

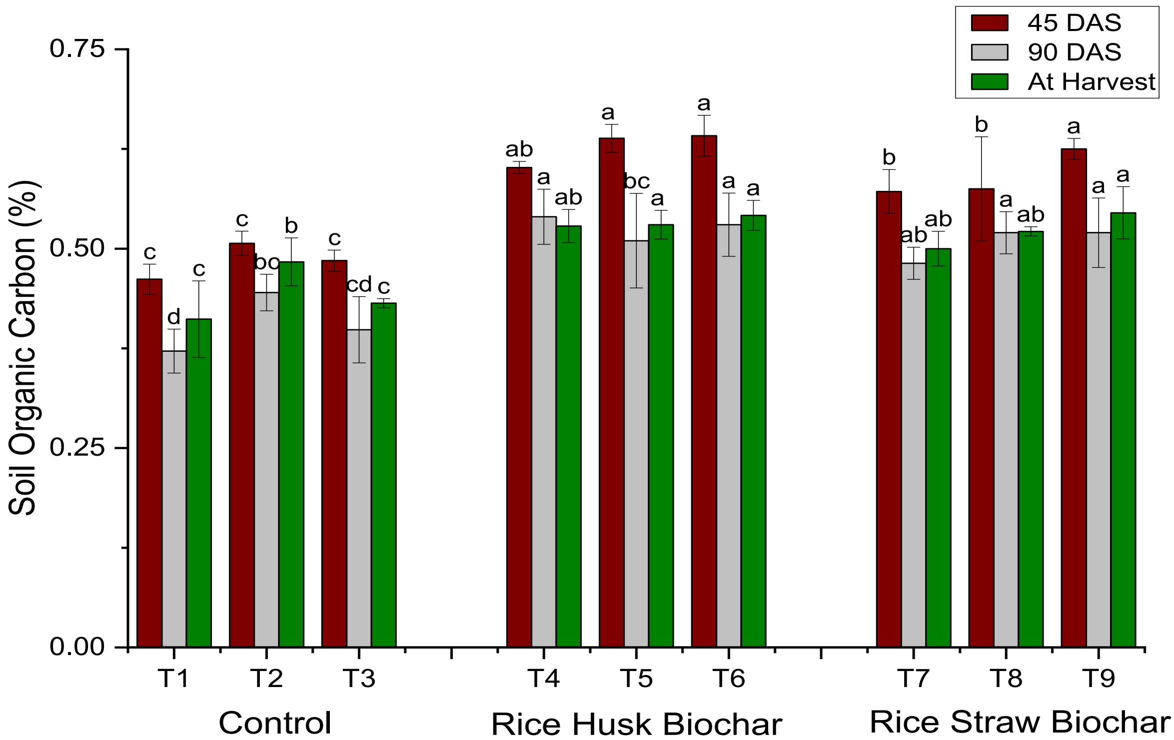


Figure 4.17. Effect of different biochar doses on soil organic carbon (%) at 45 and 90 DAS and at harvest.

The results in **Table 4.19** demonstrate the considerable influence of biochar on soil available nitrogen at different stages during the 2022-2023 season. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum available nitrogen at 45 DAS, 90 DAS, and harvest, i.e., 454.7 kg/ha, 364.5 kg/ha, and 245.7 kg/ha, respectively. The maximum available nitrogen at harvest was recorded in T4 (245.7 kg/ha) followed by T5 (233.9 kg/ha), T7 (231.3 kg/ha), T8 (219.5 kg/ha), T6 (213 kg/ha), T9 (205.2 kg/ha), T2 (201.2 kg/ha), T3 (198.6 kg/ha) and T1 (180 kg/ha). As compared to control (T1), there was a significant percentage increase of available nitrogen in treatments T4 (36.5%), T5 (29.9%), T7 (28.5%), T8 (21.9%), T6 (18.3%), T9 (14%), T2 (11.8%) and T3 (10.4%).

Throughout the 2023-2024 season, a significant impact of biochar on the soil's available nitrogen was observed at various stages of growth. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum available nitrogen at 45 DAS, 90 DAS, and at harvest, i.e., 431.2 kg/ha, 348.9 kg/ha, and 270.5 kg/ha, respectively. The maximum available nitrogen at harvest was recorded in T4 (270.5 kg/ha) followed by T6 (258.7 kg/ha), T5 (240.4 kg/ha), T8 (227.4 kg/ha), T6 (215.6 kg/ha), T9 (203.9 kg/ha), T2 (192.1 kg/ha), T3 (185.5 kg/ha) and T1 (184.4 kg/ha). As compared to control (T1), there was a significant percentage increase of available nitrogen in treatments T4 (46.8%), T7 (40.4%), T5 (30.5%), T8 (23.4%), T6 (17%), T9 (10.7%), T2 (4.3%) and T3 (0.7%).

The mean available nitrogen of the soil was found to be significant at all stages. The maximum available nitrogen of soil was recorded at harvest in T4 (258.1 kg/ha) followed by in the soil was recorded at harvest in T5 (16.6), followed by T9 (16.4), T8 (16.4), T6 (16.2), T4 (15.8), T7 (14.3), T3 (12.3), T2 (11.9),2.1 kg/ha). Compared to the control (T1), a substantial percentage increase was recorded in available nitrogen of soil in treatments T4 (41.7%), T7 (34.5%), T5 (30.2%), T8 (22.7%), T6 (17.7%), T9 (12.3%), T2 (8%) and T3 (5%).

Soil nitrogen availability is crucial for enhancing wheat growth and productivity, as it directly regulates essential physiological processes. Adequate nitrogen levels stimulate vigorous vegetative development, resulting in enhanced tillering. Nitrogen promotes increased grain output by increasing the number of heads per square foot and enhancing seed size. Nitrogen is also essential for chlorophyll production, which improves photosynthetic efficiency and overall plant vigour. Therefore, proper soil nitrogen management is crucial for enhancing wheat yield and ensuring sustainable agricultural practices. As a result, biochar application enhances the nitrogen availability in soil. Biochar improves nitrogen mineralisation and nitrification rates, which are essential processes for converting organic nitrogen into plant-available forms. Studies have shown that biochar application can significantly increase nitrogen mineralisation by approximately 15.3% and nitrification rates by about 48.5% compared to control treatments (Zhang et al., 2021).

Table 4.19 Effect of different doses of biochar application on soil available nitrogen (kg/ha) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**
T$_1$	215.6^{h}	207.8^{g}	211.7^{h}	203.9^{h}	196^{g}	199.9^{h}	180^{f}	184.2^{h}	182.1^{h}
T$_2$	364.5^{g}	367.2^{e}	365.8^{f}	260.0^{f}	263.9^{f}	262.0^{f}	201.2^{e}	192.1^{g}	196.7^{g}
T$_3$	363.3^{g}	346.3^{f}	354.8^{g}	240.4^{g}	258.7^{f}	249.6^{g}	198.6^{e}	185.5^{gh}	192.1^{g}
T$_4$	454.7^{a}	431.2^{a}	443.0^{a}	364.5^{a}	348.9^{a}	356.7^{a}	245.7^{a}	270.5^{a}	258.1^{a}
T$_5$	419.4^{c}	398.5^{c}	409.0^{c}	321.4^{c}	337.1^{b}	329.3^{c}	233.9^{b}	240.4^{c}	237.2^{c}
T$_6$	397.2^{e}	382.8^{d}	390.0^{d}	278.3^{e}	321.4^{c}	299.9^{e}	213.0^{cd}	215.6^{e}	214.3^{e}
T$_7$	443.0^{b}	415.5^{b}	429.2^{b}	348.9^{b}	333.2^{b}	341.1^{b}	231.3^{b}	258.7^{b}	245.0^{b}
T$_8$	409.0^{d}	385.5^{d}	397.3^{d}	313.6^{c}	309.7^{d}	311.6^{d}	219.5^{c}	227.4^{d}	223.4^{d}
T$_9$	381.5^{f}	372.4^{e}	376.9^{e}	290.1^{d}	295.3^{e}	292.7^{e}	205.2^{de}	203.9^{f}	204.5^{f}
CD ($p \leq 0.05$)	10.27	10.28	6.6	11.00	10.59	8.3	9.35	7.61	7.5
SEm (±)	3.42	3.43	2.2	3.67	3.53	2.75	3.12	19.36	2.51
Initial value	176								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

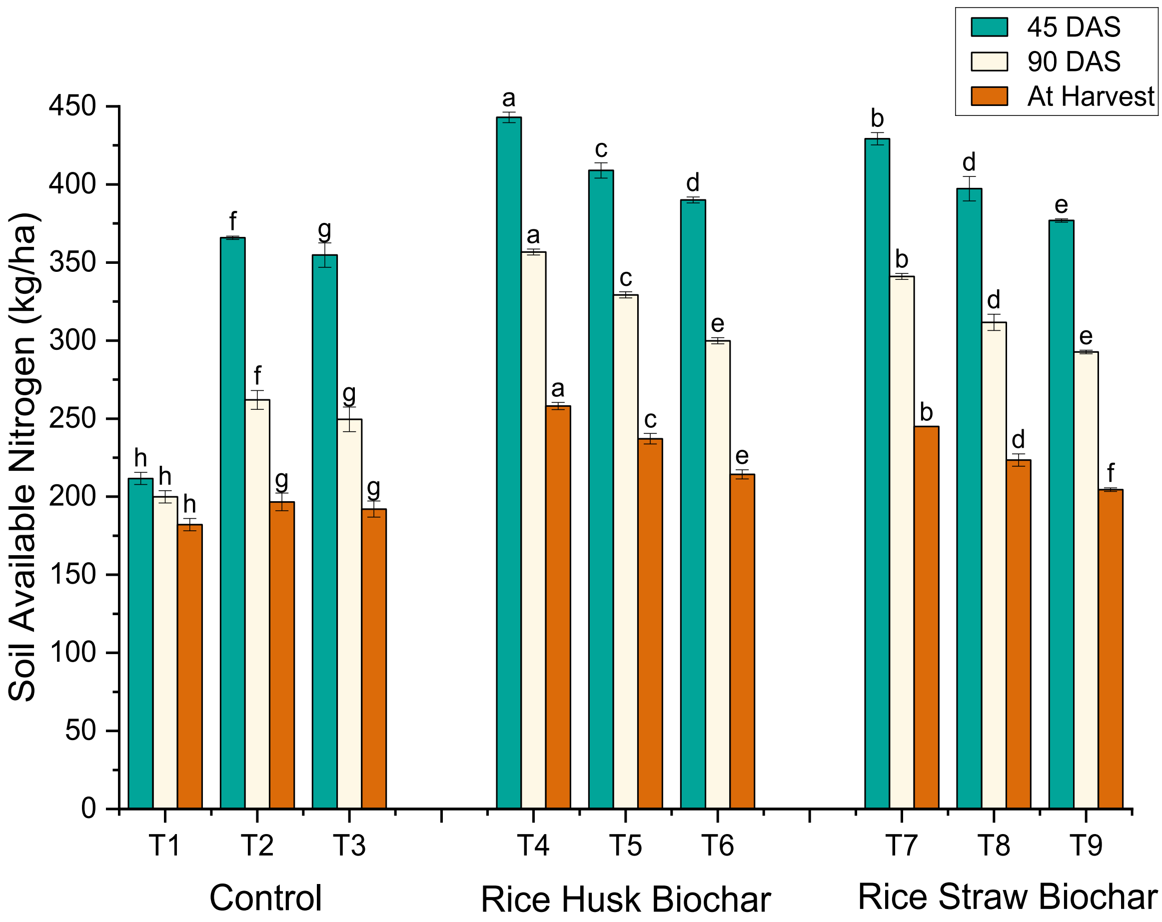


Figure 4.18. Effect of different biochar doses on soil nitrogen (kg/ha) at 45 and 90 DAS and at harvest.

Soil phosphorus is necessary for plant development and production because it plays important roles in various physiological processes. During the 2023-2024 season, a significant impact of biochar on the soil's phosphorus concentration was observed at different stages. The results are presented in **Table 4.20.** Among all treatments, T7 (45 DAS), T6 (90 DAS), and T9 (at harvesting) recorded the maximum phosphorus concentration, i.e., 27.5, 25, and 17, respectively. However, at 45 DAS (T7 & T9), at 90 DAS (T6, T7 & T9), and at harvest (T4, T5, T6, T8 & T9), all treatments showed a significant improvement in soil phosphorus compared to the other treatments. The maximum phosphorus concentration at harvest was recorded in T9 (17.4), followed by T5 (16.6), T6 (16.5), T4 (16.1), T8 (15.7), T7 (14.3), T2 (11.2), T3 (11.1) and T1 (7.6). Compared to the control (T1), a substantial percentage increase was recorded in phosphorus concentration in treatments T8 (97.8%), T5 (92.4%), T6 (83.9%), T4 (79.5%), T9 (78.6%), T7 (66.7%), T3 (56%) and T2 (45.7%).

Throughout the 2022-2023 season, a significant impact of biochar on the soil's phosphorus concentration was observed at different stages. Among all treatments, T9 (45 DAS), T7 (90 DAS), and T8 (at harvesting) recorded the maximum phosphorus concentration, i.e., 27.5, 25, and 17, respectively. However, at 45 DAS (T5, T7, T8 & T9), at 90 DAS (T6 & T9), and at harvest (T4, T5, T6, T8 & T9), significant improvements in soil phosphorus were observed compared to all other treatments. The maximum phosphorus concentration at harvest was recorded in T8 (17), followed by T5 (16.6), T6 (15.8), T4 (15.4), T9 (15.4), T7 (14.3), T3 (13.4), T2 (12.5) and T1 (8.6). Compared to the control (T1), a substantial percentage increase was recorded in phosphorus concentration in treatments T9 (127.5%), T5 (117.9%), T6 (116.5%), T4 (111.4%), T8 (105.7%), T7 (87.1%), T2 (46.3%) and T3 (45.1%).

The mean phosphorus concentration of the soil was found to be significant at all stages. However, at 45 DAS (T7 & T9), at 90 DAS (T6 & T9), and at harvest (T4, T5, T6, T8 & T9), all treatments showed a significant improvement in soil phosphorus compared to the other treatments. The maximum available nitrogen in the soil was recorded at harvest in T5 (16.6), followed by T9 (16.4), T8 (16.4), T6 (16.2), T4 (15.8), T7 (14.3), T3 (12.3), T2 (11.9), and T1 (8.1). Compared to the control (T1), a substantial percentage increase was recorded in phosphorus concentration of soil in treatments T7 (57.1%), T8 (52.4%), T4 (50.7%), T9 (46.7%), T5 (45.7%), T6 (44.8%), T2 (38.5%) and T3 (27.4%).

Phosphorus is an essential component of nucleic acids, phospholipids, and ATP, which are required for plant energy transfer and storage. Adequate phosphorus promotes healthy root development, shoot growth, blooming, and seed generation, resulting in higher agricultural yields. Phosphorus shortage can cause stunted growth, delayed maturity, and diminished disease resistance, all of which harm overall plant health. Farmers may improve crop performance and agricultural output by ensuring enough phosphorus in the soil. As a result, the application of biochar increases soil phosphorus availability. Initially, biochar can act as a slow-release phosphorus fertiliser. Zhang revealed that biochar significantly enhances plant-available phosphorus in soils, with a meta-analysis indicating an average increase in phosphorus availability by a factor of 4.6, particularly in acidic and neutral soils (Zhang et al., 2019). Biochar's alkaline properties increase soil pH, reducing the adsorption of phosphorus by iron and aluminium oxides and increasing its availability for plant uptake (Smith et al., 2024).

Table 4.20 Effect of biochar application on soil available phosphorus (mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			At Harvest		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	6.4^{e}	6.9^{e}	6.6^{e}	6.7^{f}	7.3^{e}	7.0^{f}	8.6^{e}	7.6^{d}	8.1^{d}
T_2	9.6^{d}	8.4^{de}	9.0^{d}	8.1^{ef}	10.4^{d}	9.2^{e}	12.5^{d}	11.2^{c}	11.9^{c}
T_3	8.9^{d}	9.9^{d}	9.4^{d}	8.3^{e}	9.7^{d}	9.0^{e}	13.4^{cd}	11.1^{c}	12.3^{c}
T_4	18.1^{c}	20.3^{bc}	19.2^{c}	16.3^{d}	18.1^{c}	17.2^{d}	15.4^{abc}	16.1^{ab}	15.8^{ab}
T_5	22.8^{b}	22.6^{ab}	22.7^{b}	18.2^{c}	20.2^{b}	19.2^{c}	16.6^{a}	16.6^{a}	16.6^{a}
T_6	22.8^{b}	18.4^{c}	20.6^{c}	23.9^{a}	25.0^{a}	24.4^{a}	15.8^{ab}	16.5^{a}	16.2^{a}
T_7	25.7^{a}	24.1^{a}	24.9^{a}	25.0^{a}	18.5^{bc}	21.8^{b}	14.3^{bcd}	14.3^{b}	14.3^{b}
T_8	23.4^{b}	22.6^{ab}	23.0^{b}	21.8^{b}	20.5^{b}	21.2^{b}	17.0^{a}	15.7^{ab}	16.4^{a}
T_9	27.5^{a}	22.2^{ab}	24.8^{a}	24.5^{a}	23.6^{a}	24.1^{a}	15.4^{abc}	17.4^{a}	16.4^{a}
CD ($p \leq 0.05$)	2.2	2.6	1.8	1.6	2.1	1.5	2.1	2.2	1.7
SEm (±)	0.7	0.9	0.6	0.5	0.7	0.5	0.7	0.7	0.6
Initial value	8.95								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

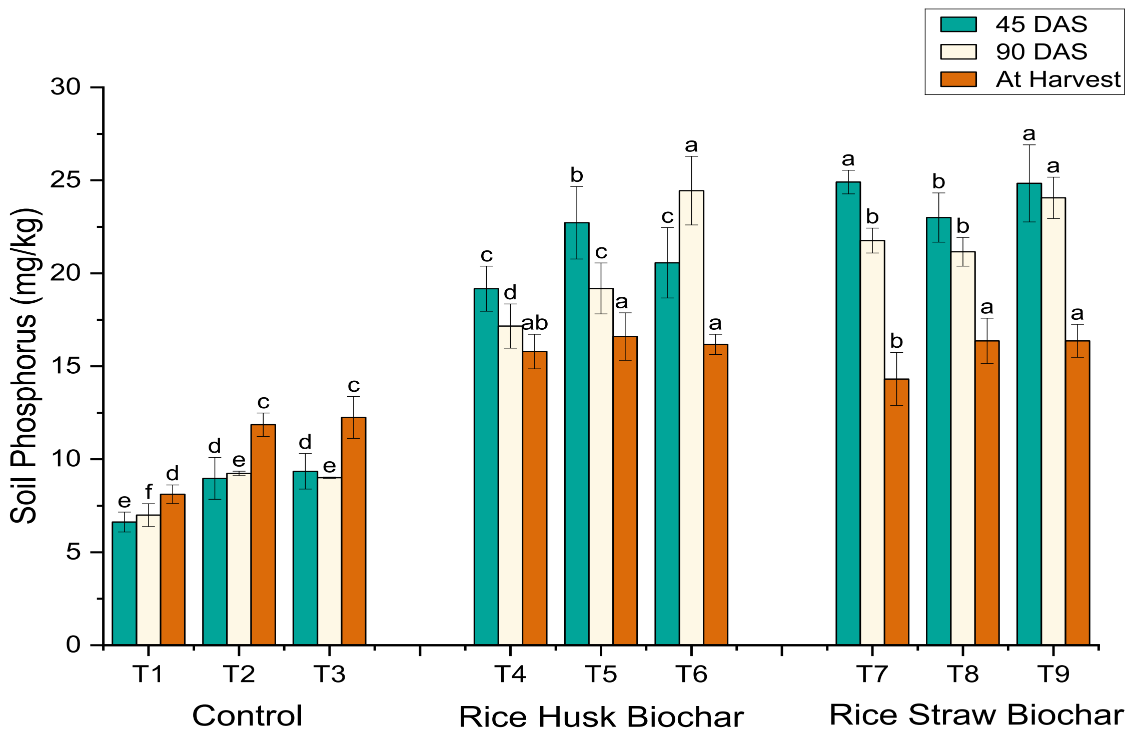


Figure 4.19. Effect of different biochar doses on soil phosphorus (mg/kg) at 45 and 90 DAS and at harvest.

Soil-available potassium is essential for optimal plant development and soil health. During the 2022-2023 season, a significant impact of biochar on soil potassium concentration was observed at various stages of growth. However, at 45 DAS (T5, T6 & T9), and at 90 DAS and harvest (T6 & T9), a significant improvement in soil Potassium Was Observed compared to all other treatments. The results are presented in **Table 4.21.** Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum potassium concentration at harvest, i.e., 123.7. At 45 DAS and 90 DAS, treatment with T6 (i.e., rice husk biochar at 15 tons/ha) resulted in the maximum potassium concentration, i.e., 153.6 and 142.9, respectively. The maximum potassium concentration at harvest was recorded in T9 (123.7), followed by T9 (97.1), T8 (92.4), T7 (81.1), T5 (80.1), T4 (66.4), T2 (44.9), T3 (41.3) and T1 (36.7). Compared to the control (T1), a substantial percentage increase was recorded in potassium concentration in treatments T9 (236.7%), T6 (164.4%), T8 (151.5%), T7 (120.9%), T5 (118.1%), T4 (81.6%), T2 (22.1%) and T3 (12.4%).

The 2023-2024 season results indicate a significant influence of biochar on the potassium concentration in soil at different stages. However, at 45 DAS (T6 & T9) and harvest (T6 & T9), the soil potassium levels showed a significant improvement compared to all other treatments. Among all treatments, T6 recorded a maximum potassium concentration at 45 DAS and 90 DAS, i.e. 156.6 and 146.8, respectively. During harvest treatment, T9 (i.e., rice straw biochar at 15 tons/ha) resulted in a maximum potassium concentration of 113.6. The maximum potassium concentration at harvest was recorded in T9 (113.6), followed by T6 (106), T5 (97.5), T8 (94.4), T4 (86.3), T7 (85.4), T2 (55.2), T3 (52.4) and T1 (41.5). Compared to the control (T1), a substantial percentage increase was recorded in potassium concentration in treatments T9 (173.8%), T6 (155.3%), T5 (134.9%), T8 (127.5%), T4 (108%), T7 (105.9%), T2 (33%) and T3 (26.3%).

The mean potassium concentration of the soil was found to be significant at all stages. However, 45 DAS (T6 & T9) and 90 DAS (T6 & T9) showed a significant improvement in soil Potassium compared to all other treatments. The maximum potassium concentration of the soil was recorded at harvest in T9 (118.7), followed by T6 (101.6), T8 (93.4), T5 (88.8), T4 (83.3), T3 (76.5), T2 (50), T1 (46.9), and T1 (39.1). Compared to the control (T1), a substantial percentage increase was recorded in potassium concentration of soil in treatments T9 (203.3%), T6 (159.6%), T8 (138.8%), T5 (127%), T7 (112.9%), T4 (95.6%), T2 (27.9%) and T3 (19.8%).

Potassium, an essential macronutrient, enables plants to perform vital physiological tasks such as photosynthesis, enzyme activity, and osmoregulation. The direct addition of K from biochar can significantly enhance plant growth and increase their resistance to infections and abiotic stresses. Furthermore, potassium promotes soil particle aggregation, which improves aeration and moisture retention. Ensuring enough potassium availability is vital for sustainable agriculture operations and maintaining healthy ecosystems. Biochar application increases soil potassium availability through several mechanisms that enhance nutrient dynamics in the soil. One of the primary ways is by improving the soil's cation exchange capacity, which allows for better retention and availability of potassium ions. Biochar has a high porosity and specific surface area, which contributes to its ability to retain K and other nutrients, thus preventing leaching and enhancing plant uptake (Smith et al., 2023). Additionally, biochar can directly supply potassium to the soil, particularly when produced from feedstocks rich in potassium. Research indicates that the total potassium content in biochar can vary significantly, with some types containing as much as 4–91 mg/kg^{1} of K. This direct addition of K from biochar can significantly increase the available K levels in the soil. For instance, a study found that applying peanut shell biochar increased available K by 125.78% after 30 months compared to control treatments (Lee et al., 2023).

Table 4.21: Effect of different doses of biochar application on soil available potassium (mg/kg) at 45 DAS, 90 DAS, and harvest during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	51.6^{g}	51.7^{e}	51.7^{g}	44.7^{g}	44.1^{f}	44.4^{f}	36.7^{e}	41.5^{f}	39.1^{g}
T_2	88.4^{e}	66.9^{d}	77.7^{e}	73.4^{e}	57.3^{e}	65.3^{d}	44.9^{e}	55.2^{e}	50.0^{f}
T_3	79.0^{f}	61.6^{d}	70.3^{f}	59.8^{f}	52.3^{e}	56.1^{e}	41.3^{e}	52.4^{e}	46.9^{f}
T_4	139.2^{cd}	135.8^{b}	137.5^{c}	111.7^{cd}	117.8^{d}	114.8^{c}	66.7^{d}	86.3^{d}	76.5^{e}
T_5	148.5^{ab}	142.2^{b}	145.3^{b}	104.9^{d}	136.8^{b}	120.8^{bc}	80.1^{c}	97.5^{bc}	88.8^{cd}
T_6	153.6^{a}	156.6^{a}	155.1^{a}	142.9^{a}	146.8^{a}	144.9^{a}	97.1^{b}	106.0^{ab}	101.6^{b}
T_7	135.2^{d}	126.2^{c}	130.7^{d}	121.7^{bc}	118.9^{d}	120.3^{bc}	81.1^{c}	85.4^{d}	83.3^{d}
T_8	143.9^{bc}	137.1^{b}	140.5^{bc}	129.3^{b}	125.3^{c}	127.3^{b}	92.4^{b}	94.4^{cd}	93.4^{c}
T_9	151.9^{a}	152.9^{a}	152.4^{a}	141.3^{a}	139.5^{b}	140.4^{a}	123.7^{a}	113.6^{a}	118.7^{a}
CD ($p \leq 0.05$)	7.7	6.8	5.9	11.7	5.6	7.2	8.8	10.8	5.7
SEm (±)	2.6	2.3	2.0	3.9	1.9	2.4	2.9	3.6	1.9
Initial value	41								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

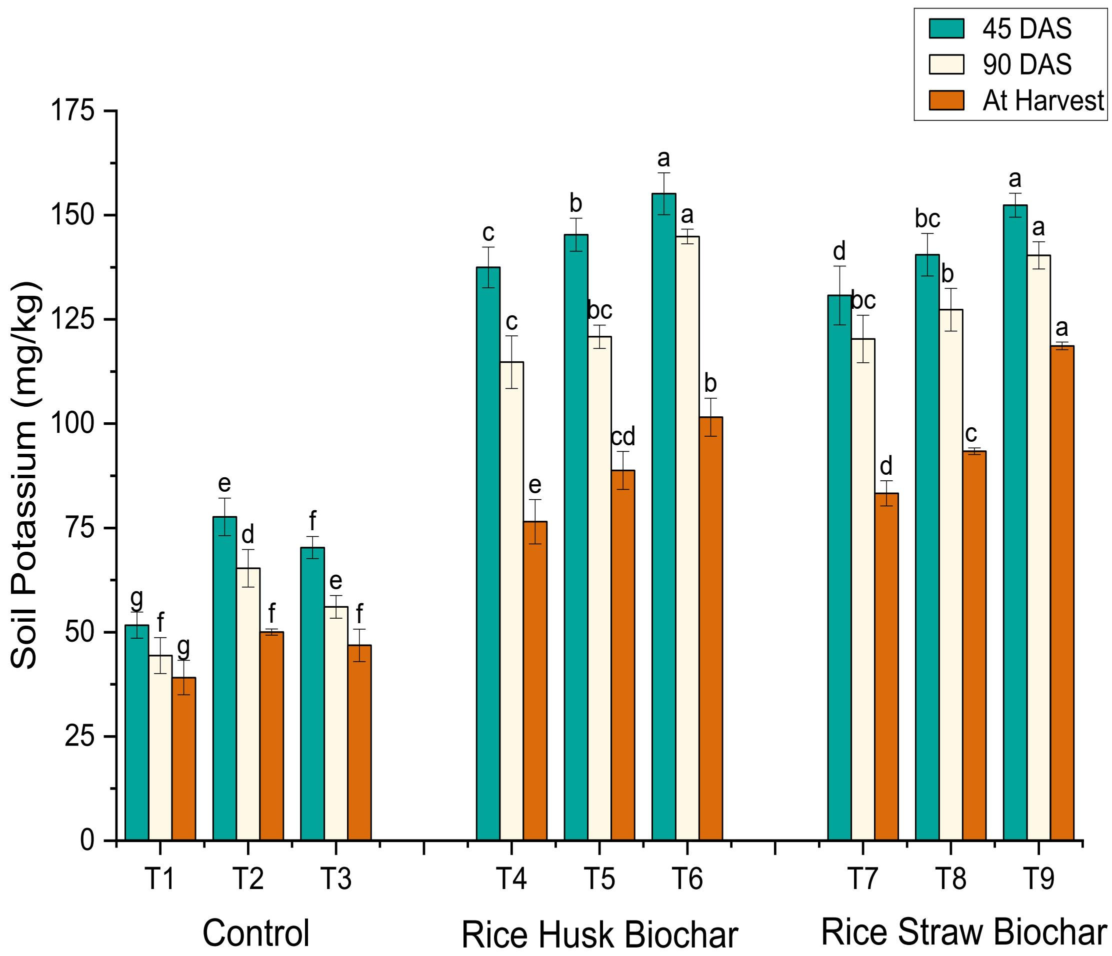


Figure 4.20. Effect of different biochar doses on soil potassium (mg/kg) at 45 and 90 DAS and at harvest.

Soil sulphur is a key component in the production of amino acids, proteins, and vitamins, supporting various metabolic activities required for plant growth. During the 2022-2023 season, a significant impact of biochar on the sulphur concentration of soil was observed at different stages. The results are presented in **Table 4.21.** Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum sulphur concentration at 45 DAS, i.e., 17.9. In comparison, at 90 DAS and harvest treatment T8 (i.e., rice straw biochar at 10 tons/ha), the maximum sulphur concentration was observed, i.e., 14.6 and 12.5, respectively. However, at 45 DAS (T6 & T9), at 90 DAS (T5, T7, T8 & T9) and at harvest (T6, T8 & T9) were exhibited no statistical difference from one another. The maximum sulphur concentration at harvest was recorded in T9 (12.5), followed by T6 (12.3), T9 (11.6), T8 (9.7), T5 (9.7), T4 (9.4), T3 (6.8), T2 (6.7) and T1 (7.1). Compared to the control (T1), a substantial percentage increase was recorded in sulphur concentration in treatments T8 (76.6%), T6 (75%), T9 (63.8%), T5 (37%), T7 (36.8%), and T4 (32.5%).

Throughout the 2023-2024 season, a significant impact of biochar was observed on the sulphur concentration of soil during different stages. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum sulphur concentration at 45 DAS, i.e., 15.8. In contrast, at 90 DAS (T6) and at harvest (T8), the maximum sulphur concentration was 13.5 and 11.6, respectively. However, at 45 DAS, (T4, T5, T6, T7, T8 & T9), at 90 DAS (T5, T6 & T9) and at harvest (T4, T5, T6, T7, T8 & T9) were exhibited no statistical difference from one another. The maximum sulphur concentration at harvest was recorded in T8 (12), followed by T9 (11.2), T6 (11), T5 (10.2), T4 (10), T7 (9.8), T2 (6.8), T1 (6.7) and T3 (6.6). Compared to the control (T1), a substantial percentage increase was recorded in sulphur concentration in treatments T8 (82%), T9 (69.6%), T5 (68.1%), T4 (65.7%), T7 (55.7%), T6 (52.2%) and T2 (9.1%).

The mean sulphur concentration of soil was found to be significant at all stages. However, at 45 DAS, (T6 & T9), at 90 DAS (T5, T6, T8 & T9) and at harvest (T6, T8 & T9) were exhibited no statistical difference from one another. The maximum sulphur concentration in the soil was recorded at harvest in T8 (12), followed by T9 (11.2), T6 (11), T5 (10.2), T4 (10), T7 (9.8), T2 (6.8), T1 (6.7), and T3 (6.6). Compared to the control (T1), a substantial percentage increase was recorded in potassium concentration of soil in treatments T8 (79.1%), T9 (66.6%), T6 (64.2%), T5 (51.8%), T4 (48.3%), T7 (45.8%) and T3 (1.3%).

Adequate sulphur availability improves crop resistance to pathogens and environmental stresses, improving overall plant health. Sulphur also has an essential function in improving the nutritional quality of grains by positively influencing protein content and flavour profiles in crops such as wheat and oilseed rape. As a result, proper sulphur management strategies are critical for increasing agricultural productivity and maintaining high-quality food output. As per the results, biochar incorporation increases soil sulphur availability. Initially, it acts as a slow-release sulphur fertiliser, especially when biochar is enriched with sulphur during production. This enriched biochar can release sulphur compounds into the soil, making them available for plant uptake. Studies have shown that applying sulphur-enriched biochar can significantly improve soil sulphur content and availability, leading to enhanced plant growth and yield (Mousa et al., 2023).

Table 4.22 Effect of different doses of biochar application on soil available sulphur (mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	7.3^{d}	8.6^{b}	7.9^{e}	5.9^{d}	8.0^{d}	6.9^{d}	7.1^{c}	6.4^{b}	6.7^{c}
T_2	8.3^{d}	9.0^{b}	8.6^{e}	6.4^{d}	8.5^{d}	7.4^{d}	6.7^{c}	6.9^{b}	6.8^{c}
T_3	8.4^{d}	8.1^{b}	8.3^{e}	7.0^{d}	8.5^{d}	7.7^{d}	6.8^{c}	6.4^{b}	6.6^{c}
T_4	14.4^{b}	13.6^{a}	14.0^{d}	11.0^{c}	12.4^{ab}	11.7^{c}	9.4^{b}	10.6^{a}	10.0^{b}
T_5	15.6^{b}	15.1^{a}	15.4^{bc}	13.7^{ab}	12.6^{ab}	13.1^{ab}	9.7^{b}	10.7^{a}	10.2^{b}
T_6	17.8^{a}	14.4^{a}	16.1^{ab}	12.5^{bc}	13.5^{a}	13.0^{ab}	12.3^{a}	9.7^{a}	11.0^{ab}
T_7	12.8^{c}	14.1^{a}	13.4^{d}	13.3^{ab}	10.6^{c}	12.0^{bc}	9.7^{b}	9.9^{a}	9.8^{b}
T_8	15.0^{b}	14.2^{a}	14.6^{cd}	14.6^{a}	12.3^{b}	13.4^{a}	12.5^{a}	11.6^{a}	12.0^{ab}
T_9	17.9^{a}	15.8^{a}	16.9^{a}	13.5^{ab}	13.0^{ab}	13.2^{a}	11.6^{a}	10.8^{a}	11.2^{ab}
CD ($p \leq 0.05$)	1.3	2.3	1.3	2.0	1.1	1.8	1.7	1.9	1.6
SEm (±)	0.4	0.8	0.4	0.7	0.4	0.4	0.6	0.6	0.5
Initial value	10.21								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

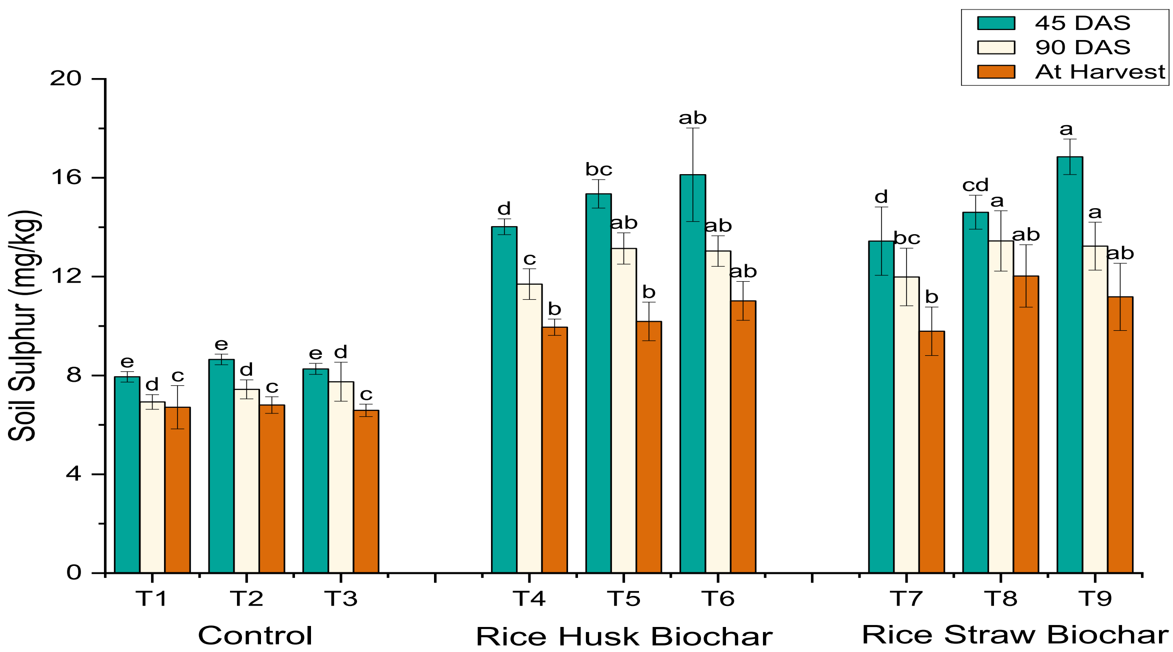


Figure 4.21. Effect of different biochar doses on soil sulphur (mg/kg) at 45 and 90 DAS and at harvest.

Soil calcium plays a crucial role in various physiological processes, including cell wall formation, enzyme activity, and nutrient uptake, all of which are essential for healthy plant development. During the 2022-2023 season, a significant impact of biochar on the soil's calcium concentration was observed at various stages of development. The results are presented in **Table 4.22**. Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the maximum calcium concentration at 45 and 90 DAS, i.e., 324 and 266.7 mg/kg, respectively. During harvest, treatment with T9 (i.e., rice straw biochar at 15 tons/ha) resulted in the maximum calcium concentration, specifically 284.3 mg/kg. However, at 45 DAS (T6 & T9), at 90 DAS (T5 & T6), and at harvest (T5, T6, T8 & T9), significant improvements in soil calcium were observed compared to all other treatments. The maximum calcium concentration at harvest was recorded in T9 (284.3), followed by T6 (282.7), T5 (281.1), T8 (272.1), T7 (267.5), T4 (268.2), T2 (262.1), T3 (259.6) and T1 (238.1). Compared to the control (T1), a substantial percentage increase was recorded in calcium concentration in treatments T9 (19.4%), T6 (18.7%), T5 (18.1%), T8 (14.3%), T4 (12.7%), T7 (12.3%), T2 (10.1%) and T3 (9%).

The calcium concentration in soil was significantly influenced by biochar throughout different stages during the 2023-2024 season. Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the maximum calcium concentration at 45, 90 DAS, and harvest, i.e., 336.4, 262.4, and 278.2, respectively. However, at 45 DAS (T5, T6 & T9), at 90 DAS (T2, T4, T5, T6, T7 & T9), and at harvest (T4, T5, T6 & T9), soil calcium levels showed a significant improvement compared to all other treatments. The maximum calcium concentration at harvest was recorded in T6 (278.2), followed by T9 (272.1), T5 (271.5), T4 (268.0), T8 (264.4), T7 (257.4), T2 (246.0), T3 (239.3), and T1 (232.9). Compared to the control (T1), a substantial percentage increase was recorded in calcium concentration in treatments T6 (19.5%), T9 (16.8%), T5 (16.6%), T4 (15.1%), T8 (13.5%), T7 (10.5%), T2 (5.6%) and T3 (2.7%).

The mean calcium concentration of the soil was found to be significant at all stages. However, at 45 DAS (T6 & T9), at 90 DAS (T4, T5, T6 & T9), and at harvest (T5, T6 & T9), the treatments showed a significant improvement in soil calcium compared to all other treatments. The maximum calcium concentration in the soil was recorded at harvest in T6 (280.5), followed by T9 (278.2), T5 (276.3), T8 (268.3), T4 (268.1), T7 (262.4), T2 (254.0), T3 (249.4), and T1 (235.5). Compared to the control (T1), a substantial percentage increase was recorded in the calcium concentration of soil in treatments T6 (19.1%), T9 (18.1%), T5 (17.3%), T4 (13.9%), T8 (13.9%), T7 (11.4%), T2 (7.9%) and T3 (5.9%).

Optimal calcium levels promote root development and enhance plant resistance to both biotic and abiotic stressors. Furthermore, calcium is essential for enhancing grain quality, as it affects protein content and overall nutritional value in crops. Effective soil calcium management is crucial for promoting sustainable agricultural practices and achieving high-quality crop yields. As shown in the results, the application of biochar significantly enhances soil calcium availability. The primary reason is that biochar contains significant amounts of calcium, which can be directly added to the soil as a nutrient source. This addition can lead to increased levels of exchangeable calcium in the soil, as demonstrated in studies where biochar application resulted in significant increases in soil exchangeable calcium content compared to control treatments (Silber et al., 2020).

Table 4.23 Effect of different doses of biochar application on soil available calcium (mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	225.1^{f}	221.8^{f}	223.5^{f}	211.9^{f}	220.2^{d}	216.1^{e}	238.1^{d}	232.9^{e}	235.5^{d}
T_2	258.2^{e}	262.1^{e}	260.2^{e}	242.7^{d}	238.6^{abcd}	240.7^{bcd}	262.1^{c}	246.0^{d}	254.0^{c}
T_3	246.6^{e}	255.5^{e}	251.1^{e}	233.1^{e}	226.6^{bcd}	229.9^{de}	259.6^{c}	239.3^{de}	249.4^{c}
T_4	289.7^{d}	318.9^{bc}	304.3^{cd}	254.4^{b}	253.5^{ab}	254.0^{ab}	268.2^{bc}	268.0^{ab}	268.1^{b}
T_5	304.3^{cd}	324.0^{abc}	314.1^{bc}	262.5^{a}	258.8^{a}	260.7^{a}	281.1^{ab}	271.5^{ab}	276.3^{a}
T_6	324.0^{a}	336.4^{a}	330.2^{a}	266.7^{a}	262.0^{a}	262.4^{a}	282.7^{a}	278.2^{a}	280.5^{a}
T_7	291.2^{d}	303.4^{d}	297.3^{d}	247.2^{cd}	247.7^{abc}	247.5^{bc}	267.5^{c}	257.4^{c}	262.4^{b}
T_8	308.3^{bc}	316.9^{cd}	312.6^{c}	255.2^{b}	222.7^{cd}	238.9^{cd}	272.1^{abc}	264.4^{bc}	268.3^{b}
T_9	320.6^{ab}	331.9^{ab}	326.2^{ab}	252.1^{bc}	245.9^{abcd}	249.0^{abc}	284.3^{a}	272.1^{ab}	278.2^{a}
CD ($p \leq 0.05$)	15.1	14.0	13.0	6.7	27.3	14.0	13.6	10.3	7.5
SEm (±)	5.1	4.7	4.3	2.2	9.1	4.7	4.5	3.4	2.5
Initial value	174.2								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

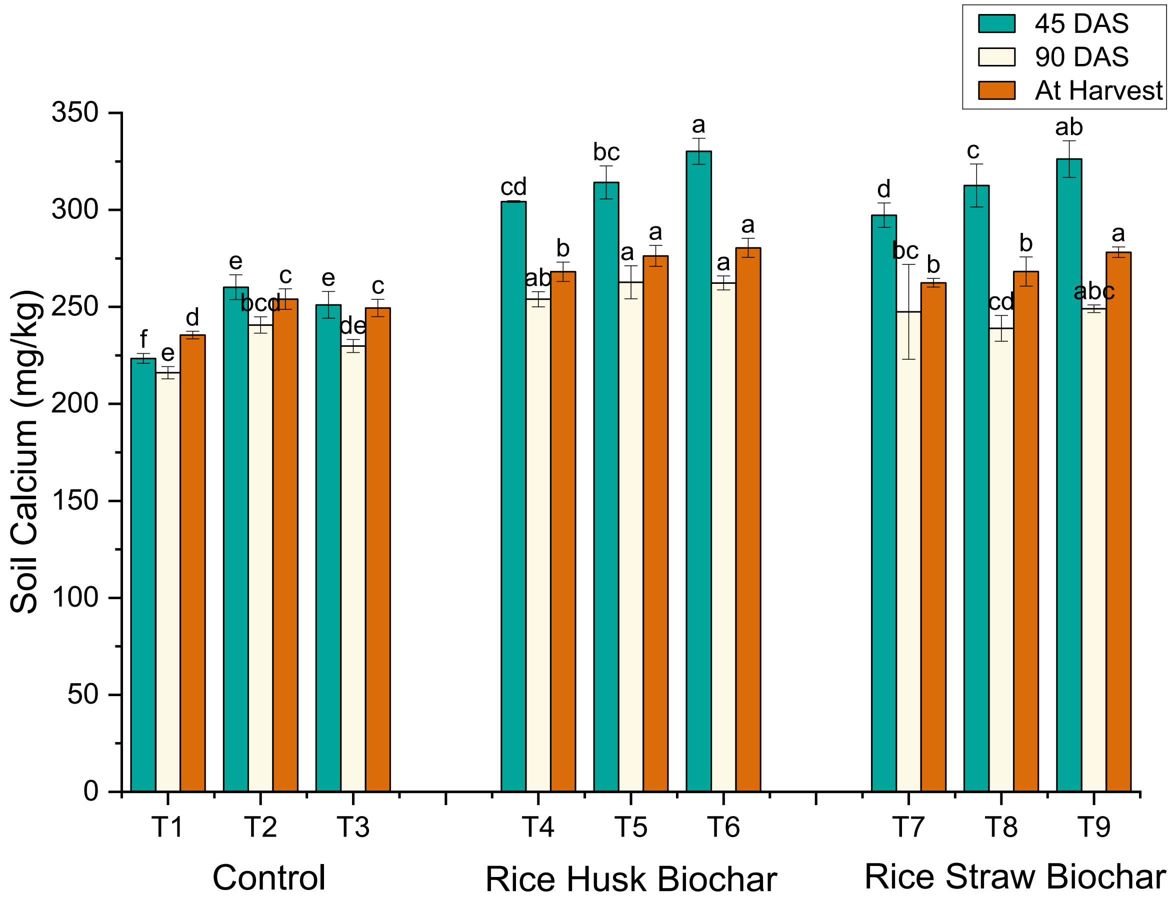


Figure 4.22: Effect of different biochar doses on soil calcium (mg/kg) at 45 and 90 DAS and at harvest.

The magnesium concentration in soil was notably influenced by biochar during various stages of the 2022-2023 season, as shown in **Table 4.23.** Among all treatments (45 and 90 DAS) and T5 (at harvest), the maximum magnesium concentration was observed, i.e., 130.8, 98.2, and 145.3, respectively. However, at 45 DAS (T1, T2 & T3), at 90 DAS (T1 & T3), and at harvest (T3, T5, T6 & T7), the treatments showed a significant improvement in soil magnesium compared to all other treatments. The maximum magnesium concentration at harvest was recorded in T5 (145.3), followed by T3 (142.2), T7 (139.1), T6 (137.7), T8 (133.3), T1 (133.2), T9 (132.9), T10 (132.1), and T4 (126.6). Compared to the control (T1), a substantial percentage increase was recorded in magnesium concentration in treatments T5 (9.1%), T3 (6.8%), T7 (4.5%), T6 (3.4%) and T8 (0.1%).

Throughout the 2023-2024 season, a significant impact of biochar on soil magnesium concentration was observed at various stages. Among all treatments, T1 (45 and 90 DAS) and T7 (at harvest) resulted in the maximum magnesium concentration, i.e., 176.2, 158.9, and 179, respectively. However, at 90 DAS (T1 & T2) and at harvest (T1, T2, T3, T4, T5, T6, T7, T8 & T9), a significant improvement in soil magnesium was observed compared to all other treatments. The maximum magnesium concentration at harvest was recorded in T7 (179 mg/kg), followed by T9 (171.8 mg/kg), T2 (171.6 mg/kg), T8 (171.4 mg/kg), T4 (170.6 mg/kg), T5 (169.1 mg/kg), T1 (169.1 mg/kg), and T6 (168.6 mg/kg). Compared to the control (T1), a substantial percentage increase was recorded in magnesium concentration in treatments T7 (5.9%), T3 (2.8%), T9 (1.6%), T8 (1.4%), T2 (1.5%), and T4 (0.8%).

The mean magnesium concentration of the soil was found to be significant at all stages. However, at 45 DAS (T1 & T2), at 90 DAS (T1 & T2), and at harvest (T1, T2, T3, T5, T6, T7, T8 & T9), soil magnesium levels showed a significant improvement compared to all other treatments. The maximum magnesium concentration in the soil was recorded at harvest in T7 (159.1), followed by T3 (158.1), T5 (157.2), T6 (153.2), T8 (152.4), T9 (152.4), T2 (151.9), T1 (151.2), and T4 (148.6). Compared to the control (T1), a substantial percentage increase was recorded in the magnesium concentration of soil in treatments T7 (5.2%), T3 (4.6%), T5 (4%), T6 (1.3%), T8 (0.8%), T9 (0.8%), and T2 (0.5%).

Magnesium in soil is an essential macronutrient that influences plant growth, soil health, and grain quality. It is a key component of chlorophyll, permitting photosynthesis and energy generation, which are critical for plant life and productivity. Magnesium is also essential for enzyme activation, which aids in various metabolic activities that improve nutrition intake and utilisation. Furthermore, magnesium improves grain quality by increasing nutritional content and flavour profiles, making its control crucial for sustainable agriculture, and the availability of soil magnesium through the incorporation of biochar. Increased cation exchange capacity allows for better retention and availability of magnesium ions. The porous nature of biochar increases the surface area for ion exchange, facilitating the retention of magnesium and other essential nutrients in the soil solution, thus making them more accessible to plants (Zhang et al., 2023).

Table 4.24 Effect of different doses of biochar application on soil available magnesium (mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			AT HARVEST		
	2022-23	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**	**2022-23**	**2023-24**	**Mean**
T_1	130.8^{a}	176.2^{a}	153.5^{a}	98.2^{a}	158.9^{a}	128.6^{a}	133.2^{bc}	169.1^{a}	151.2^{ab}
T_2	128.4^{abc}	155.8^{b}	142.1^{b}	91.9^{abc}	145.3^{bc}	118.6^{b}	132.1^{bc}	171.6^{a}	151.9^{ab}
T_3	133.1^{a}	163.1^{b}	148.1^{ab}	97.0^{ab}	156.5^{ab}	126.7^{ab}	142.2^{ab}	173.9^{a}	158.1^{a}
T_4	116.2^{cd}	142.8^{cd}	129.5^{c}	76.7^{d}	138.4^{cd}	107.6^{c}	126.6^{c}	170.6^{a}	148.6^{b}
T_5	112.1^{cd}	138.5^{cd}	125.3^{cd}	81.2^{cd}	133.3^{cd}	107.3^{c}	145.3^{a}	169.1^{a}	157.2^{a}
T_6	109.7^{d}	132.2^{d}	121.0^{d}	83.9^{bcd}	130.6^{d}	107.3^{c}	137.7^{abc}	168.6^{a}	153.2^{ab}
T_7	121.0^{bc}	137.0^{cd}	129.0^{c}	84.7^{abcd}	130.1^{d}	107.4^{c}	139.1^{ab}	179^{a}	159.1^{a}
T_8	116.9^{cd}	134.8^{cd}	125.9^{cd}	84.5^{abcd}	129.5^{d}	107.0^{c}	133.3^{bc}	171.4^{a}	152.4^{ab}
T_9	115.8^{cd}	144.7^{c}	130.3^{c}	83.5^{bcd}	131.2^{d}	107.4^{c}	133.0^{bc}	171.8^{a}	152.4^{ab}
CD ($p \leq 0.05$)	9.5	11.1	7.5	13.9	12.0	9.1	12.0	14.6	8.2
SEm (±)	3.2	3.7	2.5	4.6	4.0	3.0	4.0	4.9	2.7
Initial value	125.8								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

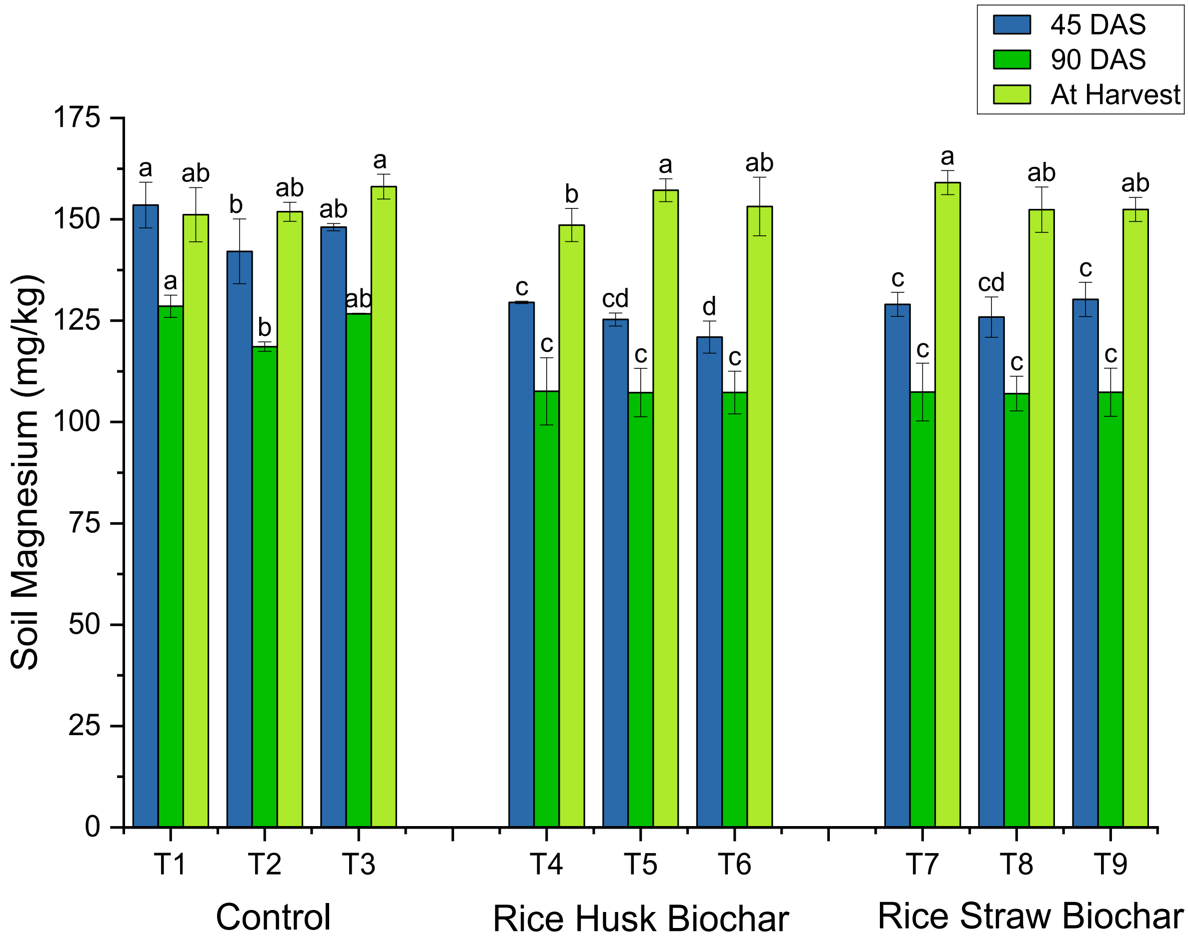


Figure 4.23. Effect of different biochar doses on soil magnesium (mg/kg) at 45 and 90 DAS and at harvest.

Iron (Fe) is an essential plant element that regulates various physiological processes, including chlorophyll production, photosynthesis, and enzyme activity. During the 2022-2023 season, a significant impact of biochar on the iron concentration of soil was observed at different stages. The results are presented in **Table 4.24.** Among all treatments, T1 (i.e., control) recorded the highest iron concentration at 45 DAS, 90 DAS, and harvest, i.e., 7.7, 10.7, and 13.1 mg/kg, respectively. However, at 45 DAS (T1, T2 & T3) and at harvest (T1, T2, T3, T4, T5, T6, T7, T8 & T9), all treatments showed a significant improvement in soil iron compared to the other treatments. The maximum iron concentration at harvest was recorded in T1 (13.1), followed by T7 (12.1), T8 (11.5), T3 (11), T4 (10.8), T2 (10.8), T9 (10.5), T5 (10.2), and T6 (9.5). As compared to control (T1), there was a significant percentage decrease in iron concentration in treatments T6 (27.6%), T5 (21.9%), T9 (19.9%), T2 (17%), T4 (17%), T3 (15%), T8 (11.7%) and T7 (7.4%).

During the 2023-2024 season, a significant impact of biochar on the iron concentration of soil was observed at different stages. Among all treatments, T1 (i.e., control) recorded the maximum iron concentration at 45 DAS, 90 DAS, and at harvest, i.e., 10.2, 11.9, and 17.2, respectively. However, at 45 DAS (T1, T2 & T3), at 90 DAS (T1 & T2), and at harvest (T1 & T2), a significant improvement in soil iron was observed compared to all other treatments. The maximum iron concentration at harvest was recorded in T1 (15.2), followed by T3 (13.7), T2 (12.3), T7 (10.8), T8 (10), T4 (9.7), T5 (8.7) and T6 (8.6). As compared to control (T1), there was a significant percentage decrease in iron concentration in treatments T6 (43.4%), T5 (42.7%), T9 (37.5%), T4 (36.1%), T8 (34.2%), T7 (28.9%), T2 (19%) and T3 (9.8%).

The mean iron concentration of soil was found to be significant at all stages. However, at 45 DAS (T1 & T2) and harvest (T1 & T2), soil iron levels showed a significant improvement compared to all other treatments. The maximum iron concentration of soil was recorded at harvest in T1 (14.1), followed by T3 (12.4), T4 (11.6), T7 (11.4), T8 (10.7), T4 (10.3), T9 (10), T5 (9.4) and T6 (9). Compared to the control (T1), a substantial percentage increase was recorded in the iron concentration of soil in treatments T6 (36.1%), T5 (33.3%), T9 (29%), T4 (26.9%), T8 (24.1%), T7 (19.1%), T2 (17.7%) and T3 (%).

Iron promotes electron transport in metabolic pathways, critical for energy generation and overall plant health. However, too much iron in the soil can cause toxicity, resulting in diminished root development, limited nutrient absorption, and chlorosis, which is characterised by yellowing leaves. High iron levels can also disrupt the balance of other essential minerals, leading to deficiencies in manganese and zinc. Thus, maintaining adequate iron levels is crucial for promoting healthy plant development and ensuring long-term agricultural sustainability. Biochar application can reduce iron availability in the soil, and biochar can alter soil pH, particularly in acidic soils. When biochar is applied, it often raises the soil pH, which can lead to the precipitation of iron as insoluble forms, thereby reducing its bioavailability to plants (Ali et al., 2022). According to Kumar, an increase in soil pH subsequently decreases the solubility of iron compounds, making them less available for plant uptake (Kumar et al., 2023). Additionally, biochar can enhance cation exchange capacity (CEC), allowing it to retain calcium and magnesium more effectively than iron.

Table 4.25 Effect of different doses of biochar application on soil available iron (mg/kg) at 45 DAS, 90 DAS and harvest, during 2022-2023 and 2023-2024.

Treatments	45 DAS			90 DAS			At Harvest		
	2022-23	2023-24	Mean	2022-23	2023-24	Mean	2022-23	2023-24	Mean
T_1	7.7^{a}	11.9^{a}	9.8^{a}	10.7^{a}	17.2^{a}	14^{a}	13.1^{a}	15.2^{a}	14.1^{a}
T_2	6.2^{abc}	9.2^{b}	7.7^{bc}	7.4^{b}	13.0^{b}	10.2^{b}	10.8^{a}	12.3^{b}	11.6^{bc}
T_3	6.8^{ab}	11.4^{a}	9.1^{ab}	8.3^{b}	14.6^{ab}	11.5^{b}	11.0^{a}	13.7^{ab}	12.4^{ab}
T_4	5.0^{cd}	7.6^{bcd}	6.3^{cde}	7.4^{b}	9.6^{c}	8.5^{c}	10.8^{a}	9.7^{cd}	10.3^{cde}
T_5	5.4^{bcd}	6.8^{cd}	6.1^{de}	4.1^{c}	8.8^{c}	6.5^{d}	10.2^{a}	8.7^{d}	9.4^{de}
T_6	4.3^{d}	5.8^{d}	5.0^{e}	4.1^{c}	8.7^{c}	6.4^{d}	9.5^{a}	8.6^{d}	9.0^{e}
T_7	6.0^{bc}	8.1^{bc}	7.0^{cd}	3.7^{c}	9.4^{c}	6.5^{d}	12.1^{a}	10.8^{c}	11.4^{bcd}
T_8	4.1^{d}	6.8^{cd}	5.5^{e}	4.3^{c}	9.1^{c}	6.7^{d}	11.5^{a}	10.0^{cd}	10.7^{bcde}
T_9	5.3^{bcd}	6.7^{cd}	6.0^{de}	3.7^{c}	7.7^{c}	5.7^{d}	10.5^{a}	9.5^{cd}	10^{cde}
CD ($p\leq0.05$)	1.7	1.8	1.5	1.6	3.0	1.6	3.9	1.5	2.1
SEm (±)	0.6	0.6	0.5	0.5	1.0	0.5	1.3	0.5	0.7
Initial value	7.14								

***** Means denoted by different letters are significantly different at $p\leq0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha.**

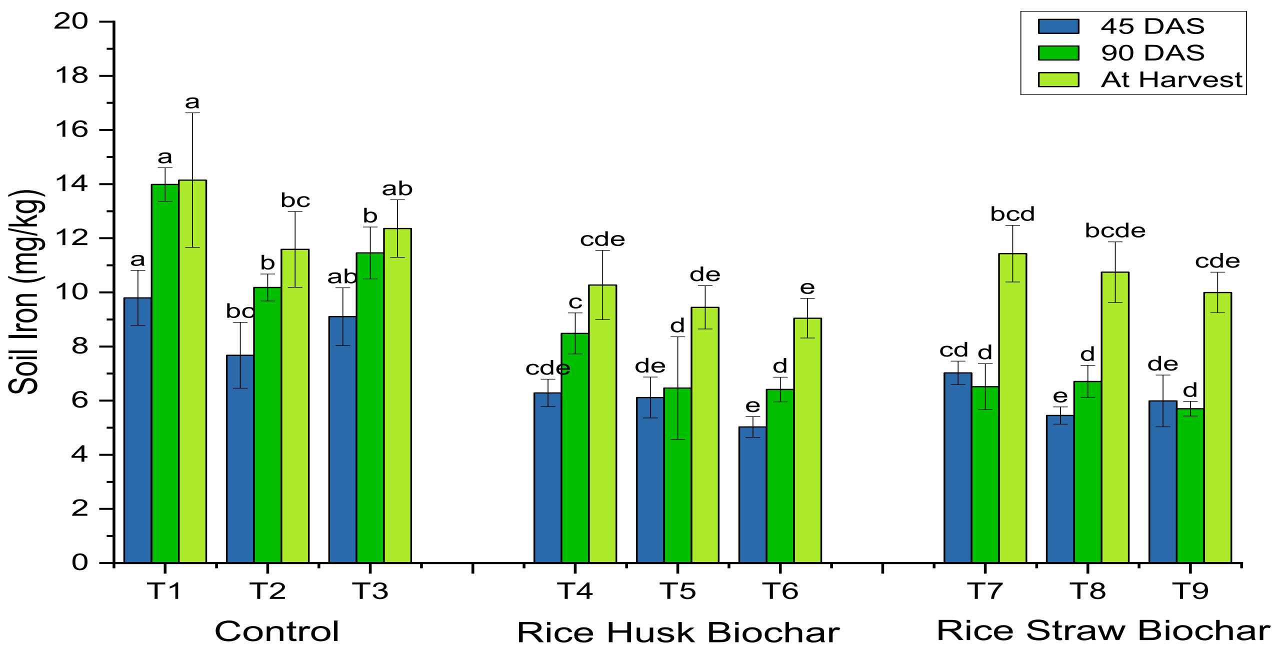


Figure 4.24. Effect of different biochar doses on soil iron (mg/kg) at 45 and 90 DAS and at harvest.

RESULTS AND DISCUSSION (Pigeon Pea)

Growth attributes

Plant height is a crucial parameter that helps determine crop growth and health. During the 2023 season, a significant impact of biochar was observed on the plant height of pigeon peas during different growth stages. However, at 30, 90, and 120 days, DAS T4 & T7 showed a significant improvement in plant height compared to all other treatments. The results are presented in **Table 4.26.** Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum plant height at 30, 90, and 120 DAS, i.e., 63 cm, 285.7 cm, and 296 cm, respectively. While at 60 DAS, treatment T7 (i.e. rice straw biochar @ 5 tons/ha) resulted in maximum plant height, i.e. 189.5 cm. The maximum plant height at 120 DAS was recorded in T4 (296.3 cm), followed by T7 (291.7 cm), T8 (277.6 cm), T5 (277.6 cm), T9 (265.7 cm), T6 (258.9 cm), T2 (216 cm), T3 (169.8 cm) and T1 (162.7 cm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T4 (82.1%), T7 (79.3%), T5 (70.6%), T8 (70.6%), T9 (63.3%), T9 (59.1%), T2 (32.8%) and T3 (4.3%).

Biochar was observed to significantly affect the height of pigeon pea plants at various growth stages during the 2024 season. However, at 60 DAS, T4 & T7 showed a significant improvement in plant height compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum plant height at 30, 60, 90, and 120 DAS, i.e., 38.4 cm, 121.1 cm, 206.3 cm, and 235.8 cm, respectively. The maximum plant height at 120 DAS was recorded in T4 (235.8 cm), followed by T7 (232.8 cm), T8 (227.5 cm), T5 (223.5 cm), T6 215.2 cm), T9 (212.1 cm), T2 (175.4 cm), T3 (158.1 cm) and T1 (132.7 cm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T4 (77.6%), T7 (75.4%), T8 (71.4%), T5 (68.2%), T6 (62.1%), T9 (59.8%), T2 (32.1%) and T3 (19.1%).

The mean plant height was found to be significant at all growth stages. However, at 60 DAS, T4 & T7 showed a significant improvement in plant height compared to all other treatments. The maximum plant height at 120 DAS was recorded in T4 (266.1 cm), followed by T7 (262.2 cm), T8 (252.5 cm), T5 (250.4 cm), T9 (238.9 cm), T6 (237 cm), T2 (195.7 cm), T3 (163.9 cm) and T1 (147.7 cm). Compared to the control (T1), a substantial percentage increase was recorded in plant height in treatments T4 (80.1%), T7 (77.5%), T8 (71%), T5 (69.5%), T9 (61.7%), T6 (60.5%), T2 (32.5%) and T3 (11%).

Table 4.26 Effect of different doses of biochar on plant height (cm) of pigeon pea on 30, 60, 90 and 120 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS			120 DAS		
	2023	**2024**	**Mean**	**2023**	**2024**	**Mean**	**2023**	**2024**	**Mean**	**2023**	**2024**	**Mean**
T_1	32.6^{e}	23^{f}	27.8^{h}	102.7^{g}	84.3^{i}	93.5^{f}	139.4^{f}	113.6^{h}	126.5^{g}	162.7^{f}	132.7^{i}	147.7^{g}
T_2	42.2^{d}	29de	35.6^{f}	137.1^{e}	95.7^{g}	116.4^{d}	201.4^{d}	159.3^{f}	180.4^{e}	216.0^{d}	175.4^{g}	195.7^{e}
T_3	36.7^{e}	27.4^{e}	32.1^{g}	121.2^{f}	88.4^{h}	104.8^{e}	154.9^{e}	143.3^{g}	149.1^{f}	169.8^{e}	158.1^{h}	163.9^{f}
T_4	63^{a}	38.4^{a}	50.7^{a}	176.9^{b}	121.1^{a}	149^{a}	285.7^{a}	206.3^{a}	246.0^{a}	296.3^{a}	235.8^{a}	266.1^{a}
T_5	53.3^{b}	35.4^{b}	44.4^{c}	155^{c}	112.3^{c}	133.6^{b}	262.4^{b}	190.0^{b}	226.2^{c}	277.6^{b}	223.3^{d}	250.4^{c}
T_6	47.6^{c}	32.8^{bc}	40.2^{de}	144.2^{de}	101^{e}	122.6^{c}	245.2^{c}	173.0^{cd}	209.1^{d}	258.9^{c}	215.2^{e}	237.0^{d}
T_7	60.8^{a}	35.1^{b}	48^{b}	189.5^{a}	116.5^{b}	153^{a}	286.9^{a}	178.7^{c}	232.8^{b}	291.7^{a}	232.8^{b}	262.2^{b}
T_8	52.3^{b}	32.4^{c}	42.4^{cd}	167.4^{b}	106.4^{d}	136.9^{b}	271.1^{b}	169.7^{de}	220.4^{c}	277.6^{b}	227.5^{c}	252.5^{c}
T_9	47^{c}	31.7^{cd}	39.3^{e}	150^{cd}	98.6^{f}	124.3^{c}	248.2^{c}	163.1^{ef}	205.7^{d}	265.7^{c}	212.1^{f}	238.9^{d}
CD ($p \leq 0.05$)	4.6	2.1	4.8	9.7	7	6.5	10.3	2	3.7	7	1.6	2.1
SEm (±)	1.5	0.7	1.6	3.3	2.2	2.2	3.9	0.7	1.2	2.3	0.5	0.7

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

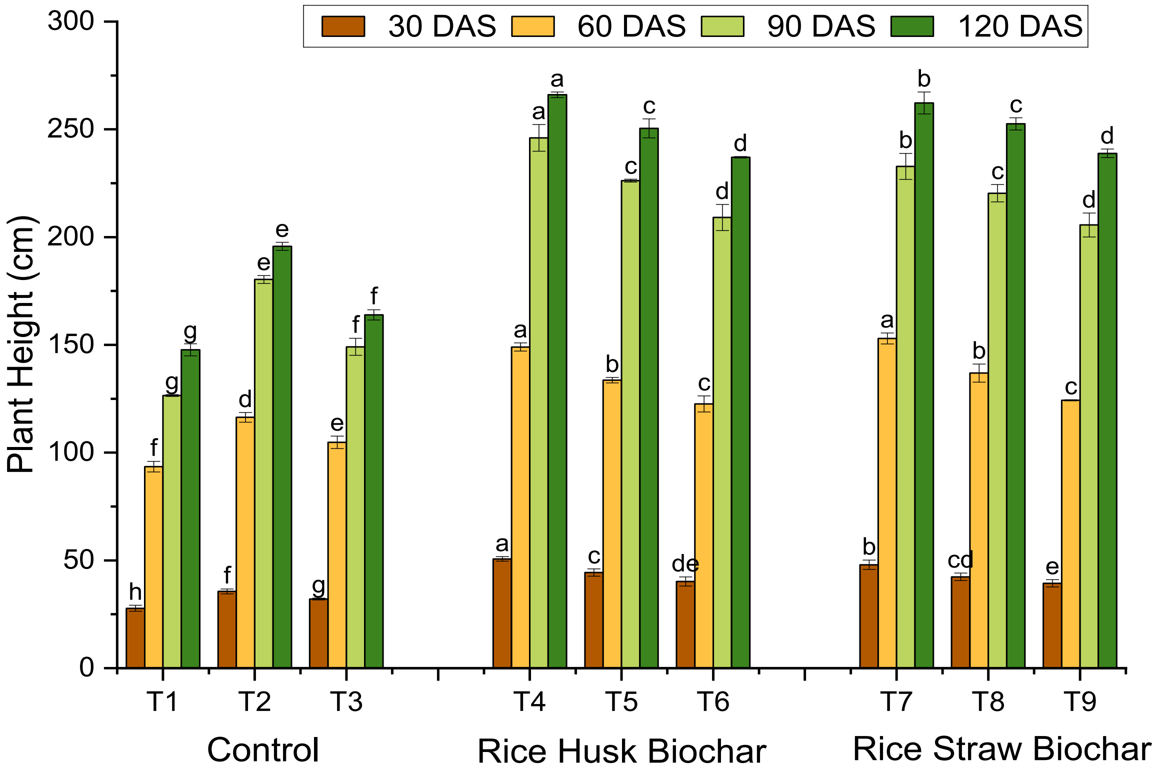


Figure 4.25. Effect of various biochar doses on plant height (cm) in pigeon pea at 30, 60, 90, and 120 DAS.

The number of primary branches in pigeon peas was notably influenced by biochar during different growth stages in the 2023 season, with results presented in **Table 4.27.** Throughout all growth stages, T4 and T7 showed a significant improvement in the number of primary branches compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum number of primary branches at 60, 90, and 120 DAS, i.e., 25.3, 37, and 46.7, respectively. The maximum number of primary branches at 120 DAS was recorded in T7 (46.7), followed by T4 (46.3), T8 (42.7), T5 (42.3), T9 (38.7), T6 (37), T2 (33.3), T3 (27.7) and T1 (22.3). Compared to the control (T1), a substantial percentage increase was recorded in the number of primary branches in treatments T7 (109 %), T4 (107.5 %), T8 (91%), T5 (89.6%), T9 (73.1%), T6 (65.7%), T2 (49.3%) and T3 (23.9%).

Throughout the 2024 season, a significant impact of biochar was observed on the number of primary branches of pigeon peas during different growth stages. However, at 60 and 120 DAS, both T4 and T7 showed a significant improvement in the number of primary branches compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum number of primary branches at 60, 90, and 120 DAS, i.e., 19.3, 30.7, and 39, respectively. The maximum number of primary branches at 120 DAS was recorded in T4 (39), followed by T7 (38.3), T5 (36), T8 (35.7), T6 (34), T9 (33.3), T2 (27.3), T3 (23.7) and T1 (21). Compared to the control (T1), a substantial percentage increase was recorded in the number of primary branches in treatments T4 (85.7%), T7 (82.5%), T5 (71.4%), T8 (69.8%), T6 (61.9%), T9 (58.7%), T2 (30.2%) and T3 (12.7%).

The mean number of primary branches was found to be significant at all growth stages. However, at 60 and 120 DAS, both T4 and T7 showed a significant improvement in the number of primary branches compared to all other treatments. The maximum number of primary branches at 120 DAS was recorded in T4 (42.7), followed by T7 (42.5), T5 (39.2), T8 (39.2), T9 (36), T6 (35.5), T2 (30.3), T3 (25.7) and T1 (21.7). Compared to the control (T1), a substantial percentage increase was recorded in the number of primary branches in treatments T4 (96.9%), T7 (96.2%), T8 (80.8%), T5 (80.8%), T9 (66.2%), T6 (63.8%), T2 (40%) and T3 (18.5%

Table 4.27 Effect of different biochar application doses on pigeon pea's primary branches at 60, 90 and 120 DAS during 2023 and 2024.

Treatments	60 DAS			90 DAS			120 DAS		
	2023	**2024**	**Mean**	**2023**	**2024**	**Mean**	**2023**	**2024**	**Mean**
T_1	6.7^{f}	6.7^{g}	6.7^{f}	14.7^{f}	13.3^{g}	14.0^{f}	22.3^{f}	21^{f}	21.7^{f}
T_2	15.7^{d}	13.0^{e}	14.3^{d}	24.3^{d}	22.7^{e}	23.5^{d}	33.3^{d}	27.3^{d}	30.3^{d}
T_3	9.3^{e}	9.7^{f}	9.5^{e}	19.0^{e}	17.3^{f}	18.2^{e}	27.7^{e}	23.7^{e}	25.7^{e}
T_4	24.7^{a}	19.3^{a}	22.0^{a}	34.0^{a}	30.7^{a}	32.3^{a}	46.3^{a}	39^{a}	42.7^{a}
T_5	21.7^{b}	17.3^{bc}	19.5^{b}	29.7^{b}	27.3^{c}	28.5^{b}	42.3^{b}	36^{b}	39.2^{b}
T_6	18.3^{c}	14.7^{d}	16.5^{c}	26.7^{c}	25.7^{d}	26.2^{c}	37^{c}	34^{c}	35.5^{c}
T_7	25.3^{a}	18.3^{ab}	21.8^{a}	37^{a}	29.0^{b}	33.0^{a}	46.7^{a}	38.3^{a}	42.5^{a}
T_8	22.3^{b}	17.7^{bc}	20.0^{b}	32.7^{b}	26.0^{cd}	29.3^{b}	42.7^{b}	35.7^{b}	39.2^{b}
T_9	19.0^{c}	16.7^{c}	17.8^{c}	28.3^{c}	24.7^{d}	26.5^{c}	38.7^{c}	33.3^{c}	36.0^{c}
CD ($p \leq 0.05$)	2.2	1.4	1.4	3.1	1.5	2	3.6	1.4	1.6
SEm (±)	0.7	0.5	0.5	1	0.5	0.07	1.2	0.5	0.5

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

The fresh biomass of pigeon peas was significantly influenced by biochar during different growth stages in the 2023 season, with results in **Table 4.28.** Throughout all growth stages, T4 and T7 showed a significant improvement in fresh biomass compared to all other treatments. Among all treatments, treatment T7 (i.e., rice straw biochar at 5 tons/ha) resulted in the maximum fresh biomass at 30 and 90 DAS, i.e., 4.9 g and 806 g, respectively. At 60 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum fresh biomass, i.e., 232.6 g. The maximum fresh biomass at 90 DAS was recorded in T7 (806 cm), followed by T4 (785.7 cm), T8 (746.7 cm), T5 (743.6 cm), T6 215.2 cm), T9 (212.1 cm), T2 (175.4 cm), T3 (158.1 cm) and T1 (132.7 cm). As compared to control (T1), there was a significant percentage increase of fresh biomass in treatments T7 (64.2%), T4 (60 %), T8 (52.1%), T5

(51.4%), T9 (36.8%), T6 (35.4%), T2 (28.4%) and T3 (7.8%). Biochar was observed to have a considerable effect on the fresh biomass of pigeon peas at various growth stages during the 2024 season.

However, at 60 and 90 DAS, both T4 and T7 showed a significant improvement in fresh biomass compared to all other treatments. Among all treatments, treatment T7 (i.e. rice straw biochar @ 5 tons/ha) resulted in maximum fresh biomass at 30, 60 and 90 DAS, i.e. (4.8 g), (218.3 g) and (596 g) respectively. The maximum fresh biomass at 90 DAS was recorded in T7 (596 g), followed by T4 (579 g), T8 (553 g), T5 (537 g), T9 (468 g), T6 (457 g), T2 (384.9 g), T3 (334.2 g) and T1 (226.1 g). As compared to control (T1), there was a significant percentage increase of fresh biomass in treatments T7 (168%), T4 (159%), T8 (141.8%), T5 (140.4%), T9 (108.7%), T6 (105.8%), T2 (70.2%) and T3 (45.6%).

The mean number of primary branches was found to be significant at all growth stages. The maximum number of primary branches at 90 DAS was recorded in T7 (701 g), followed by T4 (682.3 g), T8 (649 g), T5 (640 g), T9 (579 g), T6 (561 g), T2 (507.7 g), T3 (431.2 g) and T1 (358.6 g). Compared to the control (T1), a substantial percentage increase was recorded in the number of primary branches in treatments T7 (96.9%), T4 (91.2%), T8 (80.4%), T5 (79.5%), T9 (59.5%), T6 (57.6%), T2 (41.6%) and T3 (19.7%). Overall, when comparing at 60 & 90 DAS, both T4 and T7 were found to be more significant than all other treatments

Table 4.28 Effect of different doses of biochar application on fresh biomass (g) of pigeon pea at 30, 60 and 90 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	1.8^{e}	2.2^{f}	2.0^{h}	129.3^{d}	124.3^{e}	127^{e}	491^{f}	226.1^{f}	358.6^{f}
T_2	3.1^{cd}	2.6^{e}	2.9^{f}	154.4^{c}	142.9^{d}	148^{d}	630.4^{d}	384.9^{d}	507.7^{d}
T_3	2.6^{d}	2.4^{ef}	2.5^{g}	128.0^{d}	130.0^{e}	129^{e}	529.2^{e}	334.2^{e}	431.2^{e}
T_4	4.8^{a}	4.3^{b}	4.5^{b}	232.6^{a}	215.6^{a}	224.1^{a}	785.7^{ab}	579^{a}	682.3^{ab}
T_5	3.6^{bc}	3.7^{c}	3.7^{d}	185^{b}	184.9^{b}	185^{b}	743.6^{b}	537^{b}	640^{b}
T_6	3.2^{c}	3.3^{d}	3.2^{e}	160.6^{c}	156.7^{c}	158.7^{cd}	665.3^{c}	457c	561^{b}
T_7	4.9^{a}	4.8^{a}	4.8^{a}	220.9^{a}	218.3^{a}	219.6^{a}	806.0^{a}	596^{a}	701^{a}
T_8	3.9^{b}	4.2^{b}	4.0^{c}	190.7^{b}	194.9^{b}	192.8^{b}	746.7^{b}	553^{b}	649^{b}
T_9	3.4^{bc}	3.7^{c}	3.5^{de}	162.6^{c}	165.4^{c}	164^{c}	671.8^{c}	468^{c}	579^{c}
CD ($p\leq0.05$)	0.6	0.33	0.32	20.5	12.7	18	60.6	53.7	53
SEm (±)	0.2	0.1	0.1	6.8	4.2	6	20.3	17.9	17

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

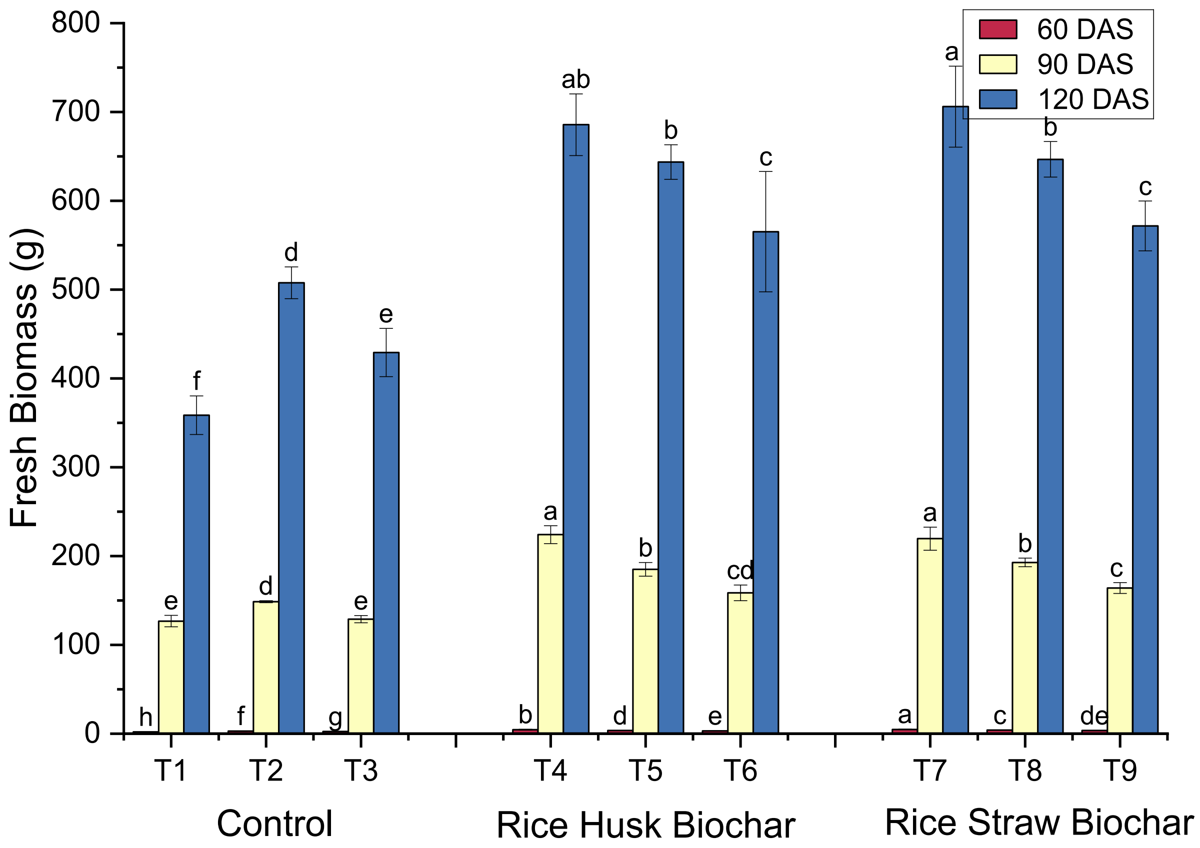


Figure 4.26. Effect of various biochar doses on fresh biomass (g) in pigeon pea at 60, 90, and 120 DAS.

The dry biomass of pigeon peas was significantly influenced by biochar during different growth stages in the 2023 season, as shown in **Table 4.29.** Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum dry biomass at 30 and 90 DAS, i.e., 2.28 g and 314.6 g, respectively. While at 60 DAS, treatment T4 (i.e. rice husk biochar @ 5 tons/ha) resulted in maximum dry biomass, i.e. 81.9 g. The maximum dry biomass at 90 DAS was recorded in T7 (314.6 g), followed by T4 (298.2 g), T8 (291.6 g), T5 (285.5 g), T9 (278.6 g), T6 (273.2 g), T2 (238.5 g), T3 (220.8 g) and T1 (195.2 g). As compared to control (T1), there was a significant percentage increase of dry biomass in treatments T7 (61.2%), T4 (52.8%), T8 (49.4%), T5 (46.3%), T9 (42.7%), T6 (40%), T2 (22.2%) and T3 (13.1%). However, at 60 DAS, T4 and T7 showed a significant improvement in dry biomass compared to all other treatments.

Throughout the 2024 season, a significant impact of biochar was observed on the dry biomass of pigeon peas during different growth stages. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum dry biomass at 30 and 90 DAS, i.e., 1.97 g and 264.6 g, respectively. While at 60 DAS, treatment T4 (i.e. rice husk biochar @ 5 tons/ha) resulted in maximum dry biomass, i.e. 76.9 g. The maximum dry biomass at 90 DAS was recorded in T7 (264.6 g), followed by T4 (248.2 g), T8 (241.6 g), T5 (235.5 g), T9 (228.6 g), T6 (223.2 g), T2 (188.5 g), T3 (170.8 g) and T1 (145.2 g). As compared to control (T1), there was a significant percentage increase of dry biomass in treatments T4 (71%), T7 (82.3%), T8 (66.4%), T5 (62.2%), T9 (57.5%), T6 (53.7%), T2 (29.8%) and T3 (17.7%). However, at 60 DAS, both T4 and T7 showed a significant improvement in dry biomass compared to all other treatments.

The mean dry biomass was found to be significant at all growth stages. The maximum dry biomass at 90 DAS was recorded in T7 (289.6 g), followed by T4 (273.2 g), T8 (266.6 g), T5 (260.5 g), T9 (253.5 g), T6 (248.2 g), T2 (213.5 g), T3 (195.8 g) and T1 (170.2 g). As compared to control (T1), there was a significant percentage increase of dry biomass in treatments T7 (70.2%), T4 (60.6%), T8 (56.7%), T5 (53.1%), T9 (49%), T6 (45.8%), T2 (25.4%) and T3 (15.1%). However, at 60 DAS, both T4 and T7 were found to be more significant than all other treatments.

Table 4.29 Effect of different doses of biochar application on dry biomass (g) of pigeon pea at 30, 60 and 90 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	0.85^{f}	0.85^{g}	0.9^{h}	32.8^{g}	27.8^{g}	30.3^{g}	195.2^{h}	145.2^{h}	170.2^{h}
T_2	1.22^{e}	1.22^{e}	1.2^{f}	54.8^{e}	49.8^{e}	52.3^{e}	238.5^{f}	188.5^{f}	213.5^{f}
T_3	1.00^{f}	1.00^{f}	1.0^{g}	38.0^{f}	33.0^{f}	35.5^{f}	220.8^{g}	170.8^{g}	195.8^{g}
T_4	1.64^{c}	1.61^{c}	1.6^{c}	81.9^{a}	76.9^{a}	79.4^{a}	298.2^{b}	248.2^{b}	273.2^{b}
T_5	1.51^{cd}	1.50^{cd}	1.5^{de}	79.3^{ab}	74.3^{ab}	76.8^{ab}	285.5^{cd}	235.5^{cd}	260.5^{cd}
T_6	1.42^{de}	1.41^{d}	1.4^{e}	73.3^{cd}	68.3^{cd}	70.8^{cd}	273.2^{e}	223.2^{e}	248.2^{e}
T_7	2.28^{a}	1.97^{a}	2.1^{a}	81.8^{a}	76.8^{a}	79.3^{a}	314.6^{a}	264.6^{a}	289.6^{a}
T_8	1.87^{b}	1.78^{b}	1.8^{b}	74.6^{bc}	69.6^{bc}	72.1^{bc}	291.6^{bc}	241.6^{bc}	266.6^{bc}
T_9	1.56^{cd}	1.57^{c}	1.6^{cd}	68.5^{d}	63.5^{d}	66.0^{d}	278.6^{de}	228.6^{de}	253.6^{de}
CD ($p \leq 0.05$)	0.21	0.14	0.11	5.1	5.1	5.1	11.7	11.7	11.7
SEm (±)	0.07	0.05	0.04	1.7	1.7	1.7	3.8	3.8	3.8

***** Means denoted by different letters are significantly different at $p \leq 0.05$, treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

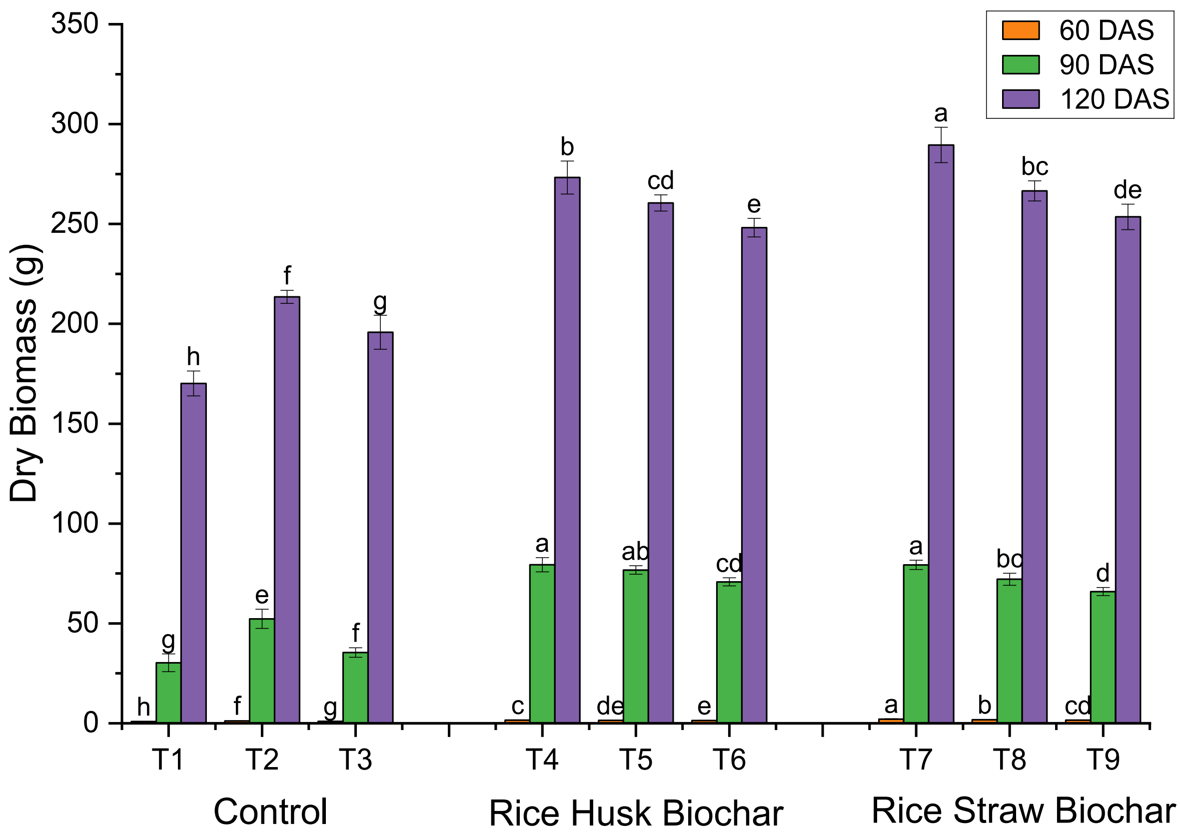


Figure 4.27. Effect of various biochar doses on dry biomass in pigeon pea at 60, 90, and 120 DAS.

The number of trifoliate leaves on pigeon peas was notably influenced by biochar during different growth stages in the 2023 season, with results in **Table 4.30**. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum number of trifoliate leaves at 30 and 60 DAS, i.e., 19 and 242, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum number of trifoliate leaves, i.e., 415. The maximum number of trifoliate leaves at 90 DAS was recorded in T4 (415), followed by T7 (405), T5 (388), T8 (381), T6 (366), T9 (360), T2 (344), T3 (311 cm) and T1 (276). Compared to the control (T1), a substantial percentage increase was recorded in the number of trifoliate leaves in treatments T4 (50.1%), T7 (46.4%), T5 (40.4%), T8 (37.7%), T6 (32.4%), T9 (30.4%), T2 (24.3%) and T3 (12.7%). However, at 30 and 90 DAS, both T4 and T7 showed a significant improvement in the number of trifoliate leaves compared to all other treatments.

Subsequently, in the 2024 season, a significant impact of biochar was observed on the number of trifoliate leaves of pigeon peas during different growth stages. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum number of trifoliate leaves at 30 and 60 DAS, i.e., 20 and 240, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum number of trifoliate leaves, i.e., 439. The maximum number of trifoliate leaves at 90 DAS was recorded in T4 (439), followed by T7 (436), T5 (405), T8 (403), T9 (386), T6 (384), T2 (298), T3 (266 cm) and T1 (220). Compared to the control (T1), a substantial percentage increase was recorded in the number of trifoliate leaves in treatments T4 (98.9%), T7 (97.9%), T5 (83.7%), T8 (82.6%), T9 (75.2%), T6 (74%), T2 (35.3%) and T3 (20.8%). However, at 30 and 90 DAS, both T4 and T7 showed a significant improvement in the number of trifoliate leaves compared to all other treatments.

The mean number of trifoliate leaves was found to be significant at all growth stages. The maximum dry biomass was recorded at 90 DAS in T4 (427.2), followed by T7 (420), T5 (396.8), T8 (392), T6 (375.2), T9 (373.7), T2 (321.3), T3 (289.2), and T1 (248.7). As compared to control (T1), there was a significant percentage increase of dry biomass in treatments T4 (71.8%), T7 (69.2%), T5 (59.6%), T8 (57.6%), T6 (50.9%), T3 (50.6%), T2 (29.2%) and T1 (16.3%). However, at 30 and 90 DAS, both T4 and T7 were found to be more significant than all other treatments.

Table 4.30 Effect of different doses of biochar application on the number of trifoliate leaves of pigeon pea at 30, 60 and 90 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	9.3^{g}	11.3^{g}	10.3^{f}	82.7^{h}	74^{g}	78.3^{i}	276.7^{h}	220.7^{e}	248.7^{f}
T_2	11.0^{f}	13.7^{ef}	12.3^{e}	118.0^{f}	113.7^{e}	115.8^{g}	344^{f}	298.7^{c}	321.3^{d}
T_3	10.0^{fg}	12.3^{fg}	11.2^{f}	97.7^{g}	88.7^{f}	93.2^{h}	311.7^{g}	266.7^{d}	289.2^{e}
T_4	18.3^{ab}	19.3^{ab}	18.8^{ab}	230.3^{b}	213.7^{b}	222.0^{b}	415.3^{a}	439.0^{a}	427.2^{a}
T_5	16.7^{cd}	17.7^{bc}	17.2^{c}	205.3^{c}	188.3^{c}	196.8^{d}	388.3^{bc}	405.3^{b}	396.8^{b}
T_6	14.3^{e}	16.3^{cd}	15.3^{d}	148.0^{e}	167.7^{d}	157.8^{f}	366.3^{de}	384.0^{b}	375.2^{c}
T_7	19.0^{a}	20.0^{a}	19.5^{a}	242^{a}	240.0^{a}	241.0^{a}	405^{ab}	436.7^{a}	420.8^{a}
T_8	17.7^{bc}	18.3^{ab}	18.0^{bc}	194.7^{c}	215.3^{b}	205.0^{c}	381^{cd}	403.0^{b}	392^{b}
T_9	16.0^{d}	15.3^{de}	15.7^{d}	173.0^{d}	188.3^{c}	180.7^{e}	360.7^{ef}	386.7^{b}	373.7^{c}
CD ($p \leq 0.05$)	1.3	1.6	1	11	11	7.7	17.5	23.4	13
SEm (±)	0.4	0.5	0.3	0.4	3.6	2.5	5.9	7.8	4

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

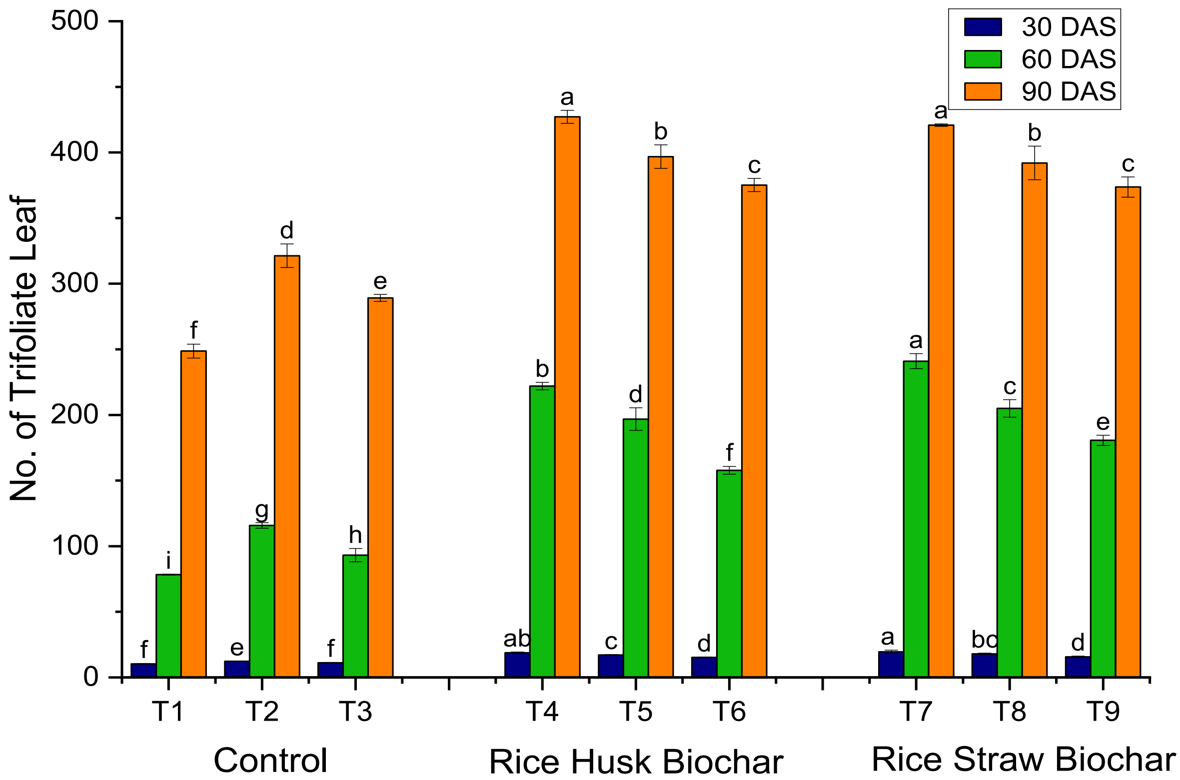


Figure 4.28. Effect of different biochar doses on no. of trifoliate leaf in pigeon pea at 30, 60, and 90 DAS.

The results in **Table 4.31** emphasise the considerable influence of biochar on the stem girth of pigeon peas during various growth stages in the 2023 season. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum stem girth at 30, 60, and 90 DAS, i.e., 3.4 mm, 15.1 mm, and 22.3 mm, respectively. The maximum stem girth at 90 DAS was recorded in T7 (22.3 mm), followed by T4 (21.9 mm), T8 (21.4 mm), T5 (20.8 mm), T9 (20.3 mm), T6 (19.7 mm), T2 (18.8 mm), T3 (17.7 mm) and T1 (15.9 mm). Compared to the control (T1), a substantial percentage increase was recorded in the stem girth leaves in treatments T7 (40.9 %), T4 (38 %), T8 (35%), T5 (31.2%), T9 (27.8%), T96 (24.2%), T2 (18.7%) and T3 (11.4%). However, at 30 and 90 DAS, both T4 and T7 showed a significant improvement in stem girth compared to all other treatments.

Subsequently, in the 2024 season, a significant impact of biochar was observed on the stem girth of pigeon peas during different growth stages. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum stem girth at 30 and 60 DAS, i.e., 2.9 mm and 15.9 mm, respectively. While the maximum stem girth at 90 DAS was recorded in T7 (20.4 mm), followed by T4 (20.2 mm), T8 (18.8 mm), T5 (18.3 mm), T6 (18.2 mm), T9(17.6 mm), T2 (17.3 mm), T3 (15.5 mm) and T1 (13.4 mm). Compared to the control (T1), a substantial percentage increase was recorded in the stem girth leaves in treatments T7 (52.2%), T4 (50.7%), T8 (40%), T5 (36.8%), T6 (35.6%), T9 (31.3%), T2 (29.4%) and T3 (15.9%).

The mean stem girth was found to be significant at all growth stages. The maximum stem girth at 90 DAS was recorded in T7 (21.4 mm), followed by T4 (21 mm), T8 (20.1 mm), T5 (19.6 mm), T6 (18.9 mm), T9 (18.9 mm), T2 (18.1 mm), T3 (16.6 mm) and T1 (14.6 mm). Compared to the control (T1), a substantial percentage increase was recorded in stem girth in treatments T7 (46.1%), T4 (43.9%), T8 (37.3%), T5 (33.8%), T6 (29.4%), T9 (29.4%), T2 (23.6%) and T3 (13.5%). Overall, when comparing all growth stages, the impact of T4 and T7 was found to be more significant than all other treatments.

Table 4.31 Effect of different doses of biochar application on stem girth (mm) of pigeon peas at 30, 60 and 90 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	2.2^{g}	2.3^{f}	2.3^{g}	8.9^{g}	8.7^{f}	8.8^{f}	15.9^{h}	13.4^{e}	14.6^{f}
T_2	2.8^{e}	2.5^{d}	2.7^{e}	10.7^{e}	12.1^{e}	11.4^{d}	18.8^{f}	17.3^{c}	18.1^{d}
T_3	2.6^{f}	2.4^{e}	2.5^{f}	9.8^{f}	11.3^{e}	10.5^{e}	17.7^{g}	15.5^{d}	16.6^{e}
T_4	3.3^{ab}	2.9^{a}	3.1^{a}	14.1^{b}	15.9^{a}	15.0^{a}	21.9^{ab}	20.2^{a}	21.0^{a}
T_5	3.2^{c}	2.8^{a}	3.0^{b}	13.5^{c}	14.7^{bc}	14.1^{b}	20.8^{cd}	18.3^{bc}	19.6^{bc}
T_6	2.9^{d}	2.7^{b}	2.8^{d}	12.3^{d}	13.9^{cd}	13.1^{c}	19.7^{e}	18.2^{bc}	18.9^{cd}
T_7	3.4^{a}	2.8^{a}	3.2^{a}	15.1^{a}	15.1^{ab}	15.1^{a}	22.3^{a}	20.4^{a}	21.4^{a}
T_8	3.3^{bc}	2.7^{b}	3.0^{c}	14.2^{b}	14.3^{bcd}	14.2^{b}	21.4^{bc}	18.8^{b}	20.1^{b}
T_9	3^{d}	2.6^{c}	2.8^{d}	12.5^{d}	13.6^{d}	13.1^{c}	20.3^{de}	17.6^{c}	18.9^{cd}
CD ($p \leq 0.05$)	0.12	0.06	0.05	0.54	0.87	0.54	0.78	1.1	0.87
SEm (±)	0.04	0.02	0.017	0.18	0.29	0.18	0.26	0.37	0.29

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

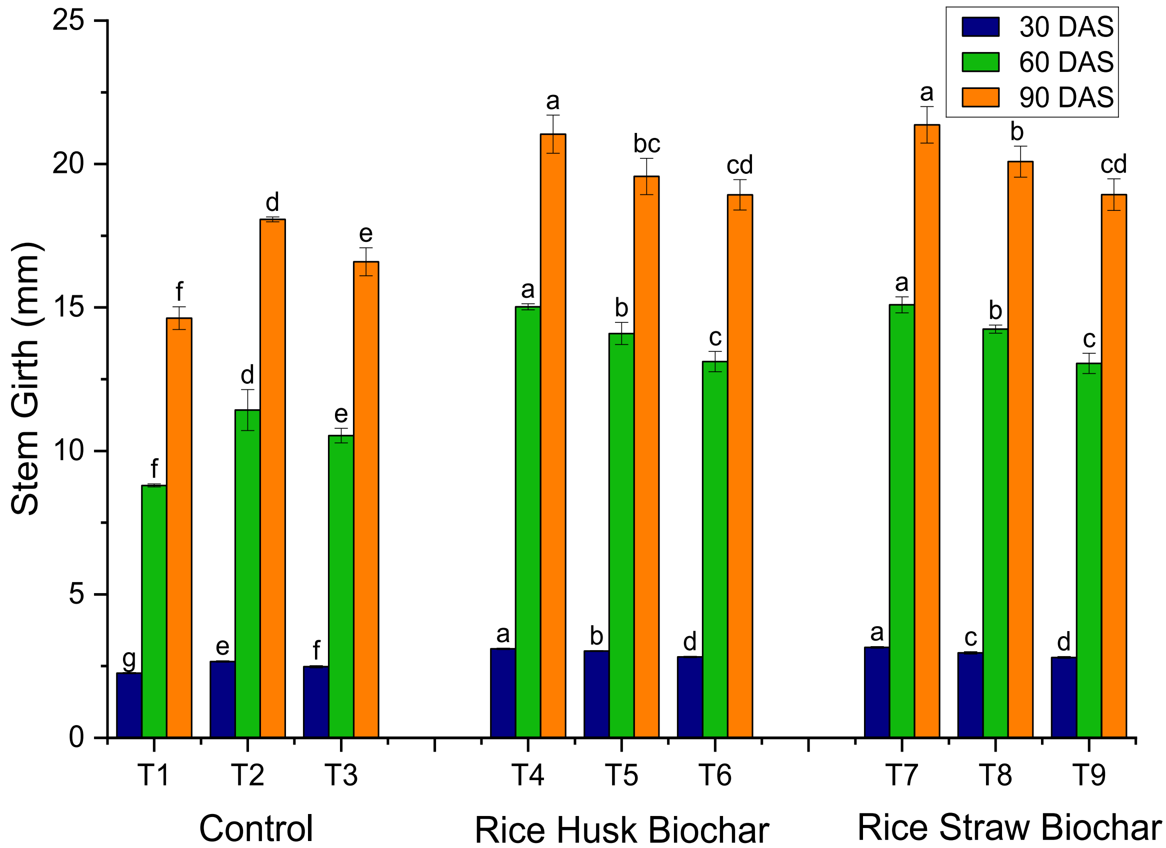


Figure 4.29. Effect of different biochar on stem girth (mm) in pigeon pea at 30, 60, and 90 DAS.

The growth attributes of pigeon peas (*Cajanus cajan*), such as plant height, number of primary branches, fresh and dry biomass, number of trifoliate leaves, and stem girth, are critical indicators of the plant's overall health and productivity. These parameters are intricately linked to the crop yield. For instance, increased plant height and a more significant number of branches typically correlate with enhanced light interception and photosynthetic capacity, which directly contribute to biomass accumulation and seed production. The number of trifoliate leaves is particularly significant, as it reflects the plant's ability to harness sunlight for photosynthesis, which in turn influences growth rates and final yield (Bhadru et al., 2010). Additionally, measurements of fresh and dry biomass provide insights into plant resource allocation strategies; higher biomass often suggests a more vigorous growth phase, which can lead to increased pod formation and seed yield (Ade et al., 2018).

From a physiological perspective, these growth attributes are manifestations of the plant's adaptive responses to environmental conditions and the availability of nutrients. Enhanced growth parameters indicate efficient physiological processes, including nutrient uptake, water retention, and metabolic activity. For example, taller plants with more branches can effectively capture more sunlight, increasing photosynthetic efficiency. Moreover, biochar application has been shown to improve soil structure and nutrient retention capabilities, supporting better root development and overall plant vigour (Nataraja et al., 2024). The physiological benefits of biochar include improved water-holding capacity and enhanced microbial activity in the soil, both of which contribute to healthier plants that can achieve optimal growth attributes.

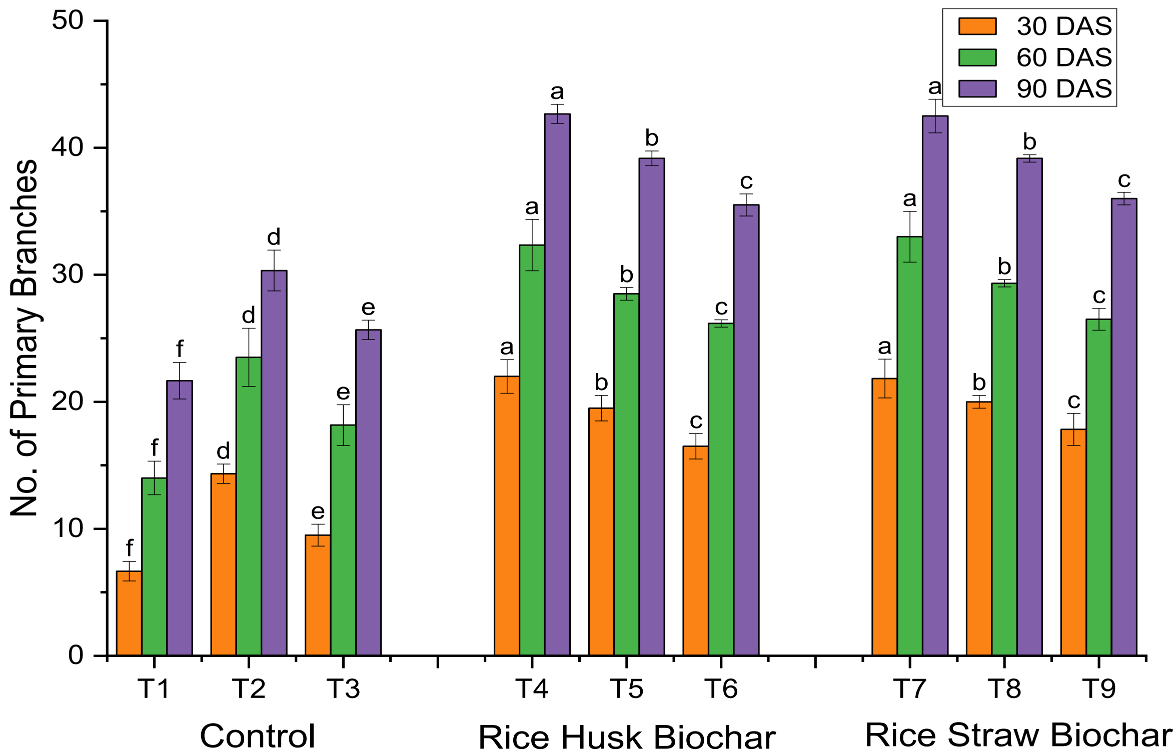


Figure 4.30. Effect of different biochar doses on the number of primary branches in pigeon pea at 30, 60, 90, and 120 DAS.

4.5 Physiological parameters

The total chlorophyll content of pigeon peas was significantly influenced by biochar during different growth stages in the 2023 season, as shown in **Table 4.32**. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum Total chlorophyll content at 30, 60, and 90 DAS, i.e., 0.80 mg/g, 1.11 mg/g, and 2.60 mg/g, respectively. However, at 30 DAS (T4, T7 & T8), and at 60 and 90 DAS (T4 & T7), a significant improvement in total chlorophyll content was observed compared to all other treatments. The maximum Total chlorophyll content at 90 DAS was recorded in T7 (2.60 mg/g) followed by T4 (2.49 mg/g), T5 (2.39 mg/g), T8 (2.31 mg/g), T6 (2.29 mg/g), T9 (2.23 mg/g), T2 (2.02 mg/g), T3 (1.92 mg/g) and T1 (1.26 mg/g). Compared to the control (T1), a substantial percentage increase was recorded in Total chlorophyll content in treatments T7 (106.5%), T4 (98.3%), T5 (90%), T8 (83.7%), T6 (81.8%), T9 (77%), T2 (60.6%) and T3 (52.4%).

Throughout the 2024 season, a significant impact of biochar was observed on the total chlorophyll content of pigeon peas during different growth stages. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum Total chlorophyll content at 30, 60, and 90 DAS, i.e., 1.13 mg/g, 1.61 mg/g, and 3.18 mg/g, respectively. However, at 30 DAS (T4 & T7) and 60 DAS (T4, T5, T6, T7, T8 & T9), a significant improvement in total chlorophyll content was observed compared to all other treatments. The maximum Total chlorophyll content at 90 DAS was recorded in T7 (3.18 mg/g) followed by T8 (2.93 mg/g), T4 (2.70 mg/g), T9 (2.66 mg/g), T5 (2.51 mg/g), T6 (2.36 mg/g), T2 (2.11 mg/g), T3 (1.97 mg/g) and T1 (1.68 mg/g). Compared to the control (T1), a substantial percentage increase was recorded in Total chlorophyll content in treatments T7 (89.1%), T8 (74.3%), T4 (60.4%), T9 (57.8%), T5 (48.9%), T6 (40%), T2 (25.5%) and T3 (17.5%).

The mean Total chlorophyll content was found to be significant at all growth stages. The maximum Total chlorophyll content at 90 DAS was recorded in T7 (2.89 mg/g) followed by T8 (2.62 mg/g), T4 (2.60 mg/g), T5 (2.45 mg/g), T9 (2.44 mg/g), T6 (2.32 mg/g), T2 (2.07 mg/g), T3 (1.95 mg/g) and T1 (1.47 mg/g). Compared to the control (T1), a substantial percentage increase was recorded in Total chlorophyll content in treatments T7 (96.5%), T8 (78.3%), T4 (76.6%), T5 (66.5%), T9 (66%), T6 (57.9%), T2 (40.5%) and T3 (32.3%). However, 30 DAS (T4 & T7) and 60 DAS (T4, T5, T7 & T8) were found to be more significant than all other treatments.

Table 4.32 Effect of different doses of biochar application on total chlorophyll content (mg/g) of pigeon pea at 30, 60 and 90 DAS, during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	0.46^{d}	0.55^{g}	0.50^{g}	0.58^{f}	0.71^{b}	0.65^{d}	1.26^{f}	1.68^{h}	1.47^{g}
T_2	0.60^{bc}	0.74^{e}	0.67^{e}	0.83^{de}	0.96^{b}	0.90^{c}	2.02^{e}	2.11^{f}	2.07^{e}
T_3	0.55^{c}	0.63^{f}	0.59^{f}	0.78^{e}	0.82^{b}	0.80^{cd}	1.92^{e}	1.97^{g}	1.95^{f}
T_4	0.76^{a}	1.10^{ab}	0.93^{ab}	1.09^{a}	1.36^{a}	1.23^{ab}	2.49^{ab}	2.70^{c}	2.60^{b}
T_5	0.65^{b}	1.00^{c}	0.82^{c}	0.99^{b}	1.52^{a}	1.25^{ab}	2.39^{bc}	2.51^{d}	2.45^{c}
T_6	0.61^{bc}	0.91^{d}	0.76^{d}	0.90^{cd}	1.37^{a}	1.14^{b}	2.29^{cd}	2.36^{e}	2.32^{d}
T_7	0.80^{a}	1.13^{a}	0.97^{a}	1.11^{a}	1.61^{a}	1.36^{a}	2.60^{ab}	3.18^{a}	2.89^{a}
T_8	0.73^{a}	1.07^{b}	0.90^{b}	0.96^{bc}	1.49^{a}	1.23^{ab}	2.31^{cd}	2.93^{b}	2.62^{b}
T_9	0.63^{b}	1.01^{c}	0.82^{c}	0.91^{cd}	1.39^{a}	1.15^{b}	2.23^{d}	2.66^{c}	2.44^{c}
CD ($p \leq 0.05$)	0.08	0.05	0.04	0.07	0.40	0.20	0.12	0.06	0.07
SEm (±)	0.03	0.02	0.01	0.02	0.13	0.07	0.04	0.02	0.02

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

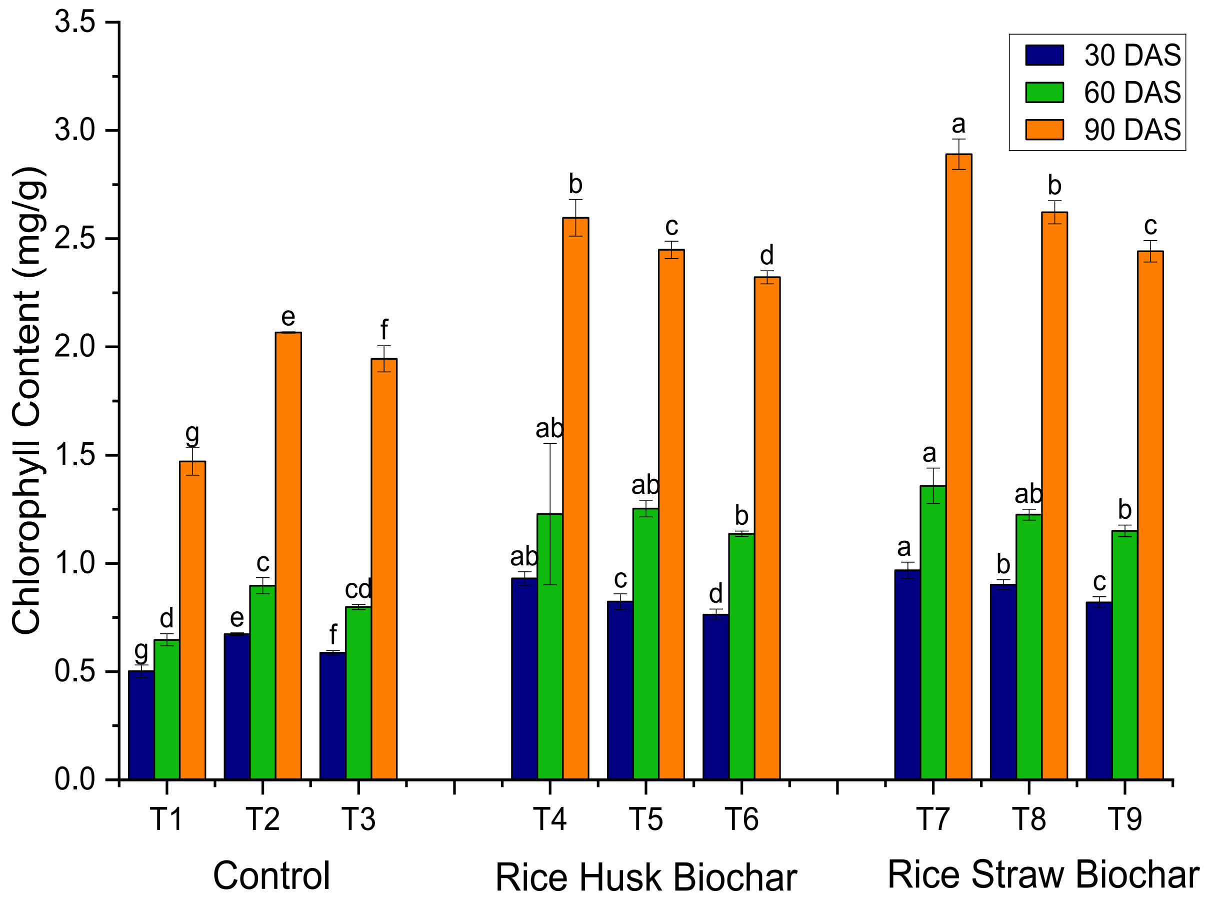


Figure 4.31. Effect of different biochar doses on chlorophyll (mg/g) in pigeon pea at 30, 60, and 90 DAS.

The total chlorophyll content of pigeon peas was significantly influenced by biochar during different growth stages in the 2023 season, as shown in **Table 4.33.** Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum relative water content at 30 and 60 DAS, i.e., 90% and 79.1%, respectively. At 90 DAS, treatment T7 (i.e., rice straw biochar at 5 tons/ha) resulted in the maximum relative water content, i.e., 74.4%. However, during all growth stages, both T4 and T7 showed a significant improvement in relative water content compared to all other treatments. The maximum relative water content at 90 DAS was recorded in T7 (74.4 %), followed by T4 (73.7 %), T8 (72.5 %), T5 (71.6 %), T9 (69.1 %), T6 (68.5 %), T2 (66.3 %), T3 (64.7 %) and T1 (61.1 %). Compared to the control (T1), a substantial percentage increase was recorded in relative water content in treatments T7 (21.8%), T4 (20.5%), T8 (18.5%), T5 (17.1%), T9 (13%), T9 (12.1%), T2 (8.5%) and T3 (5.8%).

Throughout the 2024 season, a significant impact of biochar was observed on the relative water content of pigeon peas during different growth stages. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum relative water content at 30 DAS, i.e., 90.3%. At 60 and 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum relative water content, i.e., 79.2% and 75.4%, respectively. However, 30 DAS (T4, T7 & T8) and 60 DAS (T4 & T7) showed a significant improvement in relative water content compared to all other treatments. The maximum relative water content at 90 DAS was recorded in T4 (75.4 %), followed by T4 (73.2 %), T5 (71.4 %), T8 (71.1 %), T9 (69.4 %), T6 (69.3%), T2 (66.4 %), T3 (64.6 %) and T1 (59.6 %). Compared to the control (T1), a substantial percentage increase was recorded in relative water content in treatments T4 (26.5%), T7 (22.8%), T5 (19.7%), T8 (19.4%), T9 (16.4%), T6 (16.3%), T2 (11.5%) and T3 (8.3%).

The mean relative water content was found to be significant at all growth stages. The maximum relative water content at 90 DAS was recorded in T4 (74.5 %), followed by T7 (73.8%), T8 (71.8 %), T5 (71.5 %), T9 (69.2 %), T6 (68.9 %), T2 (66.4 %), T3 (64.6 %) and T1 (60.4 %). Compared to the control (T1), a substantial percentage increase was recorded in relative water content in treatments T4 (23.4%), T7 (22.3%), T8 (18.9%), T5 (18.4%), T9 (14.7%), T6 (14.2%), T2 (9.9%) and T3 (7.1%). However, 30 DAS (T4, T7 & T8) and 60 DAS (T4 & T7) were found to be more significant than all other treatments.

4.33 Effect of different doses of biochar application on relative water content (%) of pigeon pea at 30, 60 and 90 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	71.5^{f}	71.4^{c}	71.5^{d}	66.7^{h}	66.4^{g}	66.6^{g}	61.1^{e}	59.6^{g}	60.4^{f}
T_2	75.1^{e}	73.5^{c}	74.3^{c}	71.8^{f}	72.3^{e}	72.1^{e}	66.3^{d}	66.4^{e}	66.4^{d}
T_3	73.3^{ef}	74.7^{c}	74.0^{c}	69.5^{g}	69.4^{f}	69.5^{f}	64.7^{d}	64.6^{f}	64.6^{e}
T_4	90.0^{a}	88.8^{a}	89.4^{a}	79.1^{a}	79.2^{a}	79.2^{a}	73.7^{a}	75.4^{a}	74.5^{a}
T_5	85.8^{bc}	83.8^{b}	84.8^{b}	77.0^{bc}	75.9^{b}	76.5^{b}	71.6^{b}	71.4^{c}	71.5^{b}
T_6	83.9^{cd}	82.5^{b}	83.2^{b}	74.3^{de}	74.5^{cd}	74.4^{cd}	68.5^{c}	69.3^{d}	68.9^{c}
T_7	88.3^{ab}	90.3^{a}	89.3^{a}	78.1^{ab}	78.4^{a}	78.3^{a}	74.4^{a}	73.2^{b}	73.8^{a}
T_8	86.1^{bc}	90.1^{a}	88.1^{a}	75.6^{cd}	75.5^{bc}	75.6^{bc}	72.5^{b}	71.1^{c}	71.8^{b}
T_9	82.9^{d}	84.4^{b}	83.7^{b}	73.9^{e}	73.6^{d}	73.8^{d}	69.1^{c}	69.4^{d}	69.2^{c}
CD ($p\leq0.05$)	2.7	3.7	2.7	1.6	1.2	1.2	2	1.5	1.2
SEm (±)	0.9	1.2	0.8	0.5	0.4	0.4	0.7	0.5	0.4

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

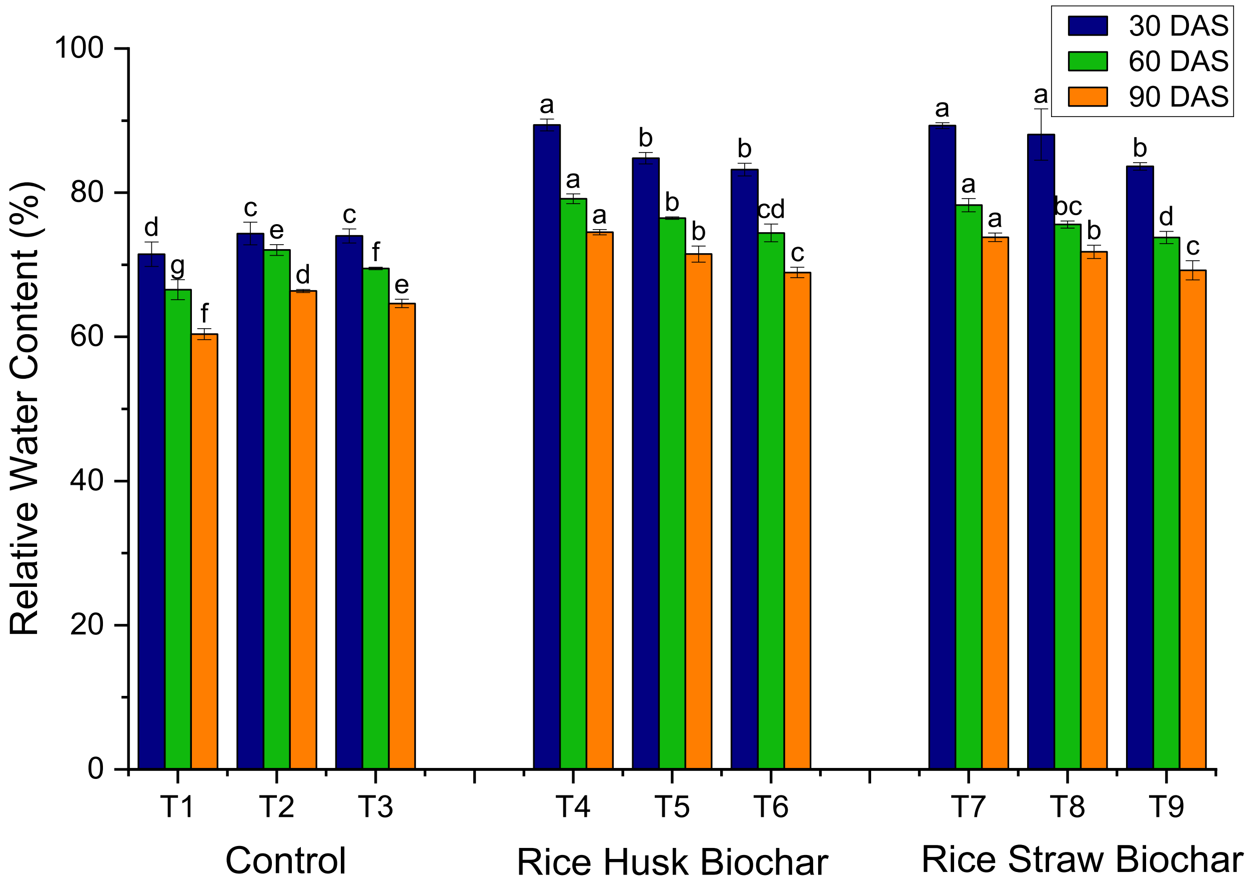


Figure 4.32. Effect of different biochar doses on RWC (%) in pigeon pea at 30, 60, and 90 DAS.

The membrane stability index of pigeon peas was significantly influenced by biochar during different growth stages in the 2023 season, as presented in **Table 4.34**. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum membrane stability index in leaves at 30 and 60 DAS, i.e., 75.7% and 80.2%, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum membrane stability index, i.e., 84.5%. However, at 60 and 90 days, DAS T4, T7, and T8 showed a significant improvement in membrane stability index compared to all other treatments. The maximum membrane stability index at 90 DAS was recorded in T4 (84.5%), followed by T5 (83.8%), T7 (83.5%), T8 (82%), T6 (80.5%), T9 (80.2%), T2 (77.7%), T3 (75.8%) and T1 (72.6%). Compared to the control (T1), a substantial percentage increase was recorded in the MSI in treatments T4 (16.3%), T5 (15.4%), T5 (15%), T8 (12.8%), T6 (10.8%), T9 (10.4%), T2 (7%) and T3 (4.4%).

Subsequently, in the 2024 season, a significant impact of biochar was observed on the membrane stability index of pigeon peas during different growth stages. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum membrane stability index in leaves at 30 and 60 DAS, i.e., 76.5% and 82.6%, respectively. At 90 DAS, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in the maximum membrane stability index, i.e., 85.4%. The maximum membrane stability index at 90 DAS was recorded in T4 (85.4%), followed by T5 (84.5%), T7 (84.5%), T8 (81.9%), T6 (80.4%), T9 (80%), T2 (80%), T3 (77.7%) and T1 (75.4%). Compared to the control (T1), a substantial percentage increase was recorded in the membrane stability index in treatments T4 (13.2%), T7 (12.1%), T5 (12%), T8 (8.6%), T6 (6.6%), T9 (6%), T2 (6%) and T3 (3%). However, 60 DAS (T4 & T7) and 90 DAS (T4, T5 & T7) showed a significant improvement in membrane stability index compared to all other treatments.

The mean membrane stability index was found to be significant at all growth stages. The maximum membrane stability index at 90 DAS was recorded in T4 (84.9 %), followed by T5 (84.1%), T7 (84 %), T8 (82 %), T6 (80.5 %), T9 (80.1 %), T2 (78.8 %), T3 (76.8 %) and T1 (74 %). Compared to the control (T1), a substantial percentage increase was recorded in membrane stability index in treatments T4 (14.7%), T5 (13.7%), T7 (13.5%), T8 (10.7%), T6 (8.7%), T9 (8.1%), T2 (6.5%) and T3 (3.7%). However, 60 DAS (T4 & T7) and 90 DAS (T4, T5 & T9) were found to be more significant than all other treatments.

Table 4.34 Effect of different doses of biochar application on membrane stability index (%) of pigeon pea at 30, 60 and 90 DAS during 2023 and 2024.

Treatments	30 DAS			60 DAS			90 DAS		
	2023	**2024**	**Mean**	**2023**	**2024**	**Mean**	**2023**	**2024**	**Mean**
T_1	59.6^{f}	62.8^{g}	61.2^{f}	64.4^{e}	66.3^{g}	65.4^{f}	72.6^{e}	75.4^{e}	74.0^{f}
T_2	65.5^{de}	66.6^{f}	66.1^{e}	72.0^{c}	75.7^{e}	73.8^{d}	77.7^{cd}	80.0^{c}	78.8^{de}
T_3	64.2^{e}	65.3^{f}	64.7^{e}	68.2^{d}	69.5^{f}	68.9^{e}	75.8^{d}	77.7^{d}	76.8^{e}
T_4	72.7^{b}	74.5^{b}	73.6^{b}	79.3^{a}	81.3^{ab}	80.3^{ab}	84.5^{a}	85.4^{a}	84.9^{a}
T_5	72.4^{bc}	71.9^{cd}	72.2^{b}	75.7^{b}	78.5^{cd}	77.1^{c}	83.8^{a}	84.5^{a}	84.1^{a}
T_6	67.1^{d}	68.6^{e}	67.8^{d}	75.6^{b}	77.4^{de}	76.5^{c}	80.5^{bc}	80.4^{bc}	80.5^{cd}
T_7	75.7^{a}	76.5^{a}	76.1^{a}	80.2^{a}	82.6^{a}	81.4^{a}	83.5^{a}	84.5^{a}	84.0^{ab}
T_8	72.4^{bc}	72.4^{c}	72.4^{b}	78.6^{a}	79.9^{bc}	79.3^{b}	82.0^{ab}	81.9^{b}	82.0^{bc}
T_9	70.2^{c}	70.6^{d}	70.4^{c}	74.7^{b}	76.6^{de}	75.7^{cd}	80.2^{bc}	80.0^{c}	80.1^{cd}
CD ($p \leq 0.05$)	2.4	1.4	1.7	2.1	2.1	1.9	2.8	1.9	2.1
SEm (±)	0.8	0.5	0.6	plant's	0.7	0.7	0.9	0.7	0.7

***** Means denoted by different letters are significantly different at $p \leq 0.05$, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

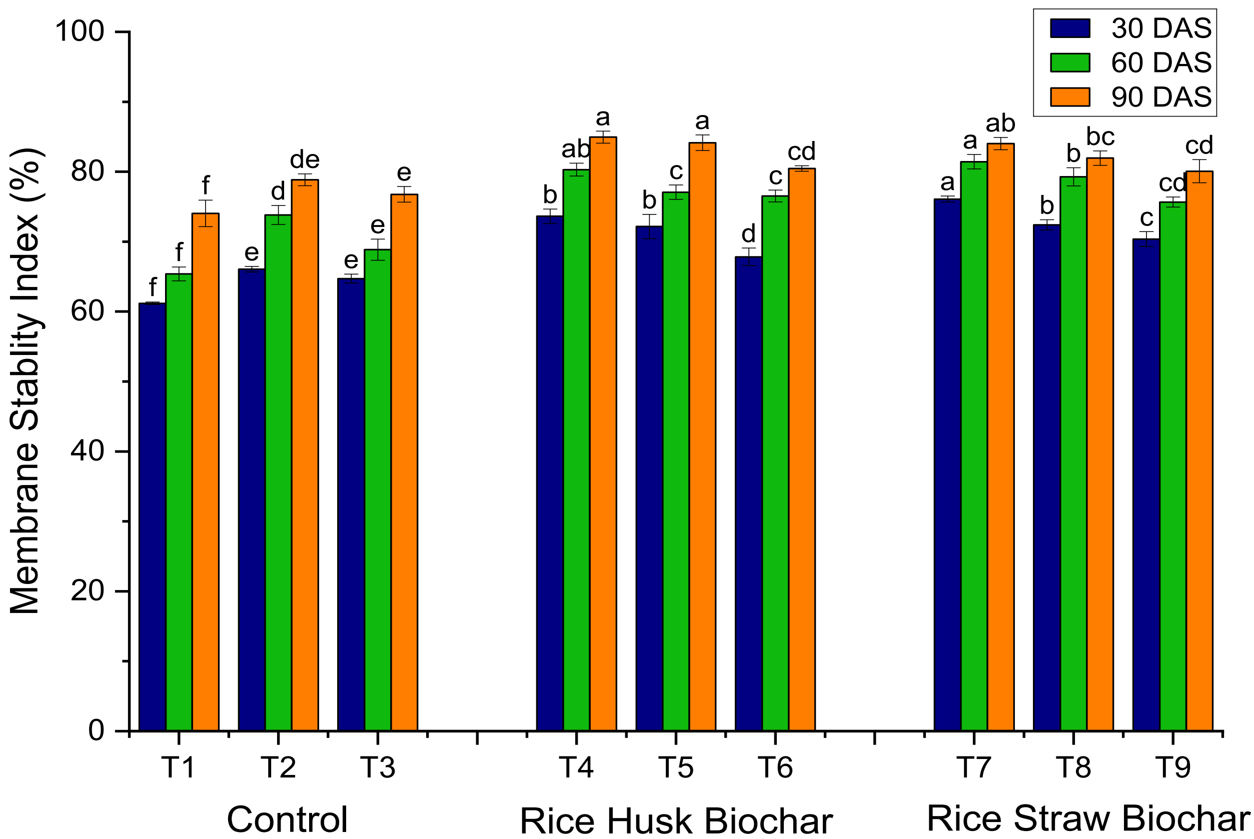


Figure 4.33. Effect of different biochar doses on MSI (%) in pigeon pea at 30, 60, and 90 DAS.

The physiological attributes of pigeon peas, including relative water content, chlorophyll content, membrane stability index, and injury index, play a crucial role in determining the plant's overall health and yield potential. These parameters are essential indicators of a plant's ability to adapt to environmental stressors, particularly water scarcity and temperature fluctuations. Relative water content reflects the plant's hydration status, which is vital for maintaining turgor pressure and facilitating various physiological processes, including photosynthesis and nutrient uptake. High RWC is associated with improved growth and yield, as it indicates that the plant can effectively manage water resources during drought or stress (Mishra et al., 2018). Chlorophyll content is another critical parameter that directly correlates with photosynthetic efficiency. Increased chlorophyll levels enhance the plant's ability to capture light energy, resulting in higher rates of photosynthesis and, consequently, greater biomass accumulation and seed yield (Ghosh et al., 2017). The membrane stability index indicates cell membrane integrity under stress conditions; higher MSI values suggest better resilience against environmental stresses, which can lead to improved growth and yield outcomes. Conversely, a lower injury index indicates reduced cellular damage, allowing for more efficient metabolic processes and the allocation of resources towards growth and reproduction.

4.6 Yield attributes

The number of pods per plant in pigeon peas was significantly influenced by biochar during the 2023 season, as shown in **Table 4.35.** Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum number of pods per plant. i.e. 993. However, T4, T7 and T8 showed a significant improvement in pod per plant compared to all other treatments. The maximum pods per plant were recorded in T7 (993), followed by T4 (958.3), T8 (894.7), T5 (825), T9 (802), T6 (766), T2 (374), T3 (354), and T1 (336.7). As compared to control (T1), there was a significant percentage increase of pods per plant in treatments T7(195%), T4 (184.7%), T8 (165.7%), T5 (145%), T9 (138.2%), T6 (127.5%), T2 (11.1%) and T3 (5.1%). **Subsequently,** throughout the 2024 season, a significant impact of biochar was observed on the number of pods per plant of pigeon pea. However, T4, T7 and T8 showed a significant improvement in pod per plant compared to all other treatments. Among all treatments, T7 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum number of pods per plant. i.e. 373.7. The maximum pod per plant was recorded in T7 (373.7), followed by T4 (368), T8 (628.2), T5 (584.5), T9 (580.2), T6 (549.8), T2 (259.3), T3 (248.7) and T1 (185.3). As compared to control (T1), there was a significant percentage increase of pods per plant in treatments T7 (101.6%), T4 (98.6%), T8 (95.1%), T9 (91.4%), T5 (85.6%), T6 (80%), T2 (39.9%) and T3 (34.2%). **Subsequently,** the mean pod per plant was found to be significant at all growth stages. However, both T4 and T7 showed a significant improvement in pods per plant compared to all other treatments. The maximum pod per plant was recorded in T7 (683.3), followed by T4 (663.2), T8 (628.2), T5 (584.5), T9 (580.2), T6 (549.8), T2 (316.7), T3 (301.3) and T1 (261). As compared to control (T1), there was a significant percentage increase of pods per plant in treatments T7

(161.8%), T4 (154.1%), T8 (140.7%), T5 (123.9%), T9 (122.3%), T6 (110.7%), T2 (21.3%) and T3 (15.5%).

The impact of biochar on the grains per pod of pigeon peas was significant during the 2023 season. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in grains per pod compared to all other treatments. Among all treatments, T7 and T4 (i.e., rice straw and husk biochar at 5 tons/ha) recorded the maximum grain per pod. i.e. 5.7. The maximum grain per pod was recorded in T7 and T4 (5.7), followed by T8 and T5 (5.3), T6 and T9 (4.7), T2 (4.3), T3 (3.7) and T1 (3.3). Compared to the control (T1), there was a significant percentage increase in grain per pod in treatments T4 and T7 (70%), T5 and T8 (60%), T6 and T9 (40%), T2 (30%), and T3 (10%). **Subsequently,** during the 2024 season, a significant impact of biochar was observed on grain per pod of pigeon peas. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in grains per pod compared to all other treatments. Among all treatments, T7 and T4 (i.e., rice straw and husk biochar at 5 tons/ha) recorded the maximum grain per pod. i.e. 5.7. The maximum grain per pod was recorded in T7 and T4 (5.7), followed by T8 and T5 (5.3), T6 and T9 (4.7), T2 (4.3), T3 (3.7) and T1 (3.3). Compared to the control (T1), there was a significant percentage increase in grain per pod in treatments T4 and T7 (70%), T5 and T8 (60%), T6 and T9 (40%), T2 (30%), and T3 (10%). **Subsequently,** the maximum mean grain per pod was recorded in T7 and T4 (i.e., rice straw and husk biochar at 5 tons/ha), which recorded the maximum grain per pod. i.e. 5.7. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in grains per pod compared to all other treatments. The maximum grain per pod was recorded in T7 and T4 (5.7), followed by T8 and T5 (5.3), T6 and T9 (4.7), T2 (4.3), T3 (3.7) and T1 (3.3). Compared to the control (T1), there was a significant percentage increase in grain per pod in treatments T4 and T7 (70%), T5 and T8 (60%), T6 and T9 (40%), T2 (30%), and T3 (10%).

Throughout the 2023 season, a significant impact of biochar was observed on the pod length of pigeon peas. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum pod length. i.e. 6.7 cm. However, both T4 and T7 showed a significant improvement in pod length compared to all other treatments. The maximum pod length was recorded in T7 (6.7 cm), followed by T4 (6.6 cm), T8 (6.3 cm), T5 (6.2 cm), T6 (5.9 cm), T9 (5.7 cm), T2 (5.3 cm), T3 (4.8 cm) and T1 (4.3 cm). Compared to the control (T1), a substantial percentage increase was recorded in pod length in treatments T4 (55.8%), T7 (55.8%), T8 (45.7%), T5 (44.2%), T6 (38%), T9 (33.3%), T2 (23.3%) and T3 (10.9%). **Subsequently,** during the 2024 season, a significant impact of biochar was observed on the length of pigeon peas' pods. However, T4, T7 and T8 showed a significant improvement in pod length compared to all other treatments. Among all treatments, T7 (i.e. rice husk biochar @ 5 tons/ha) recorded the maximum pod length. i.e. 6.3 cm. The maximum pod length was recorded in T7 (6.3 cm), followed by T4 (6.1 cm), T8 (6 cm), T9 (5.9 cm), T5 (5.8 cm), T6 (5.7 cm), T2 (5.2 cm), T3 (4.7 cm) and T1 (4.2 cm). Compared to the control (T1), a substantial percentage increase was recorded in pod length in treatments T7 (48.8%), T4 (43.3%), T8 (42.5%), T9 (39.4%), T5 (37%), T6 (33.9%), T2 (23.6%) and T3 (11.8%). **Subsequently,** the maximum mean pod length was recorded in T7 (6.5 cm), followed by T4 (6.4 cm), T8 (6.2 cm), T5 (6 cm), T9 (5.8 cm), T6 (5.8 cm), T2 (5.3 cm), T3 (4.8 cm) and T1 (4.3 cm). However, T4 and T7 showed a significant improvement in pod length compared to all other treatments. Compared to the control (T1), a substantial percentage increase was recorded in pod length in treatments T7 (52.3%), T4 (49.6%), T8 (44.1%), T5 (44.1%), T9 (36.3%), T6 (35.9%), T2 (23.4%) and T3 (11.3%).

4.35 Effect of different doses of biochar application on pod per plant, grain per pod and pod length (cm) of pigeon pea at harvest during 2023 and 2024.

Treatments	POD PER PLANT			GRAIN PER POD			POD LENGTH		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	336.7^{f}	185.3^{g}	261.0^{f}	3.3^{d}	3.3^{d}	3.3^{d}	4.3^{f}	4.2^{f}	4.3^{f}
T_2	374.0^{d}	259.3^{f}	316.7^{e}	4.3^{bcd}	4.3^{bcd}	4.3^{bcd}	5.3^{e}	5.2^{d}	5.3^{d}
T_3	354.0^{e}	248.7^{f}	301.3^{ef}	3.7^{cd}	3.7^{cd}	3.7^{cd}	4.8^{f}	4.7^{e}	4.8^{e}
T_4	958.3^{a}	368.0^{ab}	663.2^{ab}	5.7^{a}	5.7^{a}	5.7^{a}	6.6^{a}	6.1^{ab}	6.4^{a}
T_5	825.0^{bc}	344.0^{de}	584.5^{cd}	5.3^{ab}	5.3^{ab}	5.3^{ab}	6.2^{bc}	5.8^{bc}	6.0^{b}
T_6	766.0^{cd}	333.7^{e}	549.8^{d}	4.7^{abc}	4.7^{abc}	4.7^{abc}	5.9^{cd}	5.7^{c}	5.8^{c}
T_7	993.0^{a}	373.7^{a}	683.3^{a}	5.7^{a}	5.7^{a}	5.7^{a}	6.7^{a}	6.3^{a}	6.5^{a}
T_8	894.7^{ab}	361.7^{bc}	628.2^{bc}	5.3^{ab}	5.3^{ab}	5.3^{ab}	6.3^{bc}	6.0^{ab}	6.2^{b}
T_9	802.0^{bc}	354.7^{cd}	580.2^{cd}	4.7^{abc}	4.7^{abc}	4.7^{abc}	5.7^{d}	5.9^{bc}	5.8^{c}
CD ($p \leq 0.05$)	99.6	11.9	50.4	1.0	1.0	1.0	0.3	0.4	0.2
SEm (±)	33.2	3.9	16.8	0.3	0.3	0.3	0.1	0.1	0.1

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

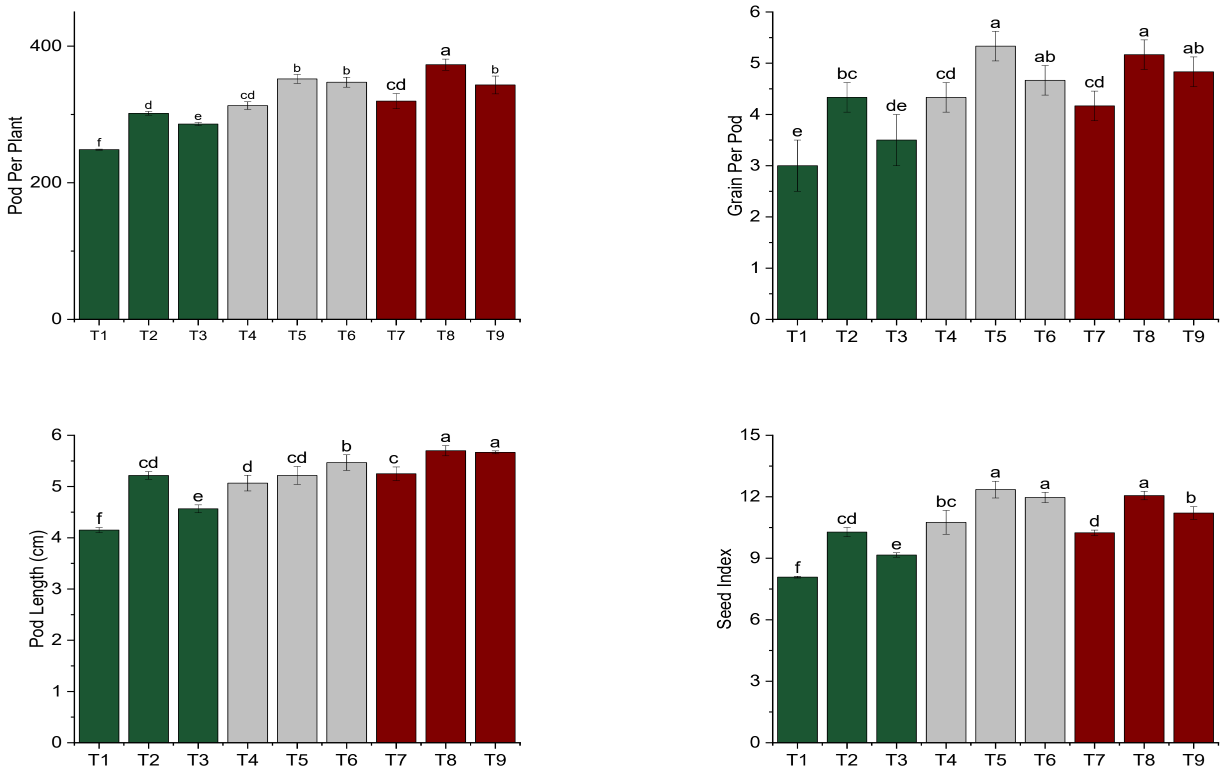


Figure 4.34. Effect of different biochar doses on pod length, grain per pod, pod length, and seed index in pigeon pea.

The yield metrics of pigeon peas were notably influenced by biochar during the 2023 season, with results in **Table 4.36.** However, T4 & T5 showed a significant improvement in seed index compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the highest seed index. i.e. 13.5. The maximum seed index was recorded in T4 (13.5), followed by T5 (13.1), T7 (12.7), T6 (12.2), T8 (11.9), T9 (11.1), T2 (10.9), T3 (9.7) and T1 (8.7). Compared to the control (T1), a substantial percentage increase was recorded in seed index in treatments T4 (54.2%), T5 (50.4%), T7 (45.6%), T6 (39.2%), T8 (36.2%), T9 (27.4%), T2 (24.9%) and T3 (11%). **Subsequently,** during the 2024 season, a significant impact of biochar was observed on the seed index of pigeon peas. However, T4, T5 and T7 showed a significant increase in seed index compared to all other treatments. Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the highest seed index. i.e. 13.1. The maximum seed index was recorded in T4 (13.1), followed by T7 (13), T5 (12.9), T6 (12.4), T8 (11.9), T9 (11.4), T2 (10.6), T3 (9.8) and T1 (8.7). Compared to the control (T1), a substantial percentage increase was recorded in seed index in treatments T4 (49.8%), T7 (47.9%), T5 (46.5%), T6 (41%), T8 (36%), T9 (30.2%), T2 (16.5%) and T3 (12.2%). **Subsequently,** the mean seed index was found to be significant at all growth stages. However, T4, T5 and T7 showed a significant improvement in seed index compared to all other treatments. The maximum seed index was recorded in T4 (13.3), followed by T5 (13), T7 (12.8), T6 (12.3), T8 (11.9), T9 (11.3), T2 (10.6), T3 (9.8) and T1 (8.7). Compared to the control (T1), a substantial percentage increase was recorded in seed index in treatments T4 (52%), T5 (48.6%), T7 (46.7%), T6 (40.1%), T8 (36.1%), T9 (28.8%), T2 (20.7%) and T3 (11.6%).

During the 2023 season, a significant impact of biochar was observed on the biological yield of pigeon peas. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the highest biological yield. i.e. 236.2 q/ha. The maximum biological yield was recorded in T7 (236.2 q/ha), followed by T4 (211.4 q/ha), T8 (204.6 q/ha), T9 (180.8 q/ha), T5 (179.1 q/ha), T6 (167.4 q/ha), T2 (153.7 q/ha), T3 (137 q/ha) and T1 (116.2 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in biological yield in treatments T7 (103.3%), T4 (81.9%), T8 (76.1%), T9 (55.6%), T5 (54.1%), T6 (44.1%), T2 (32.3%) and T3 (17.9%). **Subsequently,** during the 2024 season, a significant impact of biochar was observed on the biological yield of pigeon peas. However, both T4 and T5 showed a significant improvement in biological yield compared to all other treatments. Among all treatments, T4 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum biological yield. i.e. 169 q/ha. The maximum biological yield was recorded in T4 (169 q/ha) followed by T5 (164.3 q/ha), T7 (161.3 q/ha), T8 (154.3 q/ha), T6 (151.3 q/ha), T9 (142.3 q/ha), T2 (126.3 q/ha), T3 (116.7 q/ha) and T1 (87.7 q/ha q/ha). Compared to the control (T1), a substantial percentage increase was recorded in biological yield in treatments T4 (92.8%), T5 (87.5%), T7 (84%), T8 (76%), T6 (72.6%), T9 (62.4%), T2 (44.1%) and T3 (33.1%). **Subsequently,** the mean biological yield was found to be significant. The maximum biological yield was recorded in T7 (198.8 q/ha), followed by T4 (190.2 q/ha), T8 (179.5 q/ha), T5 (171.7 q/ha), T9 (161.6 q/ha), T6 (159.4 q/ha), T2 (140 q/ha), T3 (126.8 q/ha) and T1 (101.9 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in biological yield in treatments T7 (95%), T4 (86.6%), T8 (76.1%), T5 (68.5%), T9 (58.5%), T6 (56.4%), T2 (37.3%) and T3 (24.4%).

During the 2023 season, a significant impact of biochar was observed on the grain yield of pigeon peas. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the highest grain yield. i.e. 19 q/ha. The maximum grain yield was recorded in T7 (19 q/ha), followed by T4 (17.8 q/ha), T8 (16.7 q/ha), T5 (15.8 q/ha), T9 (15.2 q/ha), T6 (14 q/ha), T2 (10.5 q/ha), T3 (9.4 q/ha) and T1 (7.8 q/ha). Compared to the control (T1), a substantial percentage increase was recorded in grain yield in treatments T7 (143.7%), T4 (129.1%), T8 (115%), T5 (103.4%), T9 (95.3%), T6 (79.4%), T2 (34.3%) and T3 (20.4%). **Subsequently,** during the 2024 season, a significant impact of biochar on the grain yield of pigeon peas was observed. However, both T4 and T7 showed a significant improvement in pod length compared to all other treatments. Among all treatments, T4 (i.e., rice straw biochar at 5 tons/ha) recorded the highest grain yield. i.e. 12.1 q/ha. The maximum grain yield was recorded in T4 (12.1 q/ha) followed by T7 (11.9 q/ha), T5 (11.3 q/ha), T6 (11.2 q/ha), T8 (11 q/ha), T9 (10.5 q/ha), T2 (8.1 q/ha), T3 (6.2 q/ha) and T1 (4.6 q/ha q/ha). As compared to control (T1), there was a significant percent increase in grain yield in treatments T4 (162.3%), T7 (159.4%), T5 (146.4%), T6 (142.8%), T8 (139.9%), T9 (129%), T2 (76.1%) and T3 (34.8%). **Subsequently,** the maximum mean grain yield was recorded in T7 (15.5 q/ha), followed by T4 (15 q/ha), T8 (13.9 q/ha), T5 (13.6 q/ha), T9 (12.9 q/ha), T6 (12.6 q/ha), T2 (9.3 q/ha), T3 (7.8

q/ha) and T1 (6.2 q/ha). As compared to control (T1), there was a significant percent increase in grain yield in treatments T7 (149.5%), T4 (141.5%), T8 (124.2%), T5 (119.4%), T9 (107.8%), T6 (103%), T2 (49.8%) and T3 (25.8%).

During the 2023 season, a significant impact of biochar was observed on the harvest index of pigeon peas. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in harvest index compared to all other treatments. Among all treatments, T5 (i.e., rice husk biochar at 10 tons/ha) recorded the highest harvest index. i.e. 8.8. The maximum harvest index was recorded in T5 (8.8), followed by T4 (8.5), T6 (8.4), T9 (8.4), T8 (8.2), T7 (8), T3 (6.9), T2 (6.8) and T1 (6.8). Compared to the control (T1), a substantial percentage increase was recorded in harvest index in treatments T5 (30.6%), T4 (24.9%), T9 (24.1%), T6 (23.3%), T8 (20.7%), T7 (18.7%), T3 (1.2%) and T2 (0.4%). **Subsequently,** during the 2024 season, a significant impact of biochar was observed on the harvest index of pigeon peas. However, T4, T6, T7, T8 and T9 showed a significant improvement in harvest index compared to all other treatments. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the highest harvest index. i.e. 7.5. The maximum harvest index was recorded in T7 (7.5), followed by T9 (7.4), T6 (7.4), T8 (7.2), T4 (7.1), T5 (6.9), T2 (6.4), T3 (5.3) and T1 (5.2). Compared to the control (T1), a substantial percentage increase was recorded in harvest index in treatments T9 (41.3%), T7 (41.3%), T6 (40.8%), T8 (36.7%), T4 (36.4%), T5 (31.7%), T2 (22.4%) and T3 (1.5%). **Subsequently,** the mean harvest index was found to be significant at all growth stages. However, T4, T5, T6, T7, T8 and T9 showed a significant improvement in harvest index compared to all other treatments. The maximum harvest index was recorded in T5, T6, and T9 (7.9), followed by T4 (7.8), T8 and T7 (7.7), T2 (6.6), T3 (6.1), and T1 (6.0). Compared to the control (T1), a substantial percentage increase was recorded in harvest index in treatments T9 (31.6%), T5 (31.1%), T6 (31%), T4 (29.9%), T7 (28.5%), T8 (27.7%), T2 (10%) and T3 (1.4%).

The application of biochar has been shown to significantly enhance various growth attributes of pigeon peas (Cajanus cajan), including grain per pod, pods per plant, pod length, seed index, biological yield, grain yield, and harvest index. The number of grains per pod and the total number of pods per plant are critical indicators of yield potential. A higher number of pods directly correlates with increased grain yield, as each pod contributes to the overall harvest. Studies have demonstrated that biochar application can enhance pod formation by improving nutrient availability and soil structure, leading to a more robust root system that supports more tremendous reproductive success (Shaon Kumar Das et al., 2018). Pod length is another vital attribute that affects the seed index—the weight of seeds in a pod, which is directly related to overall yield. Longer pods tend to contain more or larger seeds, enhancing the seed index. Research indicates that biochar can enhance soil properties, including pH and nutrient retention, which in turn promotes longer pod development and larger seeds. Biological yield refers to the total biomass produced by a plant, while grain yield is the portion harvested as food. The relationship between these two metrics is essential; increased biological yield often leads to higher grain yields. Biochar has been shown to enhance photosynthetic activity and nutrient uptake, contributing to increased biomass production (Brewer et al., 2011). The harvest index measures the efficiency with which a plant converts biomass into economic yield (grain). A higher harvest index indicates that a greater proportion of biomass is allocated to grain production rather than vegetative growth. This symbiotic relationship between plants and soil microbes enhances photosynthesis through improved leaf area index and chlorophyll content, directly impacting biomass accumulation and grain filling.

Table 4.36 Effect of different doses of biochar application on seed index, biological yield (q/ha), grain yield (q/ha) and harvest index of pigeon pea at harvest, during 2023 and 2024.

Treatments	SEED INDEX			BIOLOGICAL YIELD			GRAIN YIELD			HARVEST INDEX		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	8.7^{g}	8.8^{f}	8.7^{f}	116.2^{f}	87.7^{g}	101.9^{g}	7.8^{h}	4.6^{g}	6.2^{g}	6.8^{b}	5.2^{d}	6.0^{c}
T_2	10.9^{e}	10.2^{e}	10.6^{d}	153.7^{d}	126.3^{e}	140.0^{e}	10.5^{f}	8.1^{e}	9.3^{e}	6.8^{b}	6.4^{c}	6.6^{b}
T_3	9.7^{f}	9.8^{e}	9.8^{e}	137.0^{e}	116.7^{f}	126.8^{f}	9.4^{g}	6.2^{f}	7.8^{f}	6.9^{b}	5.3^{d}	6.1^{c}
T_4	13.5^{a}	13.1^{a}	13.3^{a}	211.4^{b}	169.0^{a}	190.2^{b}	17.8^{b}	12.1^{a}	15.0^{b}	8.5^{a}	7.1^{ab}	7.8^{a}
T_5	13.1^{ab}	12.9^{ab}	13.0^{a}	179.1^{c}	164.3^{ab}	171.7^{c}	15.8^{cd}	11.3^{b}	13.6^{c}	8.8^{a}	6.9^{b}	7.9^{a}
T_6	12.2^{cd}	12.4^{bc}	12.3^{b}	167.4^{cd}	151.3^{c}	159.4^{d}	14.0^{e}	11.2^{bc}	12.6^{d}	8.4^{a}	7.4^{a}	7.9^{a}
T_7	12.7^{bc}	13.0^{a}	12.8^{a}	236.2^{a}	161.3^{b}	198.8^{a}	19.0^{a}	11.9^{a}	15.5^{a}	8.0^{a}	7.5^{a}	7.7^{a}
T_8	11.9^{d}	11.9^{cd}	11.9^{b}	204.6^{b}	154.3^{c}	179.5^{c}	16.7^{c}	11.0^{c}	13.9^{c}	8.2^{a}	7.2^{ab}	7.7^{a}
T_9	11.1^{e}	11.4^{d}	11.3^{c}	180.8^{c}	142.3^{d}	161.6^{d}	15.2^{d}	10.5^{d}	12.9^{d}	8.4^{a}	7.4^{a}	7.9^{a}
CD ($p \leq 0.05$)	0.7	0.6	0.6	15.3	5.2	8.2	1.0	0.3	0.5	0.8	0.3	0.4
SEm (±)	0.2	0.2	0.2	5.1	1.7	2.7	0.3	0.1	0.2	0.3	0.1	1.0

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

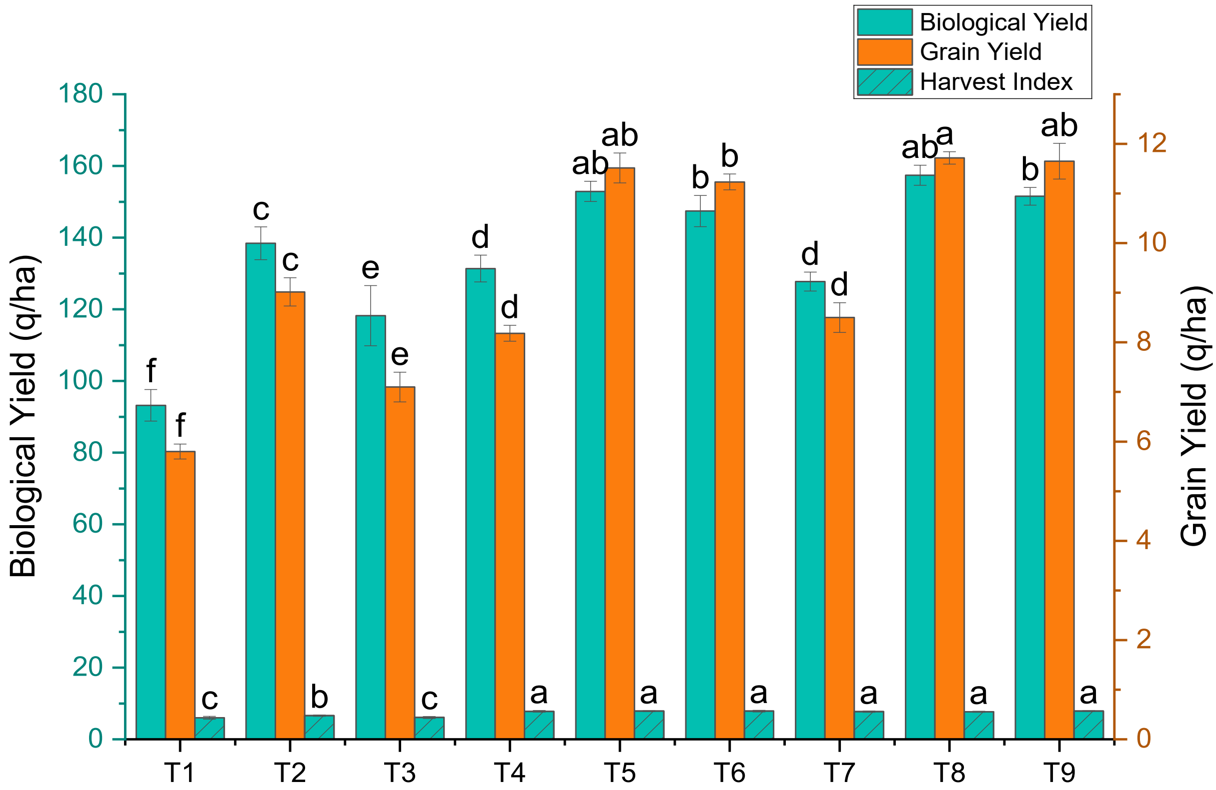


Figure 4.35. Effect of different biochar doses on biological, grain yield and harvest index in pigeon pea.

The benefit-cost ratio of pigeon pea expresses the extent of benefit or profit earned by applying a particular treatment over its cost. The calculations were performed for the different treatment combinations in both seasons, as presented in **Table 4.37.** During the 2023-2.24 season, the highest benefit-cost ratio was recorded under treatment T7 (3), followed by T8 (2.4), T9 (2.0), T4 (1.8), T2 (1.8), T3 (1.7), T1 (1.5), T5 (1.1) and T6 (0.7). During the 2024-2025 season, the highest benefit-cost ratio was recorded under T7 (rice straw biochar @ 5 t/ha) (2.0), T8 (1.7), T2 (1.5), T9 (1.4), T4 (1.3), T3 (1.2), T1 (0.9), T5 (0.8) and T6 (0.6).

The highest B: C ratio was produced by rice straw biochar at 5 t ha^{-1} (T7), primarily because straw biochar entails a relatively lower cost of production and application compared to husk biochar, while simultaneously enhancing soil fertility and crop yields to a greater extent. This combination of lower input costs with higher yield responses accounts for its economic superiority in pigeon peas. Recommended NPK (T2) and 10 t ha^{-1} straw biochar (T8) also yielded promising returns, highlighting the importance of maintaining balanced nutrients and moderate biochar application in achieving profitability. Greater applications of husk biochar (T5 and T6) were not economical because the high cultivation cost exceeded the benefits of improved yields. Moderate husk biochar (T4) and increased straw biochar (T9) resulted in very modest profitability, once again illustrating that both dose and type of biochar significantly affect the cost-benefit ratio. Overall, the results affirm that rice straw biochar at 5 t ha^{-1} is the most profitable choice for pigeon pea production (Blackwell et al., 2010).

Table 4.37: Effect of Different Doses of Biochar Application on Benefit-Cost Ratio (B: C Ratio).

Treatments	Cost of cultivation	2023 season			2024 season		
		Gross return	Net return	B: C ratio	Gross return	Net return	B: C ratio
T_1	33910	51370	17460	1.5	32200	-1710	0.9
T_2	37346	68970	31624	1.8	56700	19354	1.5
T_3	36446	61864	25418	1.7	43400	6954	1.2
T_4	66446	117700	51254	1.8	84466	18020	1.3
T_5	96446	104500	8054	1.1	79333	-17112	0.8
T_6	126446	92180	-34266	0.7	78166	-48279	0.6
T_7	41446	125180	83734	3.0	83533	42087	2.0
T_8	46446	110440	63994	2.4	77233	30787	1.7
T_9	51446	100320	48874	2.0	73733	22287	1.4

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

4.8 Soil attributes

Biochar was observed to have a considerable effect on soil pH at various stages of the 2023 season, as shown in **Table 4.36**. However, at 45 DAS (T4, T5, T6, T7 & T8), at 90 DAS (T4, T5, T6, T7, T8 & T9), and at harvest (T5, T6 & T9), the soil pH showed a significant improvement compared to all other treatments. The maximum soil pH at harvest was recorded in T5 (8.3), followed by T9 (8.2), T6 (8.2), T8 (8.0), T4 (8.0), T7 (7.8), T2 (7.6), T3 (7.4), and T1 (7.2). As compared to control (T1), there was a significant percent increase in soil pH in treatments T5 (15.2%), T9 (12.9%), T6 (12.9%), T4 (11.1%), T8 (10.6%), T7 (7.4%), T2 (5.5%) and T3 (2.8%). **Subsequently,** in the 2024 season, a significant impact of biochar on soil pH was observed at different stages. However, at 45 DAS (T6 & T9), at harvest (T8 & T9), and at harvest (T6, T8 & T9), a significant improvement in soil pH was observed compared to all other treatments. The maximum soil pH at harvest was recorded in T9 (8.2), followed by T8 (8.1), T6 (8), T7 (7.9), T4 (7.8), T5 (7.7), T2 (7.3), T3 (7.3) and T1 (7.2). As compared to control (T1), there was a significant percent increase in soil pH in treatments T9 (14%), T8 (12.6%), T6 (11.6%), T7 (9.8%), T4 (9.3%), T5 (7.9%), T2 (2.3%) and T3 (2.3%).

The mean soil pH was found to be significant at all growth stages. The maximum soil pH at harvest was recorded in T9 (8.2), followed by T6 (8.1), T5 (8.0), T8 (8.0), T4 (7.9), T7 (7.8), T2 (7.5), T3 (7.4), and T1 (7.2). As compared to control (T1), there was a significant percentage increase in membrane stability index in treatments T9 (13.4%), T6 (12.3%), T5 (11.6%), T8 (11.6%), T4 (10.2%), T7 (8.6%), T2 (3.9%)

and T3 (2.5%). Overall, at 45 DAS (T5, T6, T8 & T9), at 90 DAS (T6, T8 & T9), and at harvest (T6, T7, and T9), the effects were found to be more significant than those of all other treatments.

Soil pH affects the activity of beneficial soil microbes, which are essential for nutrient cycling and organic matter decomposition, thereby sustaining soil fertility. As a result, maintaining soil pH within an acceptable range is crucial for enhancing agricultural productivity and promoting sustainable farming practices. According to the results, biochar enhances soil pH through several processes that help neutralise soil acidity. One of the key reasons is the alkaline nature of biochar, which contains numerous basic cations, including calcium, magnesium, and potassium. (Kammann & Flessa, 2012). Adding biochar to acidic soils reduces acidity and raises soil pH by reacting with hydrogen ions (H^+) and aluminium ions (Al^{3+}). Biochar has been shown to dramatically alter the pH of acidic soils, with some studies indicating increases of 0.5 to 1 unit following application. (Tan & Zhang, 2020).

Table 4.38 Effect of different doses of biochar application on soil pH at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	7.2^{c}	7.4^{g}	7.3^{e}	7.0^{d}	7.1^{g}	7.1^{e}	7.2^{e}	7.2^{d}	7.2^{f}
T_2	7.4^{c}	7.8^{e}	7.6^{d}	7.4^{bc}	7.5^{e}	7.4^{d}	7.6^{c}	7.3^{d}	7.5^{e}
T_3	7.3^{c}	7.6^{f}	7.4^{e}	7.3^{cd}	7.3^{f}	7.3^{de}	7.4^{d}	7.3^{d}	7.4^{e}
T_4	8.1^{ab}	8.4^{c}	8.3^{bc}	7.8^{a}	7.8^{d}	7.8^{c}	8.0^{b}	7.8^{bc}	7.9^{cd}
T_5	8.3^{ab}	8.6^{b}	8.4^{a}	7.8^{a}	8.0^{c}	7.9^{bc}	8.3^{a}	7.7^{c}	8.0^{bc}
T_6	8.2^{ab}	8.8^{a}	8.5^{a}	8.1^{a}	8.2^{b}	8.1^{a}	8.2^{ab}	8.0^{ab}	8.1^{ab}
T_7	8.2^{ab}	8.3^{d}	8.3^{c}	7.8^{a}	8.0^{c}	7.9^{bc}	7.8^{c}	7.9^{bc}	7.8^{d}
T_8	8.3^{a}	8.5^{c}	8.4^{ab}	8.0^{a}	8.3^{ab}	8.1^{ab}	8.0^{b}	8.1^{a}	8.0^{bc}
T_9	8.1^{b}	8.8^{a}	8.4^{ab}	7.7^{ab}	8.3^{a}	8.0^{abc}	8.2^{ab}	8.2^{a}	8.2^{a}
CD ($p \leq 0.05$)	0.3	0.2	0.1	0.4	0.3	0.2	0.2	0.1	0.1
SEm (±)	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.1
Initial value	7.4								

***** Means denoted by different letters are significantly different at p≤0.05, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

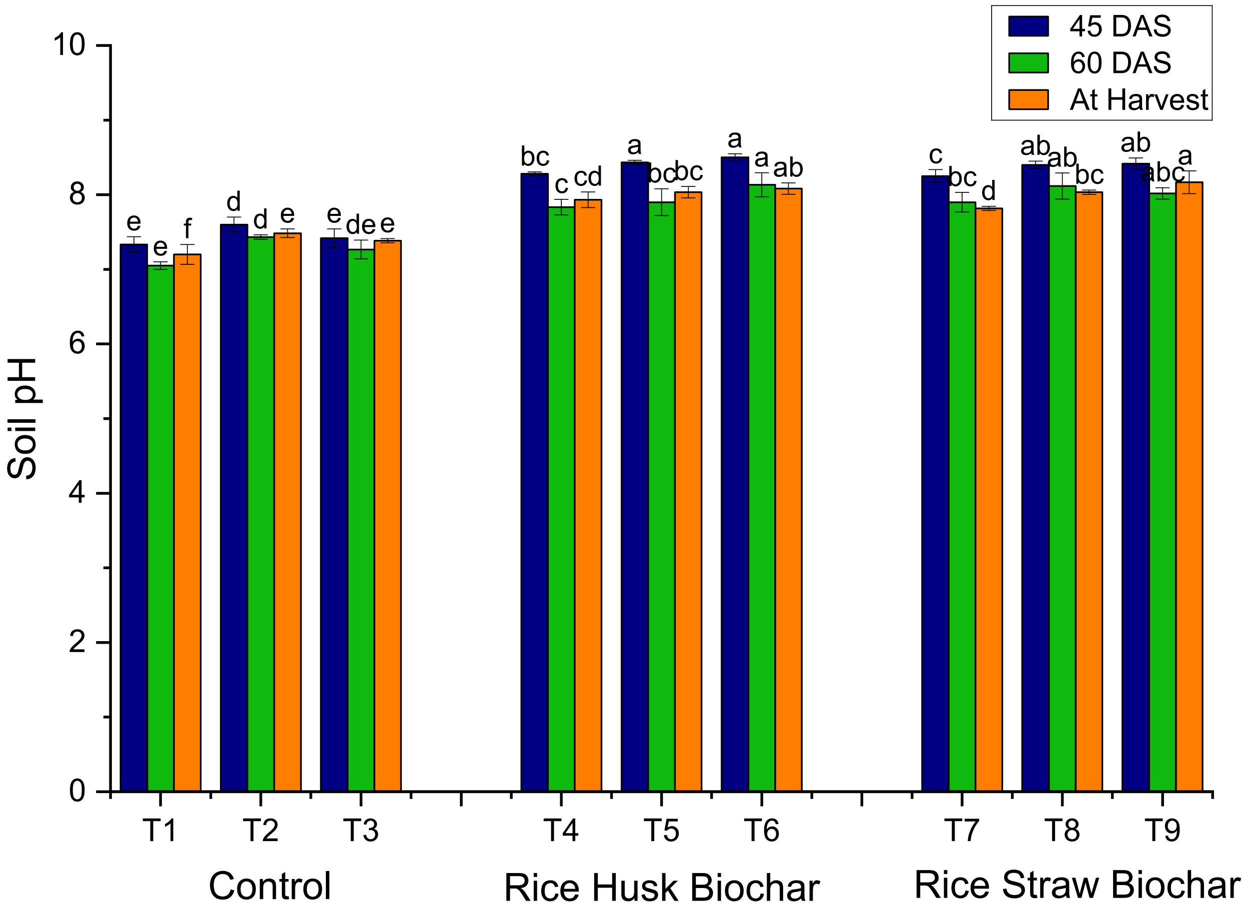


Figure 4.36. Effect of various biochar doses on soil pH under pigeon pea at 45 and 90 DAS and at harvest.

Soil electrical conductivity is crucial for evaluating soil health and its influence on crop yield. During the 2023 season, a significant impact of biochar on the electrical conductivity of soil was observed at different stages, as shown in **Table 4.37**. However, at 45 DAS (T6, T8 & T9), at 90 DAS (T5, T6, T8 & T9), and at harvest (T5, T6 & T9), significant improvements in soil electrical conductivity were observed compared to all other treatments. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum Electrical conductivity at sowing time, 45 DAS, 90 DAS, and harvest, i.e., 0.38 mS/cm, 0.33 mS/cm, 0.28 mS/cm, and 0.31 mS/cm, respectively. The maximum Electrical conductivity at harvest was recorded in T9 (0.31 m mhos/cm) followed by T5 (0.30 m mhos/cm), T6 (0.29 m mhos/cm), T8 (0.28 m mhos/cm), T7 (0.26 m mhos/cm), T4 (0.26 m mhos/cm), T2 (0.24 m mhos/cm), T3 (0.22 m mhos/cm) and T1 (0.21 m mhos/cm). As compared to control (T1), there was a significant percentage increase of Electrical conductivity in treatments T9 (51.6%), T5 (43.5%), T6 (40.3%), T8 (35.5%), T4 (27.4%), T7 (24.2%), T2 (17.7%) and T3 (8.1%).

Throughout the 2024 season, a significant impact of biochar on the soil's Electrical conductivity was observed at different stages. Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the maximum Electrical conductivity at sowing time and 90 DAS, i.e., 0.40 mS/cm and 0.27 mS/cm, respectively. At 45 DAS and harvest, treatment T9 (i.e., rice straw biochar at 15 tons/ha) resulted in maximum Electrical conductivity, i.e., 0.34 mS/cm and 0.31 mS/cm, respectively. However, at 90 DAS (T5, T6 & T9) and harvest (T6 & T9), a significant improvement in soil electrical conductivity was observed compared to all other treatments. The maximum Electrical conductivity at harvest was recorded in T9 (0.31 m mhos/cm) followed by T6 (0.29 m mhos/cm), T8 (0.28 m mhos/cm), T5 (0.27 m mhos/cm), T4 (0.26 m mhos/cm), T7 (0.25 m mhos/cm), T2 (0.23 m mhos/cm), T3 (0.23 m mhos/cm) and T1 (0.18 m mhos/cm). As compared to control (T1), there was a significant percentage increase of Electrical conductivity in treatments T9 (69.1%), T6 (60%), T8 (52.7%), T5 (49.1%), T4 (41.8%), T7 (36.4%), T2 (25.5%) and T3 (23.6%).

The mean electrical conductivity of soil was found to be significant at all growth stages. The maximum electrical conductivity of soil at harvest was recorded in T9 (0.31), followed by T6 (0.29), T5 (0.29), T8 (0.28), T4 (0.26), T7 (0.25), T2 (0.24), T3 (0.23) and T1 (0.20). As compared to control (T1), there was a significant percent increase in membrane stability index in treatments T9 (59.8%), T6 (49.6%), T5 (46.2%), T8 (43.6%), T4 (34.2%), T7 (29.9%), T2 (21.4%) and T3 (15.4%). Overall, at 45 DAS (T6 & T9) and 90 DAS (T5, T6 & T9), the results were found to be more significant than those of all other treatments.

EC is directly proportional to the concentration of dissolved salts and nutrients in the soil solution. High EC values may indicate increased nutrient availability, promoting optimal plant development. Biochar application improves soil EC through a variety of processes. One necessary explanation is the inherent electrical conductivity of biochar itself, which can vary greatly depending on its feedstock and manufacturing circumstances. (Mia et al., 2014). When biochar is introduced to the soil, it contributes soluble salts and organic compounds that dissolve in water, increasing the soil solution's total EC level. Studies indicate that applying biochar at high rates (e.g., 120 t ha^{-1}) can raise soil EC by up to 14 times, owing to the release of soluble chemicals into the soil matrix. (Haq Nawaz et al., 2018).

Table 4.39 Effect of different doses of biochar application on soil electrical conductivity (m mhos/cm) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	0.15^{d}	0.18^{g}	0.17^{e}	0.17^{e}	0.15^{g}	0.16^{f}	0.21^{f}	0.18^{g}	0.20^{f}
T_2	0.18^{d}	0.23^{e}	0.21^{d}	0.22^{cd}	0.21^{e}	0.22^{d}	0.24^{de}	0.23^{ef}	0.24^{de}
T_3	0.17^{d}	0.21^{f}	0.19^{d}	0.20^{de}	0.18^{f}	0.19^{e}	0.22^{ef}	0.23^{f}	0.23^{e}
T_4	0.27^{c}	0.30^{c}	0.29^{bc}	0.24^{bc}	0.23^{cd}	0.24^{cd}	0.26^{cd}	0.26^{cd}	0.26^{c}
T_5	0.29^{bc}	0.33^{b}	0.31^{b}	0.27^{ab}	0.24^{bc}	0.26^{abc}	0.30^{ab}	0.27^{bc}	0.29^{b}
T_6	0.31^{ab}	0.33^{a}	0.32^{a}	0.27^{a}	0.27^{a}	0.27^{a}	0.29^{ab}	0.29^{ab}	0.29^{b}
T_7	0.26^{c}	0.29^{d}	0.28^{c}	0.22^{cd}	0.22^{de}	0.22^{d}	0.26^{cd}	0.25^{de}	0.25^{cd}
T_8	0.30^{abc}	0.30^{cd}	0.30^{b}	0.27^{ab}	0.23^{cd}	0.25^{bc}	0.28^{bc}	0.28^{bc}	0.28^{b}
T_9	0.33^{a}	0.34^{b}	0.33^{a}	0.28^{a}	0.25^{ab}	0.27^{ab}	0.31^{a}	0.31^{a}	0.31^{a}
CD ($p \leq 0.05$)	0.04	0.03	0.02	0.04	0.02	0.02	0.03	0.01	0.02
SEm (±)	0.01	0.01	0.01	0.13	0.01	0.00	0.01	0.00	0.01
Initial value	0.17								

***** Means denoted by different letters are significantly different at p≤0.05, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

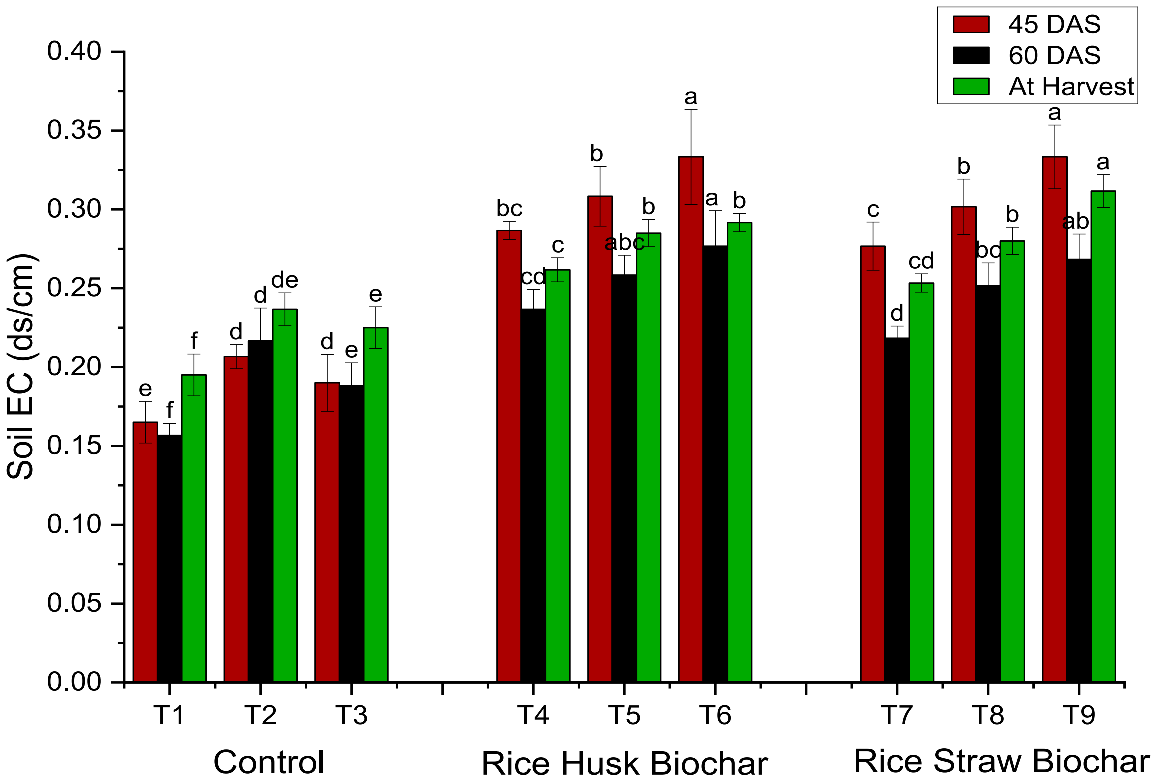


Figure 4.37. Effect of different biochar doses on soil EC (ds/cm) at 45 and 90 DAS and at harvest.

Soil organic carbon (SOC) promotes plant development and production by improving soil fertility and structure. During the 2023 season, a significant impact of biochar on the organic carbon content of soil was observed at various stages. The results are presented in **Table 4.38**. Among all treatments, T6 (i.e. rice husk biochar @ 15 tons/ha) recorded maximum organic carbon at sowing time and 45 DAS, i.e. 0.72% and 0.67%, respectively. While at 90 DAS and harvest, treatment T5 (i.e. rice husk biochar @ 10 tons/ha) resulted in maximum organic carbon, i.e. 0.53% and 0.46%, respectively. However, at 45 DAS (T5, T6 & T9), at 90 DAS (T4, T5, T6 & T7), and at harvest, except for T1, significant improvements in soil organic carbon were observed compared to all other treatments. The maximum organic carbon at harvest was recorded in T5 (0.46%), followed by T8 (0.45%), T9 (0.44%), T6 (0.44%), T7 (0.42%), T4 (0.39%), T2 (0.39%), T3 (0.37%) and T1 (0.26%). As compared to control (T1), there was a significant percent increase of organic carbon in treatments T5 (79.2%), T8 (75.3%), T6 (70.1%), T9 (68.8%), T4 (67.5%), T7 (64.9%), T2 (50.6%) and T3 (42.9%).

During the 2024 season, a significant impact of biochar was observed on the soil's organic carbon at various stages. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum organic carbon at sowing time (45 DAS, 90 DAS), and at harvest, i.e., 0.67%, 0.62%, 0.58%, and 0.47%, respectively. However, at 45 DAS (T6 & T9) and harvest (T6, T8, and T9), a significant improvement in soil organic carbon was observed compared to all other treatments. The maximum organic carbon at harvest was recorded in T9 (0.47%), followed by T6 (0.46%), T8 (0.43%), T5 (0.41%), T4 (0.39%), T7 (0.37%), T2 (0.32%), T3 (0.29%) and T1 (0.26%). As compared to control (T1), there was a significant percent increase of organic carbon in treatments T6 (74.7%), T9 (73.4%), T8 (64.6%), T5 (57%), T4 (49.4%), T7 (39.2%), T2 (22.8%) and T3 (11.4%).

The mean organic carbon of soil was found to be significant at all growth stages. The maximum organic carbon of soil at harvest was recorded in T9 (0.46%), followed by T6 (0.45%), T5 (0.44%), T8 (0.44%), T4 (0.41%), T7 (0.40%), T2 (0.36%), T3 (0.33%) and T1 (0.26%). As compared to control (T1), there was a significant percent increase of organic carbon in treatments T6 (72.4%), T9 (71.2%), T8 (69.9%), T5 (67.9%), T7 (51.9%), T4 (58.3%), T2 (36.5%) and T3 (26.9%). Overall, at 45 DAS (T6 & T9), at 90 DAS (T4, T5, T6, T7, T8 & T9), and at harvest (T4, T5, T8 & T9), the effects were found to be more significant than those of all other treatments.

SOC acts as a reservoir for critical nutrients, increasing their availability while decreasing leaching losses. SOC also enhances water retention and aeration, creating an ideal environment for root growth. Biochar treatment may significantly increase SOC levels, with one study indicating an average increase of 13.0 Mg ha ^{1}, resulting in a 29% increase in SOC stocks. (Mia et al., 2024). Additionally, biochar increases soil structure and porosity, thereby enhancing the habitat for soil microorganisms. A study demonstrated that straw biochar application significantly enhances organic carbon content by 4.0% to 26.7%, highlighting its role in increasing soil fertility and carbon sequestration.

Table 4.40 Effect of different doses of biochar application on soil organic carbon (%) at 45 DAS, 90 DAS and harvest, during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	0.41^{e}	0.38^{f}	0.40^{f}	0.39^{d}	0.35^{g}	0.37^{c}	0.26^{b}	0.26^{f}	0.26^{e}
T_2	0.49^{d}	0.44^{d}	0.46^{d}	0.44b^{cd}	0.42^{e}	0.43^{b}	0.39^{a}	0.32^{e}	0.36^{cd}
T_3	0.45^{de}	0.41^{e}	0.43^{e}	0.41^{cd}	0.39^{f}	0.40^{bc}	0.37^{a}	0.29^{ef}	0.33^{d}
T_4	0.62^{bc}	0.55^{bc}	0.59^{bc}	0.51^{ab}	0.46^{d}	0.48^{a}	0.43^{a}	0.39^{cd}	0.41^{ab}
T_5	0.64^{abc}	0.56^{b}	0.60^{b}	0.53^{a}	0.51^{c}	0.52^{a}	0.46^{a}	0.41^{bc}	0.44^{ab}
T_6	0.67^{a}	0.61^{a}	0.64^{a}	0.49^{ab}	0.54^{b}	0.52^{a}	0.44^{a}	0.46^{a}	0.45^{a}
T_7	0.61^{c}	0.53^{c}	0.57^{c}	0.48^{abc}	0.49^{c}	0.49^{a}	0.42^{a}	0.37^{d}	0.40^{bc}
T_8	0.62^{bc}	0.56^{b}	0.59^{bc}	0.44^{bcd}	0.55^{b}	0.50^{a}	0.45^{a}	0.43^{ab}	0.44^{ab}
T_9	0.65^{ab}	0.62^{a}	0.64^{a}	0.45^{bcd}	0.58^{a}	0.51^{a}	0.44^{a}	0.47^{a}	0.46^{ab}
CD ($p \leq 0.05$)	0.04	0.02	0.02	0.07	0.02	0.03	0.09	0.03	0.03
SEm (±)	0.01	0.01	0.06	0.02	0.01	0.01	0.03	0.01	0.01
Initial value	0.49								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

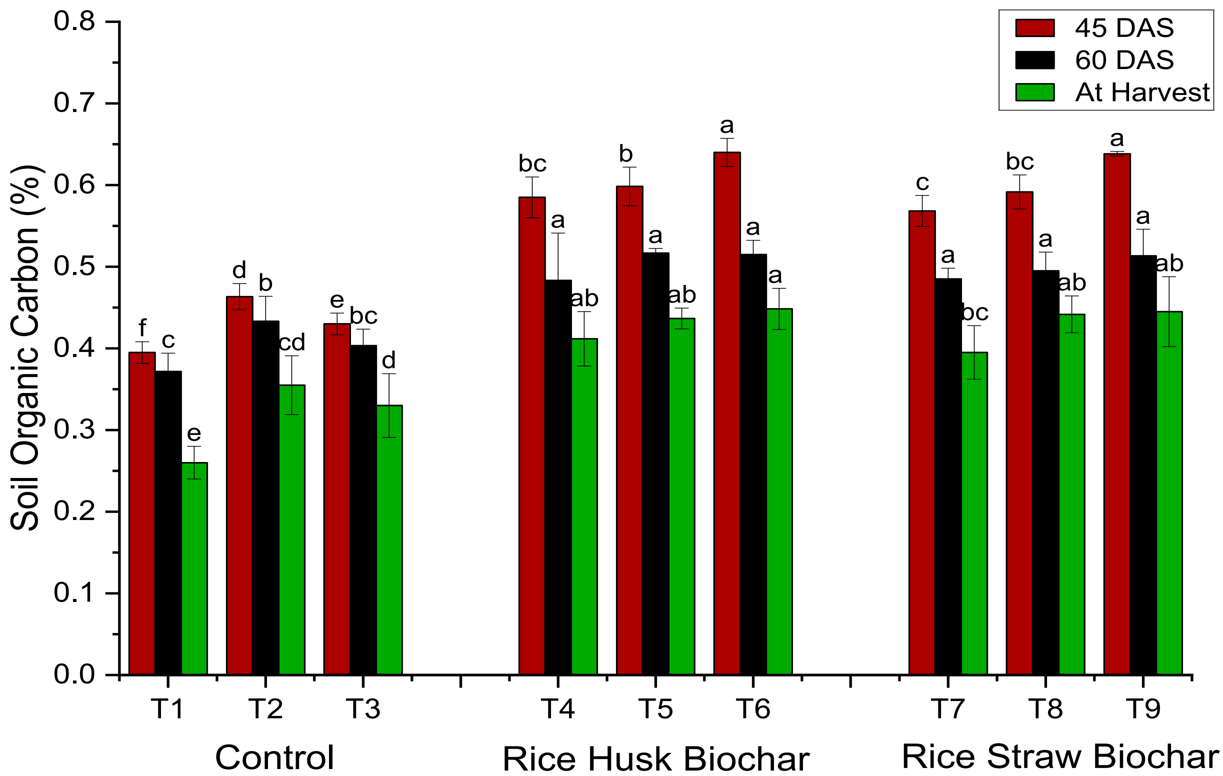


Figure 4.38. Effect of different biochar doses on soil organic carbon (%) at 45 and 90 DAS and at harvest.

Soil nitrogen availability is crucial for enhancing crop growth and productivity, as it directly regulates essential physiological processes. During the 2023 season, a significant impact of biochar on the soil's available nitrogen was observed at various stages of growth. The results are presented in **Table 4.39**. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum available nitrogen at sowing time and harvest, i.e., 366.7 kg/ha. At 45 DAS, 90 DAS, and harvest, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in maximum available nitrogen levels of 462 kg/ha, 388 kg/ha, and 290 kg/ha, respectively. However, at harvest, T4, T6, T7, T8 and T9 showed a significant improvement in soil organic carbon compared to all other treatments. The maximum available nitrogen at harvest was recorded in T4 (290 kg/ha) followed by T7 (286 kg/ha), T5 (277.5 kg/ha), T8 (266 kg/ha), T9 (258 kg/ha), T6 (254 kg/ha), T2 (231 kg/ha), T3 (220 kg/ha) and T1 (208 kg/ha). As compared to control (T1), there was a significant percent increase of available nitrogen in treatments T4 (39.2%), T7 (37.3%), T5 (33.1%), T8 (27.7%), T9 (23.8%), T6 (21.9%), T2 (10.9%) and T3 (5.8%).

During the 2024 season, a significant impact of biochar on the soil's available nitrogen was observed at various stages of growth. Among all treatments, T7 (i.e., rice straw biochar at 5 tons/ha) recorded the maximum available nitrogen at sowing time and harvest, i.e., 364 kg/ha. At 45 DAS, 90 DAS, and harvest, treatment T4 (i.e., rice husk biochar at 5 tons/ha) resulted in maximum available nitrogen levels of 462.2 kg/ha, 388 kg/ha, and 286 kg/ha, respectively. Throughout all growth stages, T4 and T7 showed a significant improvement in soil pH compared to all other treatments. The maximum available nitrogen at harvest was recorded in T4 (286 kg/ha) followed by T7 (278 kg/ha), T5 (270 kg/ha), T8 (266 kg/ha), T9 (258 kg/ha), T6 (256 kg/ha), T2 (235 kg/ha), T3 (223 kg/ha) and T1 (215 kg/ha). As compared to control (T1), there was a significant percentage increase of available nitrogen in treatments T4 (32.7%), T7 (28.9%), T5 (25.2%), T8 (23.4%), T9 (19.7%), T6 (19%), T2 (9%) and T3 (3.4%).

The mean available nitrogen of the soil was found to be significant at all growth stages. The maximum available nitrogen of soil at harvest was recorded in T4 (288 kg/ha) followed by T7 (282 kg/ha), T5 (273 kg/ha), T8 (266 kg/ha), T9 (258 kg/ha), T6 (255 kg/ha), T2 (233 kg/ha), T3 (221 kg/ha) and T1 (212 kg/ha). As compared to control (T1), there was a significant percent increase of organic carbon in treatments T4 (35.9%), T7 (33%), T5 (29.1%), T8 (25.5%), T9 (21.7%), T6 (20.5%), T2 (9.9%) and T3 (4.6%). Overall, at harvest, T4, T5 and T7 were found to be more significant than all other treatments.

Adequate nitrogen levels stimulate vigorous vegetative development, resulting in enhanced tillering. Nitrogen promotes increased grain output by increasing the number of heads per square foot and enhancing seed size. Therefore, proper soil nitrogen management is crucial for enhancing wheat yield and ensuring sustainable agricultural practices. As a result, biochar application enhances the nitrogen availability in soil. Biochar improves nitrogen mineralisation and nitrification rates, which are essential processes for converting organic nitrogen into plant-available forms. Biochar enhances microbial activity, converting organic nitrogen into ammonium (NH_4^+) and nitrate (NO_3^-), which are readily available for plant uptake. Additionally, biochar enhances the soil's cation exchange capacity, allowing it to retain more nitrogen (Dempster et al., 2020).

Table 4.41 Effect of different doses of biochar application on soil available nitrogen (kg/ha) at 45 DAS, 90 DAS and harvest, during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	239^{g}	250^{h}	245^{g}	229^{g}	235^{g}	232^{g}	208^{d}	215^{f}	212^{d}
T_2	391^{e}	403^{f}	397^{e}	317^{e}	325^{e}	321^{e}	231^{cd}	235^{e}	233^{d}
T_3	376^{f}	388^{g}	382^{f}	305^{f}	313^{f}	309^{f}	220^{d}	223^{f}	221^{d}
T_4	462^{a}	462^{a}	462^{a}	388^{a}	388^{a}	388^{a}	290^{a}	286^{a}	288^{a}
T_5	442^{c}	440^{c}	441^{c}	376^{b}	368^{b}	372^{b}	277^{ab}	270^{c}	273^{abc}
T_6	431^{d}	427^{e}	429^{d}	352^{c}	348^{d}	350^{d}	254^{abc}	256^{d}	255^{c}
T_7	454^{b}	454^{b}	454^{b}	376^{b}	372^{b}	374^{b}	286^{a}	278^{b}	282^{ab}
T_8	440^{c}	443^{c}	441^{c}	353^{c}	360^{c}	356^{c}	266^{abc}	266^{c}	266^{bc}
T_9	431^{d}	433^{d}	432^{d}	343^{d}	348^{d}	345^{d}	258^{abc}	258^{d}	258^{c}
CD ($p \leq 0.05$)	6.5	6.0	3.9	7.5	5.0	5.1	3.6	7.8	20.0
SEm (±)	2.1	2.0	1.3	2.5	1.7	1.7	1.2	2.6	7.0
Initial value	176								

***** Means denoted by different letters are significantly different at p≤0.05, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

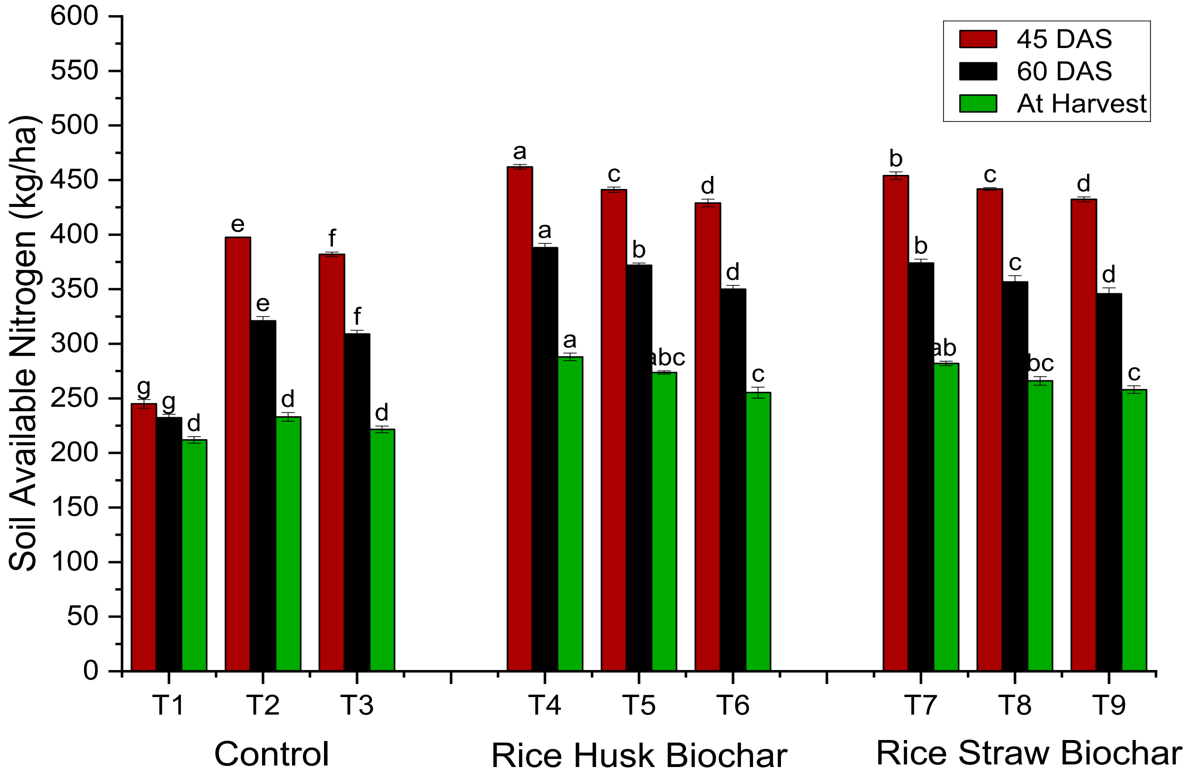


Figure 4.39. Effect of different biochar doses on soil nitrogen (kg/ha) at 45 and 90 and at harvest.

Phosphorus is an essential component of nucleic acids, phospholipids, and ATP, which are required for plant energy transfer and storage. During the 2023 season, a significant impact of biochar on the soil's phosphorus concentration was observed at various stages. The results are presented in **Table 4.40**. Among all treatments, T9 (i.e. rice straw biochar @ 15 tons/ha) recorded maximum phosphorus concentration at sowing time and 45 DAS, i.e. 38.7 and 65.7, respectively. At 90 DAS and harvest, treatment T6 (i.e., rice husk biochar at 15 tons/ha) resulted in the maximum phosphorus concentration, i.e., 45.4 and 24.4, respectively. However, T6 & T9 at 90 DAS, as well as T5, T6, T8, and T9 at harvest, showed a significant improvement in soil phosphorus compared to all other treatments. The maximum phosphorus concentration at harvest was recorded in T6 (24.4), followed by T5 (23.8), T9 (23.1), T8 (21.9), T4 (19.2), T7 (15.2), T2 (14.9), T3 (13) and T1 (9.3). As compared to control (T1), there was a significant percent increase in phosphorus concentration in treatments T5 (163.7%), T6 (156.5%), T9 (149.4%), T8 (136.3%), T4 (106.8%), T7 (64.4%), T2 (61.2%) and T3 (40.4%).

During the 2024 season, a significant impact of biochar on the soil's phosphorus concentration was observed at various stages of growth. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum phosphorus concentration at sowing time and 90 DAS, i.e., 41.1 and 51.6, respectively. At 45 DAS and harvest, treatment T6 (i.e., rice husk biochar at 15 tons/ha) resulted in the maximum phosphorus concentration, i.e., 69.7 and 34.2, respectively. However, at 45 & 90 DAS (T6 & T9) and at harvest (T5, T6 & T9), the treatments showed a significant improvement in soil phosphorus compared to all other treatments. The maximum phosphorus concentration at harvest was recorded in T6 (34.2), followed by T9 (32.7), T5 (31.5), T7 (29.0), T8 (28.4), T4 (27.0), T2 (18.5), T3 (17.4), and T1 (12.8). As compared to control (T1), there was a significant percent increase in phosphorus concentration in treatments T6 (167.6%), T9 (155.9%), T5 (146.5%), T7 (127.4%), T8 (122.2%), T4 (111.7%), T2 (45.2%) and T3 (36.6%).

The mean available nitrogen of the soil was found to be significant at all growth stages. The maximum available nitrogen in the soil at harvest was recorded in T6 (29), followed by T5 (28), T9 (27.9), T8 (25.1), T4 (23.1), T7 (22.1), T2 (16.7), T3 (15.2), and T1 (11). As compared to control (T1), there was a significant percent increase of organic carbon in treatments T6 (162.9%), T5 (153.7%), T9 (153.2%), T8 (128.1%), T4 (109.7%), T7 (100.9%), T2 (51.9%) and T3 (38.2%). Overall, at 90 DAS (T6 & T9) and harvest (T5, T6 & T9), the effects were found to be more significant than those of all other treatments.

Soil phosphorus is necessary for plant development and production because it plays important roles in various physiological processes. As a result, the application of biochar increases sa significant impact of biochar on the soil's potassium concentration was observed at various Zhang revealed that biochar significantly enhances plant-available phosphorus in soils, with a meta-analysis indicating an average increase in phosphorus availability by a factor of 4.6, particularly in acidic and neutral soils (Zhang et al., 2019). Biochar's alkaline properties increase soil pH, reducing the adsorption of iron and aluminium oxides with phosphorus and increasing its availability for plant uptake (Smith et al., 2024).

Table 4.42 Effect of different doses of biochar application on soil available phosphorus (mg/kg) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	8.2^{f}	14.6^{g}	11.4^{f}	9.1^{e}	13.5^{g}	11.3^{e}	9.3^{d}	12.8^{e}	11.0^{f}
T_2	10.2^{ef}	26.6^{e}	18.4^{e}	13.4^{d}	21.2^{e}	17.3^{d}	14.9^{cd}	16.2^{e}	16.7^{e}
T_3	10.0^{e}	22.6^{f}	16.3^{e}	10.1^{e}	17.0^{f}	13.6^{e}	13.0^{cd}	17.4^{d}	15.2^{e}
T_4	20.7^{d}	53.3^{cd}	37.0^{d}	28.6^{c}	41.1^{c}	34.9^{c}	19.2^{bc}	27.0^{c}	23.1^{cd}
T_5	26.9^{c}	63.6^{b}	45.2^{c}	31.2^{c}	46.4^{b}	38.8^{b}	23.8^{a}	31.5^{ab}	28.0^{ab}
T_6	30.1^{c}	69.7^{a}	49.9^{b}	45.4^{a}	51.4^{a}	48.4^{a}	24.4^{a}	34.2^{a}	29.0^{a}
T_7	30.1^{c}	42.0^{d}	36.1^{d}	41.4^{b}	36.4^{d}	38.9^{b}	15.2^{cd}	29.0^{bc}	22.1^{d}
T_8	53.1^{b}	52.5^{c}	52.8^{b}	39.5^{b}	42.5^{c}	41.0^{b}	21.9^{ab}	28.4^{bc}	25.1^{bc}
T_9	65.7^{a}	68.5^{a}	67.1^{a}	42.9^{a}	51.6^{a}	47.3^{a}	23.1^{ab}	32.7^{ab}	27.9^{ab}
CD($p\leq0.05$)	5.4	3.3	3.1	9.6	2.4	3.1	4.9	4.4	2.9
SEm (±)	1.8	1.1	1.0	3.2	0.8	1.0	1.6	1.4	1.0
Initial value	8.95								

***** Means denoted by different letters are significantly different at $p\leq0.05$. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar a significant impact of biochar on the soil's sulphur concentration was observed straw biochar at 15 tons/ha).**

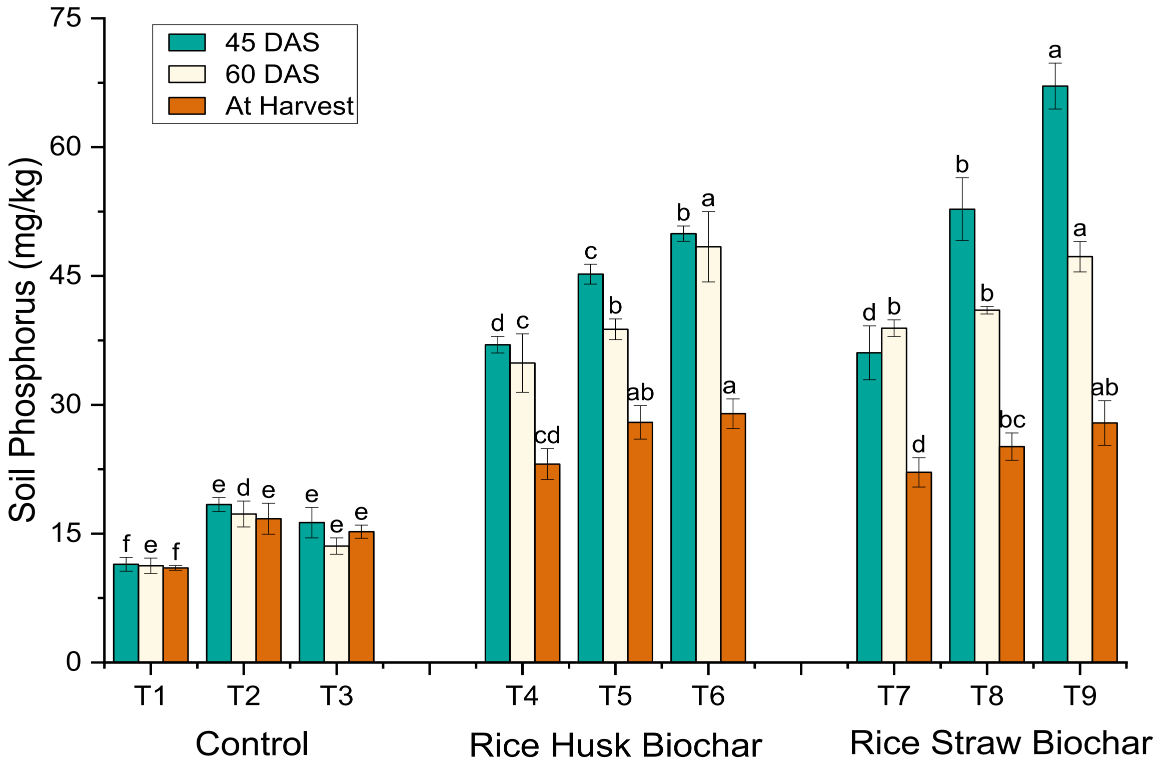


Figure 4.40. Effect of different biochar doses on soil phosphorus (mg/kg) at 45 and 90 DAS and at harvest.

Potassium is one of the primary ways to enhance the soil's 82.0), T8 (80.1), T5 (78.7), T7 (78.7), T4 (74.6), T2 (71.0), T3 (65.6), and availability of potassium ions. During the 2023 season, a significant impact of biochar on the soil's potassium concentration was observed at various stages. The results are presented in **Table 4.42**. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum potassium concentration at sowing time, 45 DAS, 90 DAS, and at harvest, i.e., 125.3, 108.4, 77.6, and 82.7, respectively. However, at 45 DAS (T8 &T9) and at harvest (T5, T6, T7, T8 &T9), showed a significant improvement in soil potassium compared to all other treatments. The maximum potassium concentration at harvest was recorded in T9 (82.7), followed by T6 (82), T8 (80.1), T5 (78.7), T7 (78.7), T4 (74.6), T2 (71), T3 (65.6) and T1 (55.4). As compared to control (T1), there was a significant percent increase in potassium concentration in treatments T8 (48.2%), T6 (48%), T9 (45.6%), T7 (42.1%), T5 (42.1%), T4 (34.7%), T2 (28.1%) and T3 (18.4%).

During the 2024 season, a significant impact of biochar on the soil's potassium concentration was observed at different stages. Among all treatments, T9 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum potassium concentration at sowing time, 45 DAS, and 90 DAS, i.e., 111, 96.2, and 72.5, respectively. During harvest, treatment T6 (i.e., rice straw biochar at 15 tons/ha) resulted in the maximum potassium concentration, i.e., 73.2. However, at 90 DAS (T6 & T9) and harvest (T5 & T6), a significant improvement in soil potassium was observed compared to all other treatments. The maximum potassium concentration at harvest was recorded in T6 (73.2), followed by T5 (70.7), T4 (66.3), T9 (66), T2 (63.7), T3 (60.6), T8 (60.4), T7 (58.9), and T2 (56.6). As compared to control (T1), there was a significant percent increase in potassium concentration in treatments T6 (29.3%), T5 (24.9%), T4 (17.1%), T9 (16.7%), T2 (12.5%), T3 (7.1%), T8 (6.7%) and T7 (4.1%).

The mean potassium concentration was found to be significant at all growth stages. The maximum potassium concentration at harvest was recorded in T6 (77.6), followed by T5 (74.7), T9 (73.4), T8 (71.3), T4 (70.5), T7 (68.8), T2 (67.3), T3 (63.1) and T1 (56). As compared to control (T1), there was a significant percent increase in potassium concentration in treatments T6 (38.5%), T5 (33.4%), T9 (31%), T8 (27.2%), T4 (25.8%), T7 (22.9%), T2 (20.2%) and T3 (12.7%). Overall, the harvest (T5 & T6) was found to be more significant than all other treatments.

Biochar application increases soil potassium availability through several mechanisms that enhance nutrient dynamics in the soil. Biochar has a high porosity and specific surface area, which contributes to its ability to retain K and other nutrients, thus preventing leaching and enhancing plant uptake (Smith et al., 2023). Additionally, biochar can directly supply potassium to the soil, particularly when produced from feedstocks rich in potassium. Research indicates that the total potassium content in biochar can vary significantly, with some types containing as much as 4–91 g/kg of potassium (Jones et al., 2022). This direct addition of K from biochar can significantly increase available K levels in the soil. For instance, a study found that applying peanut shell biochar increased available K by 125.78% after 30 months compared to control treatments.

Table 4.43 Effect of different doses of biochar application on soil available potassium (mg/kg) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	56.2^{e}	55.6^{g}	55.9^{h}	42.6^{f}	49.1^{e}	45.8^{f}	55.4^{e}	56.6^{e}	56^{g}
T_2	66.7^{d}	68.2^{ef}	67.5^{f}	51.3^{de}	56^{cd}	53.7^{de}	71.0^{cd}	63.7^{bc}	67.3^{e}
T_3	60.6^{de}	64.3^{f}	62.4^{g}	47.4^{ef}	53.5^{d}	50.5^{e}	65.6^{d}	60.6^{cd}	63.1^{f}
T_4	88.7^{c}	72.2^{de}	80.5^{e}	54.4^{d}	57.8^{c}	56.1^{d}	74.6^{bc}	66.3^{b}	70.5^{cde}
T_5	92.8^{c}	79.6^{c}	86.2^{cd}	57.6^{cd}	65.2^{b}	61.4^{c}	78.7^{ab}	70.7^{a}	74.7^{ab}
T_6	95.3^{bc}	85.8^{b}	90.5^{bc}	62.3^{bc}	70.1^{a}	66.2^{b}	82.0^{a}	73.2^{a}	77.6^{a}
T_7	95.8^{bc}	75^{cd}	85.4^{d}	57.1^{cd}	56.1^{cd}	56.6^{d}	78.7^{ab}	58.9^{d}	68.8^{de}
T_8	101.6^{ab}	86.1^{b}	93.9^{b}	68.3^{b}	63.9^{b}	66.1^{b}	80.1^{a}	60.4^{cd}	71.3^{bcd}
T_9	108.4^{a}	92.6^{a}	100.5^{a}	77.6^{a}	72.5^{a}	75.1^{a}	82.7^{a}	66.0^{b}	73.4^{bc}
CD ($p \le 0.05$)	8.5	5.9	4.6	6.7	3.7	3.9	5.7	3.6	3.7
SEm (±)	2.8	1.9	1.5	2.2	1.2	1.3	1.9	1.2	1.2
Initial value	41								

***** Means denoted by different letters are significantly different at $p \le 0.05$, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

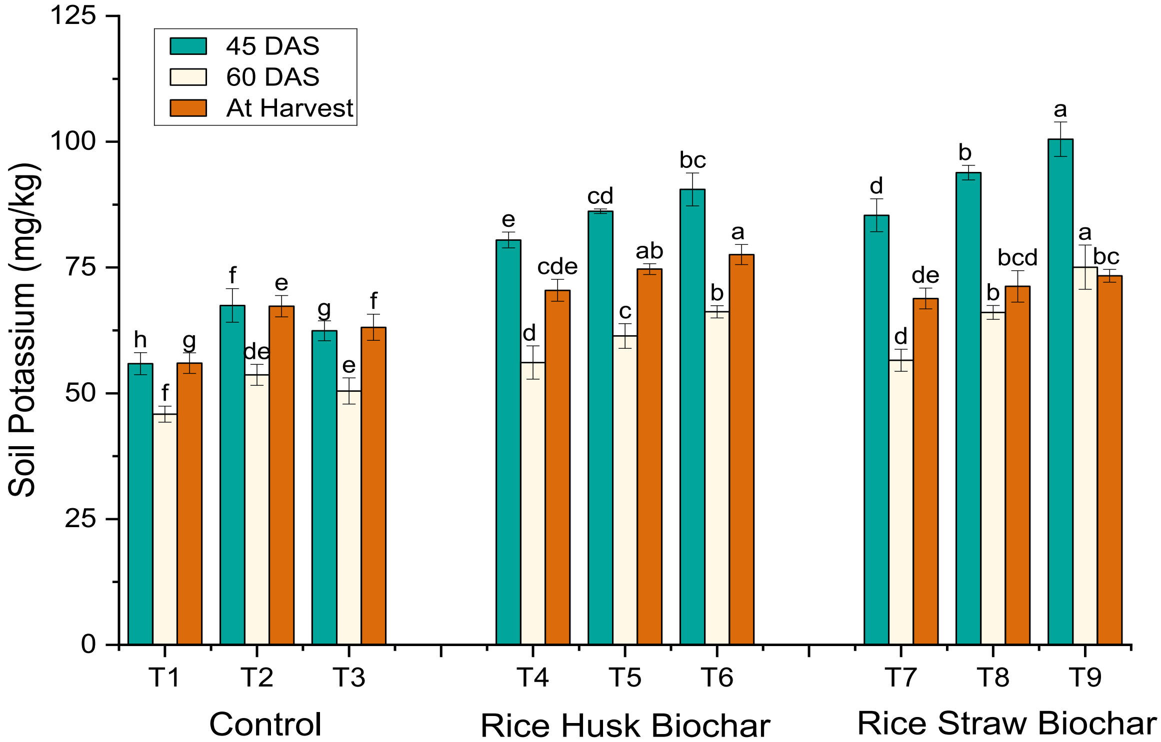


Figure 4.41. Effect of different biochar doses on soil potassium (mg/kg) at 45 and 90 DAS and at harvest.

The sulphur concentration in soil was notably influenced by biochar during different stages of the 2023 season, with results presented in **Table 4.41.** Among all treatments, T4 (i.e., rice husk biochar at 5 tons/ha) recorded the maximum sulphur concentration at sowing time, i.e., 19.4. At 45 DAS, 90 DAS, and harvest, treatment T9 (i.e., rice straw biochar at 15 tons/ha) resulted in the maximum sulphur concentration, i.e., 15.9, 12.8, and 10.7, respectively. However, at 45 DAS (T5, T7, T8 & T9), at 90 DAS (T4, T5, T6 & T9), and at harvest (T4, T5, T6, T7, T8 & T9), the treatments showed a significant improvement in soil sulphur compared to all other treatments. The maximum sulphur concentration at harvest was recorded in T9 (10.7), followed by T8 (10.6), T5 (10.6), T4 (10.1), T7 (9.9), T6 (9.7), T2 (6.9), T3 (6.4) and T1 (5.8). As compared to control, there was a significant percentage increase in sulphur concentration in treatments T5 (84.6%), T8 (84.1%), T9 (75.7%), T4 (73.8%), T7 (71%), T6 (67.1%), T2 (19.8%) and T3 (9.8%).

Throughout the 2024 season, a significant impact of biochar on the soil's sulphur concentration was observed at different stages. Among all treatments, T9 (i.e., rice straw biochar at 15 tons/ha) recorded the maximum sulphur concentration at sowing time, 90 DAS, and harvest, i.e., 21.2, 16.6, and 15.6, respectively. While at 45 DAS treatment, T6 (i.e. rice husk biochar @ 15 tons/ha) resulted in maximum sulphur concentration, i.e. 18.6. However, at 90 DAS (T5, T6, T8 & T9) and at harvest (T8 & T9), showed a significant improvement in soil sulphur compared to all other treatments. The maximum sulphur concentration at harvest was recorded in T9 (15.6), followed by T8 (14.5), T6 (14.4), T7 (12.8), T5 (12.7), T4 (11.6), T2 (7), T3 (6.4) and T1 (5.6). As compared to control (T1), there was a significant percent increase in sulphur concentration in treatments T9 (178.6%), T8 (158.3%), T6 (156.5%), T7 (128%), T5 (127.4%), T4 (107.1%), T2 (25%) and T3 (13.7%).

The mean sulphur concentration was found to be significant at all growth stages. The maximum sulphur concentration at harvest was recorded in T9 (12.9), followed by T8 (12.6), T6 (12.0), T5 (11.7), T7 (11.3), T4 (10.8), T2 (7.0), T3 (6.4), and T1 (5.7). As compared to control (T1), there was a significant percent increase in sulphur concentration in treatments T9 (126.2%), T8 (120.6%), T6 (111.1%), T5 (105.6%), T7 (99%), T4 (90.2%), T2 (22.3%) and T3 (11.7%). Overall, at 45 & 90 DAS (T6 & T9) and harvest (T5, T6, T8 & T9), the effects were found to be more significant than those of all other treatments.

According to the, rice husk biochar at 15 tons/ha) recorded the maximum calcium concentration at both sowing time and harvest, i.e., sulphur fertiliser, especially when biochar is enriched with sulphur during its production. This enriched biochar can release sulphur compounds into the soil, making them available for plant uptake (Ali et al., 2023). Studies have shown that the application of sulphur-enriched biochar can significantly improve soil sulphur content and availability, leading to enhanced plant growth and yield (Mousa et al., 2023). Furthermore, biochar improves soil microbial activity, which plays a crucial role in the mineralisation of organic and inorganic sulphur compounds.

Table 4.43 Effect of different doses of biochar application on soil available sulphur (mg/kg) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	8.6^{c}	9.1^{e}	8.9^{e}	7.4^{d}	6.6^{d}	7.0^{f}	5.8^{b}	5.6^{f}	5.7^{e}
T_2	9.0^{c}	9.9^{e}	9.4^{e}	8.5^{cd}	7.9^{d}	8.2^{e}	6.9^{b}	7.0^{e}	7.0^{d}
T_3	8.1^{c}	9.2^{e}	8.6^{e}	7.8^{d}	7.2^{d}	7.5^{ef}	6.4^{b}	6.4^{ef}	6.4^{de}
T_4	13.2^{b}	14.8^{d}	14.0^{d}	12.4^{a}	14.1^{bc}	13.3^{c}	10.1^{a}	11.6^{d}	10.8^{c}
T_5	14.8^{ab}	16.0^{bc}	15.4^{bc}	12.6^{a}	15.5^{a}	14.1^{bc}	10.6^{a}	12.7^{cd}	11.7^{abc}
T_6	13.5^{b}	18.6^{a}	16.1^{ab}	13.5^{a}	16.5^{a}	15.1^{a}	9.7^{a}	14.4^{b}	12.0^{ab}
T_7	14.1^{ab}	14.8^{d}	14.5^{cd}	9.8^{bc}	13.3^{c}	11.6^{d}	9.9^{a}	12.8^{c}	11.3^{bc}
T_8	15.0^{ab}	15.8^{cd}	15.4^{bc}	11.0^{b}	15.4^{ab}	13.2^{c}	10.6^{a}	14.5^{ab}	12.6^{a}
T_9	15.9^{a}	16.9^{b}	16.4^{a}	12.8^{a}	16.6^{a}	14.7^{ab}	10.7^{a}	15.6^{a}	12.9^{a}
CD ($p \leq 0.05$)	2.0	1.1	1.2	1.3	1.3	0.9	1.9	1.1	0.9
SEm (±)	0.7	0.3	0.4	0.4	0.4	0.3	0.7	0.4	0.3
Initial value	10.21								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

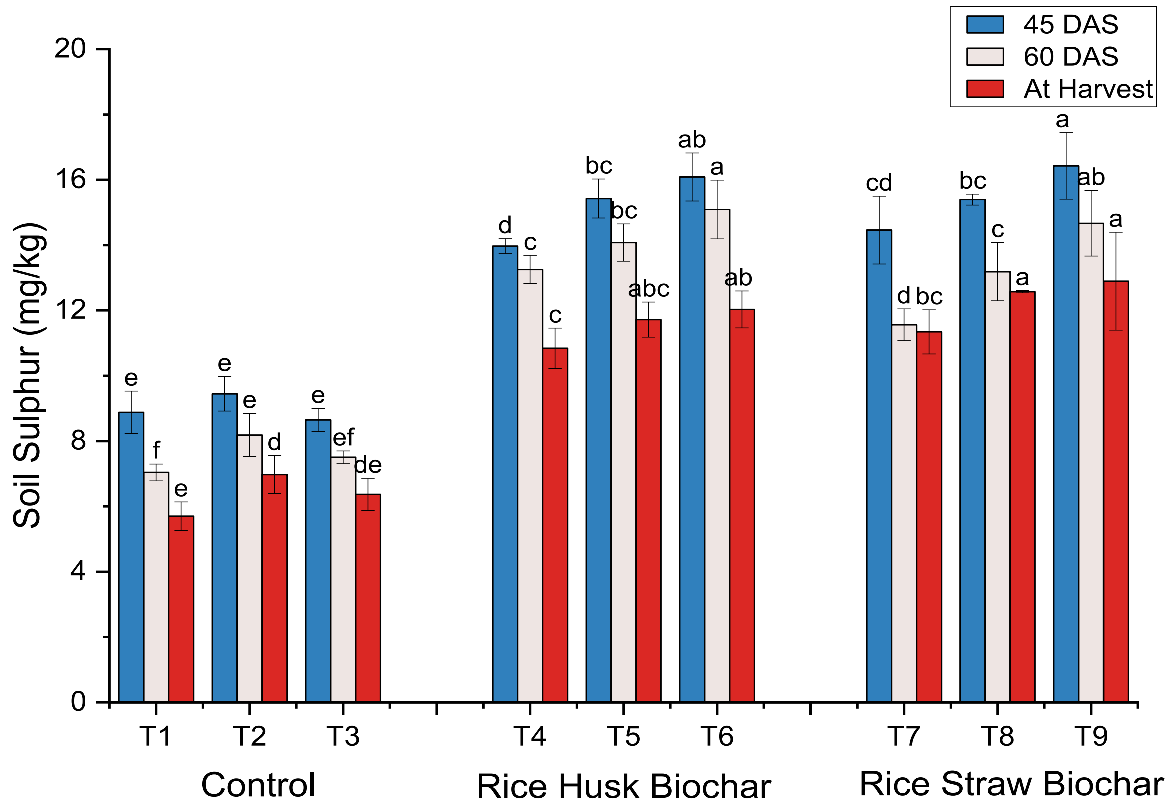


Figure 4.42. Effect of different biochar doses on soil sulphur (mg/kg) at 45 and 90 and at harvest.

The calcium concentration in soil was notably influenced by biochar during different stages in the 2023 season, with results presented in **Table 4.43.** Among all treatments, T6 (i.e. rice husk biochar @ 15 tons/ha) recorded maximum calcium concentration at sowing time and harvest, i.e. 275 and 255, respectively. While at 45 and 90, DAS treatment T9 (i.e. rice straw biochar @ 15 tons/ha) resulted in maximum calcium concentration, i.e. 259 and 247, respectively. However, at 45 DAS (T5, T6, T7, T8 & T9), at 90 DAS and at harvest (T4, T5, T6, T7, T8 & T9), a significant improvement in soil calcium was shown compared to all other treatments. The maximum calcium concentration at harvest was recorded in T6 (255), followed by T5 (252), T8 (251), T4 (249), T9 (249), T7 (248), T2 (223), T3 (220) and T1 (218). As compared to control (T1), there was a significant percent increase in calcium concentration in treatments T5 (16.8%), T6 (15.8%), T8 (15.4%), T4 (14.4%), T9 (14.3%), T7 (13.9%), T2 (2.3%) and T3 (1%).

Throughout the 2024 season, a significant impact of biochar on the soil's calcium concentration was observed at different stages. Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the maximum calcium concentration at both sowing time and harvest, i.e., 270 and 273, respectively. While at 45 and 90, DAS treatment T9 (i.e. rice straw biochar @ 15 tons/ha) resulted in maximum calcium concentration, i.e. 261 and 242, respectively. However, 90 DAS (T6 & T9) showed a significant improvement in soil calcium compared to all other treatments. The maximum calcium concentration at harvest was recorded in T6 (254), followed by T5 (251), T9 (245), T4 (241), T8 (238), T6 (229), T2 (235), T3 (232) and T1 (223). As compared to control, there was a significant percent increase in calcium concentration in treatments T6 (11.5%), T5 (10.1%), T9 (7.5%), T4 (5.8%), T8 (4.7%), T2 (3.4%), T3 (1.9%) and T7 (0.4%).

The mean magnesium concentration was found to be significant at all growth stages. The maximum magnesium concentration at harvest was recorded in T6 (253), followed by T5 (252), T9 (247), T8 (245), T4 (245), T7 (238), T2 (229), T3 (226) and T1 (223). As compared to control (T1), there was a significant percent increase in iron concentration in treatments T6 (13.6%), T5 (13.4%), T9 (10.8%), T4 (10%), T8 (9.9%), T7 (7%), T2 (2.8%) and T3 (1.5%). Overall, at 90 DAS (T6 & T9) and harvest (T5 & T6), the treatments were found to be more significant than all other treatments.

As shown in the results, the application of biochar significantly enhances soil calcium availability. The primary reason is that biochar contains significant amounts of calcium, which can be directly added to the soil as a nutrient source. This addition can lead to increased levels of exchangeable calcium in the soil, as demonstrated in studies where biochar application resulted in significant increases in soil exchangeable calcium content compared to control treatments (Silber et al., 2020). Apart from that, biochar has a high pH and can behave as a liming agent, which helps to neutralise soil acidity. This neutralisation process can improve the solubility of calcium and other nutrients, making them more available for plant uptake (Uta et al., 2023).

Table 4.45 Effect of different doses of biochar application on soil available calcium (mg/kg) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	220^{e}	208^{h}	214^{f}	209^{c}	196^{g}	203^{d}	218^{b}	228^{h}	223^{e}
T_2	247^{cd}	236^{d}	241^{d}	217^{bc}	208^{e}	212^{d}	223^{b}	235^{f}	229^{d}
T_3	242^{d}	228^{g}	235^{e}	211^{c}	200^{f}	205^{d}	220^{b}	232^{g}	226^{de}
T_4	249^{bcd}	240^{e}	244^{d}	232^{ab}	224^{d}	228^{c}	249^{a}	241^{d}	245^{b}
T_5	252^{abc}	246^{d}	249^{c}	236^{ab}	232^{c}	234^{bc}	252^{a}	251^{b}	252^{a}
T_6	256^{ab}	255^{b}	255^{b}	240^{a}	240^{ab}	240^{ab}	255^{a}	254^{a}	253^{a}
T_7	251^{abc}	248^{c}	249^{c}	237^{ab}	225^{d}	231^{bc}	248^{a}	229^{h}	238^{c}
T_8	255^{abc}	253^{b}	254^{b}	245^{a}	238^{b}	241^{ab}	251^{a}	238^{e}	245^{b}
T_9	259^{a}	261^{a}	260^{a}	247^{a}	242^{a}	245^{a}	249^{a}	245^{c}	247^{b}
CD($p\leq0.05$)	7.8	1.7	3.9	2.0	3.4	10.7	7.2	1.7	3.7
SEm (±)	2.6	0.6	1.3	0.7	1.1	3.5	2.4	0.5	1.2
Initial value	174.2								

***** Means denoted by different letters are significantly different at p≤0.05, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

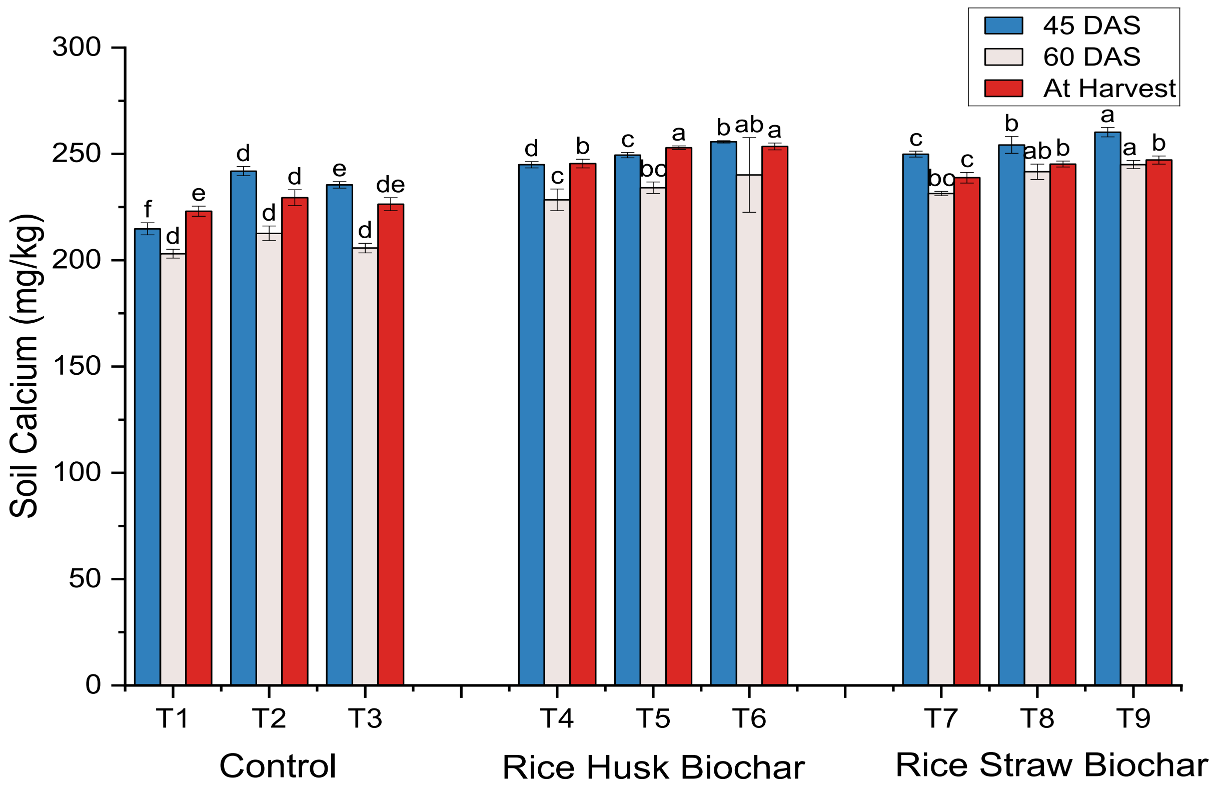


Figure 4.43. Effect of different biochar doses on soil calcium (mg/kg) at 45 and 90 DAS and at harvest.

The availability of soil magnesium increased the cation exchange capacity, allowing for better retention and availability of magnesium ions. During the 2023 season, a significant impact of biochar on the soil's magnesium concentration was observed at various stages. The results are presented in **Table 4.44**. Among all treatments, T6 (i.e. rice husk biochar @ 15 tons/ha) recorded maximum magnesium concentration at sowing, 90 DAS and at harvest, i.e. 168.5, 128.3 and 147, respectively. While at 45 DAS treatment, T9 (i.e. rice straw biochar @ 15 tons/ha) resulted in maximum magnesium concentration, i.e. However, at 45 DAS (T6, T8 & T9), at 90 DAS (T6 & T9) and harvest (T4, T5, T6, T7, T8 & T9) showed a significant improvement in soil magnesium compared to all other treatments. maximum magnesium concentration at harvest was recorded in T6 (147) followed by T9 (146.3), T5 (146), T8 (145.3), T4 (144), T7 (141.7), T2 (132.2), T3 (130) and T1 (123.3). As compared to control (T1), there was a significant percent increase in magnesium concentration in treatments T6 (19.2%), T9 (18.7%), T5 (18.4%), T8 (17.9%), T4 (16.8%), T7 (14.9%), T2 (7.2%) and T3 (5.4%).

During the 2024 season, a significant impact of biochar on the soil's magnesium concentration was observed at various stages of growth. Among all treatments, T6 (i.e., rice husk biochar at 15 tons/ha) recorded the maximum magnesium concentration at sowing and 90 DAS, i.e., 167.7 and 128.3 mg/kg, respectively. At 45 DAS, the T9 treatment (i.e., rice straw biochar at 15 tons/ha) resulted in the maximum magnesium concentration, i.e., 154.9 and 146, respectively. maximum magnesium concentration at harvest was recorded in T9 (146) followed by T7 (142.7), T6 (135.3), T8 (133.7), T5 (132), T4 (127), T2 (125.3), T3 (119.7) and T1 (117). As compared to control (T1), there was a significant percent increase in magnesium concentration in treatments T9 (24.8%), T7 (21.9%), T6 (15.7%), T8 (14.2%), T5 (12.8%), T4 (8.5%), T2 (7.1%) and T3 (2.3%).

The mean magnesium concentration was found to be significant at all growth stages. The maximum magnesium concentration at harvest was recorded in T9 (146.2), followed by T7 (142.2), T6 (141.2), T8 (139.5), T5 (139), T4 (135.5), T2 (128.8), T3 (124.8) and T1 (120.2). As compared to control (T1), there was a significant percent increase in iron concentration in treatments T9 (21.6%), T7 (18.3%), T6 (17.5%), T8 (16.1%), T5 (15.7%), T4 (12.8%), T2 (7.2%) and T3 (3.9%). Overall, at 90 DAS (T6 & T9) and harvest (T7 & T9), it was found to be more significant than all other treatments.

The porous nature of biochar increases the surface area for ion exchange, facilitating the retention of magnesium and other essential nutrients in the soil solution, thus making them more accessible to plants. Kumar states that biochar can directly contribute magnesium to the soil, especially from feedstocks containing significant amounts of this nutrient, which can enhance soil magnesium content upon application. For example, research has shown that applying biochar derived from specific biomass can lead to increased levels of exchangeable magnesium in the soil, thereby improving its availability for plant uptake (Ali et al., 2021).

Table 4.46 Effect of different doses of biochar application on soil available magnesium (g/kg) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T$_1$	131.7^{g}	123.7^{h}	127.7^{g}	113.8^{e}	104.0^{e}	108.9^{e}	123.3^{c}	117.0^{g}	120.2^{e}
T$_2$	138.4^{ef}	132.3^{f}	135.4^{e}	120.4^{cd}	117.7^{c}	119.1^{c}	132.2^{b}	125.3^{e}	128.8^{d}
T$_3$	135.2^{fe}	128.3^{g}	131.8^{f}	115.4^{de}	114.3^{d}	114.9^{d}	130.0^{bc}	119.7^{f}	124.8^{d}
T$_4$	141.1^{def}	136.7^{e}	138.9^{d}	122.1^{c}	118.3^{c}	120.2^{c}	144.0^{a}	127.0^{e}	135.5^{c}
T$_5$	147.1^{bcd}	140.7^{d}	143.9^{c}	126.9^{bc}	123.3^{b}	125.1^{b}	146.0^{a}	132.0^{d}	139.0^{bc}
T$_6$	151.2^{ab}	146.7^{c}	148.9^{b}	131.1^{ab}	128.3^{a}	129.7^{a}	147.0^{a}	135.3^{c}	141.2^{b}
T$_7$	144^{cde}	139.7^{d}	141.8^{cd}	126.4^{bc}	113.7^{d}	120.0^{c}	141.7^{a}	142.7^{b}	142.2^{ab}
T$_8$	149.6^{abc}	149.0^{b}	149.3^{b}	131.5^{ab}	117.7^{c}	124.6^{b}	145.3^{a}	133.7^{cd}	139.5^{bc}
T$_9$	154.9^{a}	151.3^{a}	153.1^{a}	137.2^{a}	122.0^{b}	129.6^{a}	146.3^{a}	146.0^{a}	146.2^{a}
CD ($p \leq 0.05$)	1.7	1.7	3.2	1.3	2.0	3.6	2.1	2.4	4.4
SEm (±)	0.6	0.6	1.1	0.4	0.7	1.2	0.7	0.8	1.4
Initial value	125.8								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

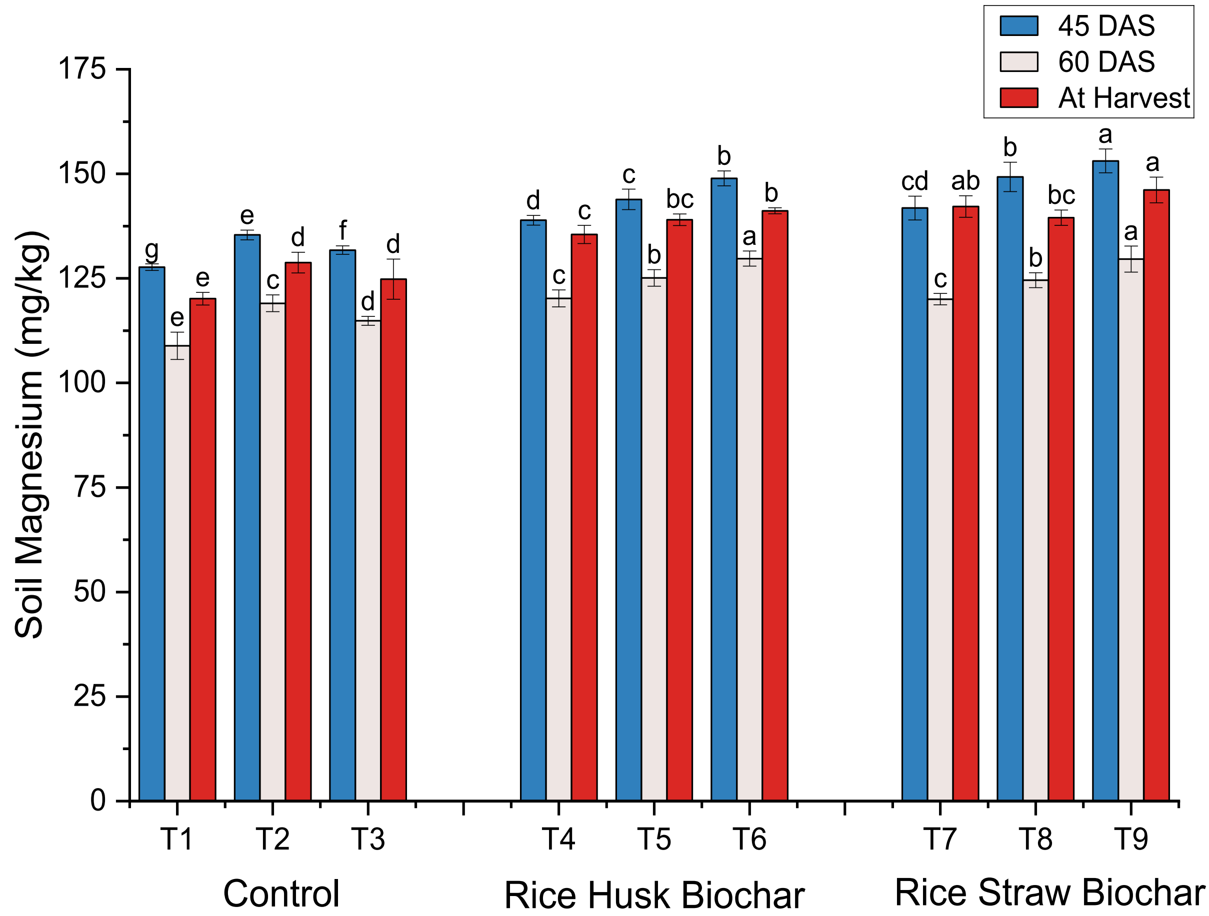


Figure 4.44. Effect of different biochar doses on soil magnesium (mg/kg) at 45 and 90 DAS and at harvest.

The results in **Table 4.45** highlight the considerable influence of biochar on the iron concentration in the soil during different stages of the 2023 season. Among all treatments, T1 (i.e., control) recorded the maximum iron concentration at sowing time, 45 DAS, 90 DAS, and harvest, i.e., 14.6, 11.5, 9.2, and 13.2, respectively. However, during all growth stages, both T1, T2 and T3 showed a significant improvement in soil iron compared to all other treatments. The maximum iron concentration at harvest was recorded in T1 (13.2), followed by T3 (12.7), T2 (11.3), T4 (10), T5 (9.7), T8 (9.7), T6 (9.6), T9 (9.4) and T7 (8.6). As compared to control (T1), there was a significant percent increase in iron concentration in treatments T7 (34.8%), T9 (28.2%), T6 (27.1%), T5 (26%), T8 (26%), T4 (24.1%), T2 (14.1%) and T3 (3.7%).

During the 2024 season, a significant impact of biochar on soil iron concentration was observed at various stages. Among all treatments, T1 (i.e., control) recorded the maximum iron concentration at sowing time, 45 DAS, 90 DAS, and harvest, i.e., 13.9, 15.8, 11.1, and 11.2, respectively. The maximum iron concentration at harvest was recorded in T1 (11.2), followed by T3 (10.4), T2 (10.0), T4 (9.3), T5 (9.1), T6 (8.7), T7 (8.6), T8 (8.4), and T9 (8.0). As compared to control (T1), there was a significant percent increase in iron concentration in treatments T9 (28.3%), T8 (25.3%), T7 (22.9%), T6 (22%), T5 (19%), T4 (17%), T2 (10.4%) and T3 (6.8%).

The mean iron concentration was found to be significant at all growth stages. The maximum iron concentration at harvest was recorded in T1 (12.2), followed by T3 (11.6), T2 (10.7), T4 (9.6), T5 (9.4), T6 (9.2), T8 (9.1), T9 (8.7) and T7 (8.6). As compared to control (T1), there was a significant percent increase in iron concentration in treatments T7 (29.3%), T9 (28.2%), T8 (25.7%), T6 (24.7%), T5 (22.8%), T4 (20.8%), T2 (12.4%) and T3 (5.1%).

Biochar application can reduce iron availability in the soil, and biochar can alter soil pH, particularly in acidic soils. When biochar is applied, it often raises the soil pH, which can lead to the precipitation of iron as insoluble forms, thereby reducing its bioavailability to plants (Ali et al., 2022). According to Kumar, an increase in soil pH subsequently decreases the solubility of iron compounds, making them less available for plant uptake. Additionally, biochar can enhance cation exchange capacity (CEC), allowing it to retain calcium and magnesium more effectively than iron. This increased retention of other cations can lead to a relative decrease in the concentration of available iron in the soil solution (Tan et al., 2020).

Table 4.47 Effect of different doses of biochar application on soil available iron (mg/kg) at 45 DAS, 90 DAS and harvest during 2023 and 2024.

Treatments	45 DAS			90 DAS			At Harvest		
	2023	2024	Mean	2023	2024	Mean	2023	2024	Mean
T_1	11.5^{a}	15.8^{a}	13.7^{a}	9.2^{a}	12.9^{a}	11.1^{a}	13.2^{a}	11.2^{a}	12.2^{a}
T_2	10.1^{a}	12.1^{c}	11.1^{b}	8.2^{abc}	9.9^{c}	9.1^{c}	11.3^{ab}	10.0^{c}	10.7^{bc}
T_3	10.8^{a}	12.7^{b}	11.8^{b}	8.6^{ab}	11.4^{b}	10.0^{b}	12.7^{a}	10.4^{b}	11.6^{ab}
T_4	6.6^{bc}	11.5^{d}	9.1^{cd}	7.6^{bcd}	8.2^{d}	7.9^{d}	10.0^{bc}	9.3^{d}	9.6^{cd}
T_5	4.9^{c}	11.5^{d}	8.2^{de}	7.0^{cd}	8.0^{d}	7.5^{de}	9.7^{bc}	9.1^{e}	9.4^{d}
T_6	5.3^{c}	10.5^{e}	7.9^{e}	6.9^{d}	7.7^{e}	7.3^{def}	9.6^{bc}	8.7^{f}	9.2^{d}
T_7	7.9^{bc}	10.6^{e}	9.2^{c}	6.5^{d}	8.1^{d}	7.3^{def}	8.6^{c}	8.6^{f}	8.6^{d}
T_8	6.4^{bc}	10.3^{e}	8.4^{cde}	6.3^{d}	7.5^{e}	6.9^{ef}	9.7^{bc}	8.4^{g}	9.1^{d}
T_9	5.6^{c}	9.5^{f}	7.6^{e}	6.5^{d}	7.0^{f}	6.8^{f}	9.4^{bc}	8.0^{h}	8.7^{d}
CD ($p \leq 0.05$)	0.0	0.4	0.9	0.0	0.2	0.6	0.4	0.2	1.0
SEm (±)	0.0	0.1	0.3	0.0	0.1	0.2	0.2	0.1	0.3
Initial value	7.14								

***** Means denoted by different letters are significantly different at $p \leq 0.05$, as determined by the least significant difference (LSD) for mean separation. The treatments were as follows: T1 (control), T2 (recommended NPK dosage), T3 (recommended NP dosage), T4 (NP with rice husk biochar at 5 tons/ha), T5 (NP with rice husk biochar at 10 tons/ha), T6 (NP with rice husk biochar at 15 tons/ha), T7 (NP with rice straw biochar at 5 tons/ha), T8 (NP with rice straw biochar at 10 tons/ha), and T9 (NP with rice straw biochar at 15 tons/ha).**

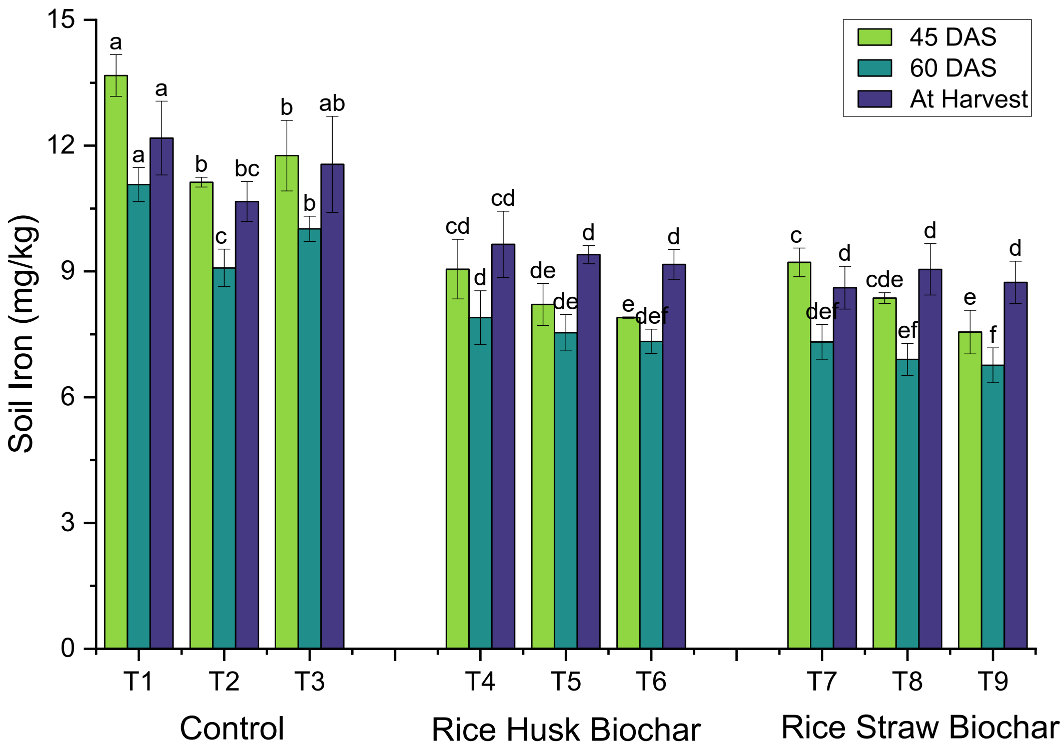


Figure 4.45. Effect of different biochar doses on soil iron (mg/kg) at 45 and 90 DAS and at harvest.

CHAPTER-V

SUMMARY AND CONCLUSION

The field experiment entitled "Impact of biochar amendment on soil fertility and crop productivity in wheat pigeon pea cropping system" was conducted in an agriculture farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab, during the 2022-2023 and 2023-24. The first objective was to evaluate the impact of biochar application on soil properties. The second objective was to assess the greenhouse gas emissions and mitigation with biochar incorporation. The last objective was to analyse the response of biochar on the growth, yield, and quality attributes of the wheat-pigeon pea cropping system, along with its economic viability. A summary of the experiment findings is given below.

1. The height of the plant was measured at 30, 60, 90 and 120 DAS. The maximum plant height was recorded at 120 DAS, at 103.1 cm in 2022-23 and 100 cm in 2023-24, respectively, under treatment T7. The minimum plant height was recorded under treatment T1, at 70 cm in 2022-23 and 72.5 cm in 2023-24.
2. The maximum Number of tillers was recorded at 120 DAS under treatment T4, which was 161 in 2022-23 and 155 in 2023-24. In contrast, the lowest was in treatment T1, which was 68 in 2022-23 and 74.7 in 2023-24.
3. The maximum Leaf area at 90 DAS was recorded in T7 (126.1 m^2) in 2022-23 and in T4 (103 m^2) in 2023-24 seasons. In contrast, the minimum leaf area recorded in T1 was 26.3 in 2022-23 and 31.5 m^2 in 2023-24.
4. The maximum leaf area index (LAI) was observed at 90 DAS. In the 2022-23 season, treatment T7 resulted in the highest LAI value of 5.6. In contrast, during the 2023-24 season, treatment T4 produced the highest LAI of 4.6. The lowest LAI values, 1.2 in 2022-23 and 1.4 in 2023-24, were recorded under treatment T1.
5. The highest node diameter was recorded at 90 DAS. The maximum node diameter under treatment T7 was 6 mm in both 2022-23 and 2023-24. The minimum node diameter under treatment T1 was 3.4 mm in both 2022-23 and 2023-24.
6. The maximum internode diameter was recorded at 90 DAS. The highest internode diameter under T7 treatment was 5 mm in 2022-23 and 5.1 mm in 2023-24. The lowest internode diameter under T1 treatment was 2.6 mm in 2022-23 and 2.7 mm in 2023-24.

7. The highest dry biomass was recorded at 120 DAS. Maximum dry matter accumulation was observed in T4 with 109.7 g in 2022-23 and in T7 with 101.4 g in 2023-24. The minimum dry matter under T1 treatment was 57.7 g in 2022-23 and 62 g in 2023-24.
8. The maximum crop growth rate (CGR) was recorded at 120 DAS. The highest CGR was observed in T4, with 6.1 in 2022-23, and in T7, with 6.2 in 2023-24. The minimum CGR under T1 was 3.4 in 2022-23 and 3.6 in 2023-24.
9. The maximum RWC was recorded at 120 DAS, with values of 66.2% in 2022-23 and 68.3% in 2023-24 under treatment T7. The minimum RWC under treatment T1 was 55.5% in 2022-23 and 56.4% in 2023-24.
10. Chlorophyll content was measured at 30, 60, and 90 DAS. The maximum chlorophyll content at 90 DAS was 1.68 mg/g in 2022-23 and 1.74 mg/g in 2023-24 under T7. The lowest content under T1 was 0.85 mg/g in 2022-23 and 0.84 mg/g in 2023-24.
11. The maximum membrane stability index (MSI) was recorded at 120 DAS. The highest MSI under T4 was 70.6% in 2022-23 and 69.6% in 2023-24. The minimum MSI under T1 was 52.9% in 2022-23 and 54.9% in 2023-24.
12. The maximum spike length was 16.7 cm in 2022-23 and 17.1 cm in 2023-24 under T4. The minimum spike length under T1 was 8.5 cm in 2022-23 and 8.8 cm in 2023-24.
13. The maximum grains per spike were 84.3 in 2022-23 and 81.1 in 2023-24 under T4. The minimum grains per spike under T1 were 43.6 in 2022-23 and 33.3 in 2023-24.
14. The maximum test weights were 49.3 g in 2022-23 and 49.4 g in 2023-24 under T4. The minimum test weights under T1 were 40.8 g in 2022-23 and 41.7 g in 2023-24.
15. The maximum biological yield was 157.8 q/ha in 2022-23 under T4 and 160.6 q/ha in 2023-24 under T7. The minimum biological yield under T1 was 94.4 tonnes per hectare in 2022-23 and 96.5 tonnes per hectare in 2023-24.
16. The maximum grain yield was 70 q/ha in 2022-23 and 69.3 q/ha in 2023-24 under T7. The minimum grain yield under T1 was 27.1 q/ha in 2022-23 and 26.1 q/ha in 2023-24.
17. The maximum harvest index was 44.8 in 2022-23 and 43.2 in 2023-24 under T7. The minimum harvest index under T1 was 28.7 in 2022-23 and 27.3 in 2023-24.
18. The maximum soil pH at harvest was 8.1 in 2022-23 and 7.9 in 2023-24 under T6. The lowest pH value under T1 was 7.3 in 2022-23 and 7.2 in 2023-24.
19. The maximum electrical conductivity at harvest was 0.26 in 2022-23 under T5 and 0.25 in 2023-24 under T9. The lowest EC under T1 was 0.17 in 2022-23 and 0.15 in 2023-24.

20. Soil organic carbon at harvest was highest in T6 with 0.54% in 2022-23 and in T9 with 0.56% in 2023-24. The minimum organic carbon under T1 was 0.39% in 2022-23 and 0.44% in 2023-24.
21. The maximum available nitrogen at harvest was 245.7 kg/ha in 2022-23 and 270.5 kg/ha in 2023-24 under T4. The minimum available nitrogen under T1 was 180 kg/ha in 2022-23 and 184.4 kg/ha in 2023-24.
22. The maximum phosphorus concentration at harvest was 17.4 mg/kg in 2022-23 under T9 and 17 mg/kg in 2023-24 under T8. The minimum phosphorus concentration under T1 was 7.6 mg/kg in 2022-23 and 8.6 mg/kg in 2023-24.
23. The maximum potassium concentration at harvest was 123.7 mg/kg in 2022-23 and 113.6 mg/kg in 2023-24 under T9. The minimum potassium concentration under T1 was 36.7 mg/kg in 2022-23 and 41.5 mg/kg in 2023-24.
24. The maximum sulphur concentration at harvest was 12.5 mg/kg in 2022-23 under T9 and 12 mg/kg in 2023-24 under T8. The minimum sulphur concentration at harvest under T1 was 7.1 mg/kg in 2022-23 and 6.6 mg/kg in 2023-24.
25. The maximum calcium concentration at harvest was 284.3 mg/kg in 2022-23 under T9 and 278.2 mg/kg in 2023-24 under T6. The minimum calcium concentration under T1 was 238.1 mg/kg in 2022-23 and 232.9 mg/kg in 2023-24.
26. The maximum magnesium concentration at harvest was 145.3 mg/kg in 2022-23 under T5 and 179 mg/kg in 2023-24 under T7. The minimum magnesium concentration was 126.6 mg/kg in 2022-23 under T4 and 168.6 mg/kg in 2023-24 under T6.
27. The maximum plant height at 120 DAS was 296.3 cm in 2023 and 235.8 cm in 2024 under T4. The minimum plant height under T1 was 162.7 cm in 2023 and 132.7 cm in 2024.
28. The maximum number of primary branches at 120 DAS was 46.7 in 2023 under T7 and 39 in 2024 under T4. The lowest number of primary branches under T1 was 22.3 in 2023 and 21 in 2024.
29. The maximum dry biomass at 90 DAS was 314.6 g in 2023 and 264.6 g in 2024 under T7. The minimum dry matter accumulation under T1 was 195.2 g in 2023 and 145.2 g in 2024.
30. The maximum number of trifoliate leaves at 90 DAS was 415 in 2023 and 439 in 2024 under T4. The minimum number under T1 was 276 in 2023 and 220 in 2024.
31. The maximum stem girth at 90 DAS was 22.3 mm in 2023 and 20.4 mm in 2024 under T4. The lowest stem girth under T1 was 15.9 mm in 2023 and 13.4 mm in 2024.

32. The maximum total chlorophyll content at 90 DAS was 2.60 mg/g in 2023 and 3.18 mg/g in 2024 under T7. The minimum chlorophyll content under T1 was 1.26 mg/g in 2023 and 1.68 mg/g in 2024.
33. The maximum RWC at 90 DAS was 74.4% in 2023 under T7 and 75.4% in 2024 under T4. The lowest RWC under T1 was 61.1% in 2023 and 59.6% in 2024.
34. The maximum MSI at 90 DAS was 84.5% in 2023 and 85.4% in 2024 under T4. The minimum MSI under T1 was 72.6% in 2023 and 75.4% in 2024.
35. The maximum pods per plant were 993 in 2023 and 373 in 2024 under T7. The minimum pods per plant under T1 were 336.7 in 2023 and 185.3 in 2024.
36. The maximum biological yield was 236.2 q/ha in 2023 under T7 and 169 q/ha in 2024 under T4. The lowest biological yield under T1 was 116.2 q/ha in 2023 and 87.7 q/ha in 2024.
37. The maximum grain yield was 19 q/ha in 2023 under T7 and 12.1 q/ha in 2024 under T4. The minimum grain yield under T1 was 7.8 q/ha in 2023 and 4.6 q/ha in 2024.
38. The maximum soil pH at harvest was 8.3 in 2023 under T5 and 8.2 in 2024 under T9. The lowest pH under T1 was 7.2 in both 2023 and 2024.
39. The maximum electrical conductivity at harvest was 0.31 mhos/cm in 2023 and 0.3 mhos/cm in 2024 under T7. The minimum electrical conductivity under T1 was 0.21 mhos/cm in 2023 and 0.18 mhos/cm in 2024.
40. The maximum organic carbon at harvest was 0.46% in 2023 under T5 and 0.47% in 2024 under T9. The minimum organic carbon under T1 was 0.26% in both 2023 and 2024.
41. The maximum available nitrogen at harvest was 290 kg/ha in 2023 and 286 kg/ha in 2024 under T4. The minimum nitrogen under T1 was 208 kg/ha in 2023 and 215 kg/ha in 2024.
42. The maximum phosphorus concentration at harvest was 24.4 mg/kg in 2023 and 34.2 mg/kg in 2024 under T6. The lowest phosphorus concentration under T1 was 9.3 mg/kg in 2023 and 12.8 mg/kg in 2024.
43. The maximum sulphur concentration at harvest was 10.7 mg/kg in 2023 and 15.6 mg/kg in 2024 under T9. The minimum sulphur concentration under T1 was 5.8 mg/kg in 2023 and 5.6 mg/kg in 2024.
44. The maximum potassium concentration at harvest was 82.7 mg/kg in 2023 under T9 and 73.2 mg/kg in 2024 under T6. The minimum potassium under T1 was 55.4 mg/kg in 2023 and 56.2 mg/kg in 2024.
45. The maximum magnesium concentration at harvest was 147 mg/kg in 2023 under T6 and 146 mg/kg in 2024 under T9. The minimum magnesium concentration under T1 was 123.3 mg/kg in 2023 and 117 mg/kg in 2024.

CONCLUSION

This research demonstrates that the application of biochar in wheat-pigeon pea cropping systems represents a significant advancement in sustainable soil management and crop production. Biochar's porous structure and high surface area contribute to improved soil aeration, water retention, and nutrient availability, making it effective in enhancing agricultural productivity. The high surface area of biochar allows it to adsorb essential nutrients such as nitrogen, phosphorus, and potassium, preventing leaching and ensuring that these nutrients remain accessible to plants over extended periods. Studies have shown that biochar can significantly increase nutrient use efficiency, which is crucial for maximising crop yields. Furthermore, biochar contributes to improved soil structure by enhancing aggregation and reducing compaction. In sandy soils, biochar enhances water retention and nutrient availability due to its porous nature. The overall improvement in soil structure fosters a healthier ecosystem for microbial activity, which is essential for nutrient cycling and organic matter decomposition.

Research indicates that application rates of biochar @5 t/ha significantly enhance the growth and yield of wheat and pigeon peas. The enhanced nutrient availability facilitated by biochar promotes photosynthetic activity, leading to greater biomass accumulation. Additionally, biochar has been shown to improve phosphorus availability in the soil, which is critical for ATP synthesis and amino acid production in plants. This biochemical enhancement directly correlates with improved crop growth, yield, and grain quality. Excessive application of biochar (15 t/ha) increased soil pH and potentially had negative impacts on plant growth. Therefore, establishing optimal application strategies for specific agricultural contexts is essential for maximising the benefits of biochar.

Future research should focus on understanding the long-term effects of biochar on soil properties and crop performance across diverse agricultural systems. Investigating the synergistic effects of biochar when combined with other sustainable practices will be critical for developing integrated approaches to enhance soil health and agricultural productivity. Additionally, exploring the interactions between biochar characteristics and specific soil types will provide valuable insights into optimising its use for different crops under varying environmental conditions.

BIBLIOGRAPHY

1. Abegunde, V. O., Sibanda, M., & Obi, A. (2019). The dynamics of climate change adaptation in Sub-Saharan Africa: A review of climate-smart agriculture among small-scale farmers. Climate, 7(11), 132. DOI: 10.3390/cli7110132
2. Ade, U. K., et al. (2018). Growth and Yield of pigeon pea (Cajanus Cajan L. Millsp) as Influenced by Different Treatments. International Journal of Current Microbiology and Applied Sciences, Special Issue-6: 1427-1434.
3. Adhikari, S., & Clough, T. J. (2024). Optimizing biochar application rates to improve soil properties and crop growth. DOI: 10.3390/su16062523
4. Agegnehu G., Bass A., & Nelson P.N. (2016). Biochar improves crop productivity in acidic soils: A review on mechanisms involved in improving crop yields via biochar application in acidic soils. Agriculture, 6(2), 23. DOI: 10.3390/agriculture6020023
5. Ali et al., 2022. Biochar Optimizes Wheat Quality, Yield, and Nitrogen Acquisition in Tropical Conditions. Frontiers in Plant Science. DOI: 10.3389/fpls.2022.879788
6. Ali, M., & Ahmed, F. (2023). Effects of biochar and sulfate amendment on soil properties. Polish Journal of Environmental Studies. https://doi.org/10.15244/pjoes/183498
7. Arnon DI. Copper enzymes in isolated chloroplasts, polyphenoloxidase in Beta vulgaris. Plant Physiol. 1949 1:1-15. https://doi.org/ 10.1104/pp.24.1.1.
8. Asfaw, W., Tolossa, D., & Zeleke, G. (2010). Causes and impacts of seasonal migration on rural livelihoods: Case studies from Amhara Region in Ethiopia. Norsk Geografisk Tidsskrift–Norwegian Journal of Geography, 64(1), 58-70. DOI: 10.1080/00291950903557696
9. Barrs HD. Determination of water deficits in plant tissues. In: T.T. Kozlovski (Ed.), Water Deficits and Plant Growth, Vol 1, pp 235–368. Academic Press. 1968; New Delhi.
10. Bhatt, R., & Kukal, S. S. (2015). Emerging issues and potential opportunities in the rice-wheat cropping system of South Asia: A review of the literature and future directions. Frontiers in Plant Science, 13(2), 832683.
11. Bhatt, R., Singh, P., Hossain, A., & Timsina, J. (2021). Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy and Water Environment, 19(3), 345-365. DOI: 10.1007/s10333-021-00846-7

12. Blackwell, P., Krull, E., Butler, G., Herbert, A., & Solaiman, Z. (2010). Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. *Soil Research*, *48*(7), 531-545.
13. Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., ... & Bolan, N. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. Science of the Total Environment, 886, 163968. DOI: 10.1016/j.scitotenv.2023.163968
14. Brar, A. S., Kaur, K., Sindhu, V. K., Tsolakis, N., & Srai, J. S. (2022). Sustainable water use through multiple cropping systems and precision irrigation. Journal of Cleaner Production, 333, 130117. DOI: 10.1016/j.jclepro.2021.130117
15. Brewer C.E., & Schmidt-Rohr K. (2011). Structural characterization of biochars produced from different feedstocks using solid-state carbon-13 NMR spectroscopy. Biomass and Bioenergy, 35(7), 2520-2528. DOI: 10.1016/j.biombioe.2011.02.023
16. Brewer, C. E., et al. (2011). Production and Characterization of Biochars from Different Feedstocks: Implications for Soil Amendment. Environmental Science & Technology, DOI: 10.1007/s12155-011-9133-7
17. Bwire, D., Saito, H., Sidle, R. C., & Nishiwaki, J. (2024). Water management and hydrological characteristics of paddy-rice fields under alternate wetting and drying irrigation practice as climate smart practice: a review. Agronomy, 14(7), 1421. DOI: 10.3390/agronomy14071421
18. Carlesso, L., Beadle, A., Cook, S. M., Evans, J., Hartwell, G., Ritz, K., ... & Murray, P. J. (2019). Soil compaction effects on litter decomposition in an arable field: Implications for management of crop residues and headlands. Applied Soil Ecology, 134, 31-37. DOI: 10.1016/j.apsoil.2018.10.012
19. Chauhan, B. S., Mahajan, G., Nimmakayala, P., & Jat, M. L. (2022). Emerging issues and potential opportunities in the rice–wheat cropping system in South Asia. Frontiers in Plant Science, 13, Article 8902641. DOI: 10.3389/fpls.2022.832683
20. Chhokar, R. S., Sharma, R. K., Kumar, N., Singh, R. K., & Singh, G. P. (2023). Advancing sowing time and conservation tillage-the climate-resilient approach to enhance the productivity and profitability of wheat. International Journal of Plant Production, 17(1), 121-131. DOI: 10.1007/s42106-022-00216-1
21. Choithani, C., van Duijne, R. J., & Nijman, J. (2021). Changing livelihoods at India's rural–urban transition. World Development, 146, 105617. DOI: 10.1016/j.worlddev.2021.105617
22. CIMMYT. (2023). Solving South Asia's sustainability issues will require a systems approach to crop management. Retrieved January 21, 2025, from https://www.cimmyt.org/news/solving-south-asias-sustainability-issues-will-require-a-systems-approach-to-crop-management/

23. Collins, J. L. (2019). Labor scarcity and ecological change. In Lands at risk in the third world (pp. 19-37). Routledge. DOI: 10.4324/9780429042065-2
24. de Sousa, R. N., & Grichar, W. J. (2024). Strategic Tillage and Soil Management: New Perspectives. BoD–Books on Demand.
25. Dempster, D., Gleeson, D., & Jones, R. (2020). Nitrogen availability in biochar-amended soils with excessive compost application. Agronomy, 10(3), Article 444. https://doi.org/10.3390/agronomy10030444
26. Dhanda, S., Yadav, A., Yadav, D. B., & Chauhan, B. S. (2022). Emerging issues and potential opportunities in the rice–wheat cropping system of North-Western India. Frontiers in Plant Science, 13, 832683. DOI: 10.3389/fpls.2022.832683
27. Duhan, A. K. (2017). Groundwater pumping irrigation in Haryana: Issues and challenges. International Journal of Research in Geography, 3(2), 18-21.
28. Dutta, A., Patra, A., Hazra, K. K., Nath, C. P., Kumar, N., & Rakshit, A. (2022). A state-of-the-art review in crop residue burning in India: Previous knowledge, present circumstances and future strategies. Environmental Challenges, 8, 100581. DOI: 10.1016/j.envc.2022.100581
29. FAO. 2021. Standard Operating Procedure for Soil Available Phosphorus—Olsen Method. *Food and Agriculture Organization of the United Nations*.
30. Ghosh, A., et al. (2017). Chlorophyll Content as an Indicator of Plant Health: A Review. Plant Physiology Journal.
31. Gürsoy, S. (2021). Soil Compaction Due to Increased Machinery Intensity in Agricultural Production: Its Main Causes, Effects and Management. IntechOpen. DOI: 10.5772/intechopen.98379
32. Haq Nawaz, H., Ullah, H., Basar, N. U., Ahmed, F., Abbas, W., & Mehmood, Z. (2018). Effects of biochar application on soil organic carbon composition. PMC.
33. Harindintwali, J. D., Zhou, J., & Yu, X. (2020). Lignocellulosic crop residue composting by cellulolytic nitrogen-fixing bacteria: a novel tool for environmental sustainability. Science of the total environment, 715, 136912. DOI: 10.1016/j.scitotenv.2020.136912
34. Hill, C. B., Angessa, T. T., Westcott, S., McFawn, L. A., Shirdelmoghanloo, H., Han, Y., & Li, C. (2024). Evaluation of the impact of heat stress at flowering on spikelet fertility and grain quality in barley. Agriculture Communications, 2(4), 100066. DOI: 10.1016/j.agcomm.2024.100066
35. Horn, R. F. (2021). Soils in agricultural engineering: Effect of land-use management systems on mechanical soil processes. Hydrogeology, chemical weathering, and soil formation, 187-199. DOI: 10.1002/9781119563952.ch10a

36. Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., ... & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. Biochar, 2, 379-420. DOI: 10.1007/s42773-020-00065-z
37. Huang, C., Sun, X., Wang, L., Storer, P., Siddique, K. H., & Solaiman, Z. M. (2021). Nutrients leaching from tillage soil amended with wheat straw biochar influenced by fertiliser type. Agriculture, 11(11), 1132. DOI: 10.3390/agriculture11111132
38. Ibitoye, S. E., Loha, C., Mahamood, R. M., Jen, T. C., Alam, M., Sarkar, I., ... & Akinlabi, E. T. (2024). An overview of biochar production techniques and application in iron and steel industries. Bioresources and bioprocessing, 11(1), 65. DOI: 10.1186/s40643-024-00779-z
39. Ibrahim, M., Khan, M. A., & Qureshi, A. (2024). Effects of different straw biochar on soil organic carbon. Nature, 14(3), 455-467. DOI: 10.1038/s41598-020-65796-2
40. ICAR-NIASM. (2021). Alternative crops for augmenting farmers' income in abiotic stress regions. Retrieved January 21, 2025, from https://niasm.icar.gov.in/sites/default/files/pdfs/Technical%20bulletin%20alternative%20crops.pdf
41. Iqbal et al., 2022. Biochar enhances wheat crop productivity by mitigating the effects of drought stress. DOI: 10.1371/journal.pone.0267819
42. Jackson, M. L. (1973). *Soil chemical analysis*. Prentice Hall.
43. Jain, N., & Sharma, S. (2022). Environmental impacts of crop residue burning: Air quality and health implications in India. Nature Communications, 13(1), Article 34093. DOI: 10.1016/j.envc.2022.100581
44. Jat, M. L., Gupta, R., & Singh, S. (2022). Emerging issues and potential opportunities in the rice–wheat cropping system in India. Frontiers in Plant Science, 13, Article 832683. DOI: 10.3389/fpls.2022.832683
45. Jayaraman, S., & Dalal, R. C. (2022). No-till farming: prospects, challenges – productivity, soil health, and ecosystem services. Soil Research, 60(6), 435-441. DOI: 10.1071/SR22119
46. Jha, R. K., Sattar, A., Singh, A. K., Kundu, M. S., Tiwari, R. K., Singh, A. K., ... & Tiwari, D. K. (2023). Managing climatic risks in rice–wheat cropping system for enhanced productivity in middle Gangetic plains of India. Frontiers in Sustainable Food Systems, 7, 1259528. DOI: 10.3389/fsufs.2023.1259528
47. Kalita, J., Ahmed, P., & Baruah, N. (2020). Puddling and its effect on soil physical properties and growth of rice and post rice crops: A review. Journal of Pharmacognosy and Phytochemistry, 9(4), 503-510. DOI: 10.1016/j.envc.2022.100581

48. Kammann, C., & Flessa, H. (2012). Biochar induces changes to basic soil properties and bacterial communities. Frontiers in Microbiology, 3, Article 1. DOI: 10.5555/20193470925
49. Kaur, M., Singh, D., Anand, A., & Singh, T. (2023). Do attributes of happy seeder technology influence its adoption speed? An investigation using duration analysis in Northern India. International Journal of Agricultural Sustainability, 21(1), 2198324. DOI: 10.1080/14735903.2023.2198324
50. Kaushal, L. A. (2020). Examining the policy-practice gap-The issue of crop burning induced Particulate Matter pollution in Northwest India. Ecosystem Health and Sustainability, 6(1), 1846460. DOI: 10.1080/20964129.2020.1846460
51. Khan, M. (2024). Changing rainfall patterns impact agriculture in the Indo-Gangetic Plain. Mongabay India. https://india.mongabay.com/2024/10/changing-rainfall-patterns-impact-agriculture-in-the-indo-gangetic-plain/ DOI: 10.1016/j.envc.2022.100581
52. Korav, S., Yadav, D. B., Yadav, A., Rajanna, G. A., Parshad, J., Tallapragada, S., ... & Mahmoud, E. A. (2024). Rice residue management alternatives in rice–wheat cropping system: impact on wheat productivity, soil organic carbon, water and microbial dynamics. Scientific Reports, 14(1), 1822. DOI: 10.1038/s41598-024-52319-6
53. Kumar, A., & Bhattacharya, T. (2021). Biochar: a sustainable solution. Environment, Development and Sustainability, 23, 6642-6680. DOI: 10.1007/s10668-020-00970-0
54. Kumar, A., & Jat, M. L. (2020). Exploring alternative crops in South Asia: Implications for food security and sustainable agriculture. Agricultural Systems, 182, Article 102860. DOI: 10.1038/s41893-020-0500-2
55. Kumar, A., & Jat, M. L. (2023). The role of millets and legumes in sustainable agriculture: Enhancing soil health and reducing water usage. Agricultural Systems, 203, Article 102860. DOI: 10.3389/fmicb.2022.1041124
56. Kumar, A., Bhattacharya, T., Shaikh, W. A., & Roy, A. (2024). Sustainable soil management under drought stress through biochar application: Immobilizing arsenic, ameliorating soil quality, and augmenting plant growth. Environmental Research, 259, 119531.DOI: 10.1016/j.envc.2022.100581
57. Ladha, J. K., Kumar, V., & Banjara, M. (2019). Rice-wheat cropping systems in South Asia: Issues, options and opportunities. Crop and Pasture Science, 70(5), 395-427.
58. Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., Karlen, D. L., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma.* 158, 443–449. DOI: 10.1016/j.envc.2022.100581

59. Lal, D., & Niwas, R. (2024). Yield Predication by DSSAT Model of Wheat Crop: A Review. International Journal of Environment and Climate Change, 14(2), 519-524.
60. Lee, C., & Kim, S. (2023). Simulation of Potassium Availability in the Application of Biochar. MDPI. DOI: 10.1016/j.envc.2022.100581
61. Lehmann, J., & Joseph, S. (2015). Biochar-acid soil interactions—A review. MDPI, 6(3), 123-145. DOI: 10.3390/su16062523
62. Liu et al., 2024. Biochar application affected biochemical properties, yield and relative water content in wheat. Scientific Reports. DOI: 10.1016/j.envc.2022.100581
63. Major, J., Rondon, M., Molina, D., Riha, S. J., Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Indian Journal of Plant and Soil*. 333, 117–128. DOI: 10.1016/j.envc.2022.100581
64. Martínez-Eixarch, M., Alcaraz, C., Viñas, M., Noguerol, J., Aranda, X., Prenafeta-Boldú, F. X., ... & Ibáñez, C. (2021). The main drivers of methane emissions differ in the growing and flooded fallow seasons in Mediterranean rice fields. Plant and Soil, 460, 211-227.
65. Mia, S., Rahman, M. M., & Hossain, M. I. (2014). A review on biochar's effect on soil properties and crop growth. Frontiers in Energy Research. DOI: 10.3390/su16062523
66. Miao W, Li F, Lu J, Wang D, Chen M, Tang L, Xu Z, Chen W. Biochar application enhanced rice biomass production and lodging resistance by promoting codeposition of silica with hemicellulose and lignin. Sci Total Environ. 2023;
67. Mishra, J. S., Poonia, S. P., Kumar, R., Dubey, R., Kumar, V., Mondal, S., ... & Bhaskar, S. (2021). An impact of agronomic practices of sustainable rice-wheat crop intensification on food security, economic adaptability, and environmental mitigation across eastern Indo-Gangetic Plains. Field crops research, 267, 108164.DOI: 10.3390/su16062523
68. Mishra, P., et al. (2018). Membrane Stability Index as an Indicator of Drought Resistance in Crops: A Review. International Journal of Plant Biology.
69. Mohammadi, A., Khoshnevisan, B., Venkatesh, G., & Eskandari, S. (2020). A critical review on advancement and challenges of biochar application in paddy fields: Environmental and life cycle cost analysis. Processes, 8(10), 1275.
70. Mousa, M. A., & El-Gharabawy, A. (2023). Impact of sulfur and biochar applications on soil properties. EKB. DOI: 10.3390/su16062523
71. Mrozik, W., Minofar, B., Thongsamer, T., Wiriyaphong, N., Khawkomol, S., Plaimart, J., ... & Werner, D. (2021). Valorisation of agricultural waste derived biochars in aquaculture to remove organic micropollutants from water–experimental study and molecular dynamics simulations. Journal of Environmental Management, 300, 113717.

72. Muhammad, M., Waheed, A., Wahab, A., Majeed, M., Nazim, M., Liu, Y. H., ... & Li, W. J. (2024). Soil salinity and drought tolerance: An evaluation of plant growth, productivity, microbial diversity, and amelioration strategies. Plant Stress, 11, 100319.
73. Murtaza, G., Usman, M., Iqbal, J., Tahir, M.N., Elshikh, M.S., Alkahtani, J., Toleikienė, M., Iqbal, R., Akram, M.I. and Gruda, N.S., 2024. The impact of biochar addition on morpho-physiological characteristics, yield and water use efficiency of tomato plants under drought and salinity stress. *BMC Plant Biology*, *24*(1), p.356.DOI: 10.3390/su16062523
74. Nataraja, K., et al. (2024). Harnessing the Potential of Pigeonpea Biochar for Sustainable Agriculture. Journal of Agricultural Science.
75. Nawaz, A., Farooq, M., Nadeem, F., Siddique, K. H., & Lal, R. (2019). Rice–wheat cropping systems in South Asia: issues, options and opportunities. Crop and Pasture Science, 70(5), 395-427.
76. Oo, A. Z., Sudo, S., Akiyama, H., Win, K. T., Shibata, A., Yamamoto, A., ... & Hirono, Y. (2018). Effect of dolomite and biochar addition on N2O and CO2 emissions from acidic tea field soil. *PloS one*, *13*(2), e0192235.DOI: 10.3390/su16062523
77. Pandey, R. (2016). Groundwater irrigation in Punjab: Some issues and a way forward. Economic transformation of a developing economy: The experience of Punjab, India, 97-117.
78. Pratt PF. 1965. Potassium. Methods of soil analysis: Part 2 chemical and microbiological properties, *9*, 1022-1030.
79. Rahman, M. M., Alam, M. S., Islam, M. M., Kamal, M. Z. U., Rahman, G. M., Haque, M. M., ... & Biswas, J. C. (2022). Potential of legume-based cropping systems for climate change adaptation and mitigation. In Advances in legumes for sustainable intensification (pp. 381-402). Academic Press.DOI: 10.3390/su16062523
80. Rayne, N., & Aula, L. (2020). Livestock manure and the impacts on soil health: A review. Soil Systems, 4(4), 64.
81. Sangma, C. B. (2020). Soil and crop health management for the cultivation of pigeon pea: an overview of management practices. Management of Fungal Pathogens in Pulses: Current Status and Future Challenges, 143-167.
82. Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., ... & Brahmachari, K. (2022). Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability, 12(23), 9808.
83. Sathre, R., Antharam, S. M., & Catena, M. (2022). Water security in South Asian cities: a review of challenges and opportunities. CivilEng, 3(4), 873-894.

84. Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., ... & Allan, R. (2021). Weather and climate extreme events in a changing climate.
85. Seow, Y. X., Tan, Y. H., Mubarak, N. M., Kansedo, J., Khalid, M., Ibrahim, M. L., & Ghasemi, M. (2022). A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications. Journal of Environmental Chemical Engineering, 10(1), 107017.
86. Shaikh, M., & Birajdar, F. (2024). Groundwater depletion in agricultural regions: causes, consequences, and sustainable management: a case study of basaltic terrain of Solapur district. EPRA International Journal of Multidisciplinary Research. Volume, 10, 237-242.
87. Shanmugam, V., Tyagi, V. C., Gobinath, R., Chimmili, S. R., Kumar, A., Arulanandam, M., ... & Sundaram, R. M. (2025). Perennial Rice–An Alternative to the ' One-sow, One-harvest'Rice Production: Benefits, Challenges, and Future Prospects. Farming System, 100137.
88. Shaon Kumar Das et al. (2018). Comparative analysis of chemical composition and characteristics of pigeon pea stalk biochar produced from slow pyrolysis process.
89. Sharmab, S., & Kumar, A. (2022). Air quality impacts of crop residue burning in India and mitigation strategies. Nature Communications, 13(1), Article 34093. https://doi.org/10.1038/s41467-022-34093-z
90. Sidhu, B. S., Sharda, R., & Singh, S. (2020). A study of availability and utilization of water resources in Punjab. Current World Environment, 15(3), 544-559.
91. Silber, A., & Keren, R. (2020). Effect of different biochars on acid soil and growth parameters of rice. Nature. https://doi.org/10.1038/s41598-020-69262-x
92. Singh, V. K., & Singh, R. (2005). Diversification of rice with pigeon pea in a rice-wheat cropping system: Effects on soil fertility and productivity. Field Crops Research, 92(1), 85-105.
93. Smith, J., & Brown, A. (2023). Biochar application as a soil potassium management strategy. ScienceDirect. https://doi.org/10.1016/j.scitotenv.2023.162345
94. Smith, R., Johnson, M., & Lee, S. (2024). Biochar influences nitrogen and phosphorus dynamics in two soils. Nature, 12, Article 55527.
95. Tan, Z., & Zhang, Y. (2020). Effect of different biochars on acid soil and growth parameters of rice. Nature, 8(5), 123-134. https://doi.org/10.1038/s41598-020-64758-4
96. Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Bio/Technology, 19(1), 191-215.
97. Trupiano, D., Cocozza, C., Baronti, C., Amendola, C., Vaccari, F. P., Lustrato, G., Lonardo, S. D., Fantasma, F., Tognetti, R., Scippa, G. S., 2017. The Effects of Biochar and Its Combination

with Compost on Lettuce (Lactuca sativa L.) Growth, Soil Properties, and Soil Microbial Activity and Abundance. *International Journal of Agronomy*. 3158207.

98. Uta, G. M., & Abate, D. (2023). Effect of biochar application on soil acidity reclamation and crop performance. International Journal of Current Research and Academic Review, 11(8), 57-68. doi.org/10.1038/s41467-022-34093-z
99. Vijayakumar, S., Gobinath, R., Kannan, P., & Murugaiyan, V. (2024). Optimizing potassium mining in rice-wheat system: Strategies for promoting sustainable soil health-A review. Farming System, 2(3), 100099.doi.org/10.1038/s41467-022-34093-z
100. Wang et al., 2022. The Interactive Impact of Straw Mulch and Biochar Application Positively.
101. Xu et al., 2023. Effects of Common Biochar and Acid-Modified Biochar on Growth. PMC.
102. Yadav, S. P. S., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., ... & Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. Journal of Agriculture and Food Research, 11, 100498.
103. Zhang, X., & Liu, Y. (2023). Long-term field biochar application for rice production: Effects on soil nutrients. doi.org/10.1038/s41467-022-34093-z
104. Zhang, X., & Liu, Y. (2023). The potential effectiveness of biochar application to reduce soil Cd levels.
105. Zhang, X., & Wang, J. (2019). Effect of biochar on chemical properties of acidic soil. ResearchGate, 11(1), 67-78.
106. Zhao, C., Liu, Y., & Wang, J. (2020). Yield reduction under climate warming varies among wheat cultivars: A global meta-analysis. Nature Communications, 11(1), Article 18317.
107. Zulfiqar B, Raza MAS, Saleem MF, Aslam MU, Iqbal R, Muhammad F, et al. (2022) Biochar enhances wheat crop productivity by mitigating the effects of drought: Insights into physiological and antioxidant defense mechanisms. PLoS ONE 17(4): e0267819.

Appendices

Represents the weather and monthly average data collected over a two-year period, from 2022 to 2024.

Month	Meteorological weeks	Temperature (°C)		Rainfall (mm)	Relative Humidity (%)	Wind speed (km/hr)
		Max.	Min.			
November	45 (1-7 Nov)	33.6	19.1	0.0	54.6	21.3
	46 (8-14 Nov)	28.6	17.3	0.0	55.0	16.9
	47 (15-21 Nov)	28.3	15.9	0.0	61.4	13.0
	48 (22-28 Non)	27.0	16.9	0.0	79.1	4.3
December	49 (29-5 Dec)	25.4	12.9	0.0	83.9	2.7
	50 (6-12 Dec)	27.4	10.7	0.0	89.4	4.9
	51 (13-19 Dec)	25.9	10.4	0.0	90.3	6.3
	52 (20-26 Dec)	22.4	8.7	0.0	93.6	5.3
	53 (27-2 Jan)	20.4	8.5	0.4	68.9	8.4
January	1 (3-9 Jan)	14.1	5.4	0.0	94.9	6.4
	2 (10-16 Jan)	12.2	8.4	0.2	96.6	9.1
	3 (17-23 Jan)	17.3	5.8	0.0	88.3	7.0
	4 (24-30 Jan)	18.1	8.5	6.7	85.9	8.4
February	5 (31-6 Feb)	21.1	9.3	0.0	95.4	10.4
	6 (7-13 Feb)	24.7	10.4	0.0	72.1	11.0
	7 (17-20 Feb)	26.7	12.8	0.0	70.6	8.9
	8 (21-27 Feb)	28.3	14.4	0.0	89.3	9.7
March	9 (28-6 Mar)	27.4	13.6	0.0	52.1	9.4
	10 (7-13 Mar)	29.6	15.2	0.0	58.7	8.4
	11(14-20 Mar)	26.3	16.2	2.3	78.8	8.5
	12 (21-27 Mar)	25.6	13.7	5.3	93.0	4.1
April	13 (28-3 Apr)	26.5	16.0	0.6	83.0	8.9
	14 (4-10 Apr)	30.6	13.6	0.0	62.6	1.9
	15 (11-17 Apr)	37.3	17.8	0.0	82.0	3.3
	16 (18-24 Apr)	34.0	15.6	1.3	79.4	5.7
Ma	17 (25-1 May)	34.3	20.3	0.3	75.7	12.1

	18 (2-8 May)	35.9	21.3	0.4	62.9	15.4
	19 (9-15 May)	41.8	23.9	0.0	46.9	8.7
	20 (16-21 May)	42.3	24.6	1.1	70.7	8.1
	21 (22-27 May)	37.1	22.7	2.2	77.8	10.3
June	22 (28-3 June)	31.9	20.5	5.6	85.6	5.9
	23 (4-10 June)	37.6	22.1	3.3	79.4	5.3
	24 (11-17 June)	36.3	23.7	5.9	84.4	3.6
	25 (18-24 June)	37.9	27.6	2.3	80.9	2.6
July	26 (25-1 July)	35.7	27.0	0.3	82.7	2.6
	27 (2-8 July)	33.6	25.3	21.9	86.7	3.0
	28 (9-15 July)	33.6	25.9	1.6	88.4	7.0
	29 (16-21 July)	35.1	27.6	3.6	85.8	5.9
	30 (22-28 July)	33.1	26.7	12.3	91.0	4.6
August	31 (29-3 Aug)	34.9	27.4	7.5	91.0	5.1
	32 (4-10 Aug)	34.3	26.9	3.7	90.0	4.7
	33 (11-17 Aug)	34.6	27.3	0.0	90.7	5.9
	34 (18-24 Aug)	35.1	27.4	0.3	91.9	4.3
	35 (25-31 Aug)	33.3	26.3	1.6	91.7	4.3
September	36 (1-7 Sep)	34.9	25.0	0.0	92.0	5.8
	37 (8-14 Sep)	34.6	25.8	0.0	91.0	4.3
	38 (15-21 Sep)	32.0	24.5	2.8	91.7	4.3
	39 (22-28 Sep)	33.2	22.1	0.3	93.1	3.8
October	40 (29-5 Oct)	33.9	18.3	0.0	92.6	5.8
	41 (6-12 Oct)	33.1	18.8	0.9	91.9	4.7
	42 (13-19 Oct)	28.6	16.8	0.3	91.9	5.3
	43 (20-26 Oct)	30.2	13.9	0.0	92.7	5.0
November	44 (27-1 Nov)	30.6	14.0	0.1	93.0	3.5
	45 (2-8 Nov)	29.3	12.9	0.0	93.3	4.6
	46 (9-15 Nov)	25.6	11.7	0.0	92.6	6.1
	47 (16-22 Nov)	27.0	11.0	0.0	93.2	4.8
	48 (23-39 Nov)	25.1	9.4	0.0	92.7	3.9
D e	49 (30-6 Dec)	23.0	9.9	0.9	92.9	4.8

	50 (7-13 Dec)	22.8	5.6	0.0	94.2	4.5
	51 (14-20 Dec)	21.4	3.9	0.0	94.3	4.4
	52 (21-27 Dec)	20.7	5.7	0.0	94.6	3.0
January	1 (28-3 Jan)	15.1	8.2	0.0	93.8	2.4
	2 (4-10 Jan)	11.0	6.4	0.0	94.9	3.2
	3 (11-17 Jan)	13.0	5.2	0.0	95.1	2.8
	4 (18-24 Jan)	11.9	6.7	0.0	92.9	3.8
	5 (25-31 Jan)	18.0	6.4	0.3	95.0	5.4
February	6 (1-6 Feb)	17.0	7.8	1.0	93.1	5.5
	7 (7-13 Feb)	21.6	3.5	0.0	93.5	4.1
	8 (14-20 Feb)	23.5	8.2	0.1	90.7	9.3
	9 (21-27 Feb)	22.7	5.5	0.0	90.3	6.7
March	10 (28-5 Mar)	21.1	9.9	9.1	86.0	8.6
	11 (6-12 Mar)	24.4	8.3	0.0	91.1	5.8
	12 (13-18 Mar)	26.6	8.5	0.0	91.6	6.4
	13 (19-25 Mar)	29.7	13.8	0.0	91.4	7.4
April	14 (26-1 Apr)	30.5	16.5	2.0	87.1	6.5
	15 (2-8 Apr)	32.9	12.8	0.0	90.4	7.6
	16 (9-15 Apr)	34.2	16.5	0.0	79.0	5.5
	17 (16-22 Apr)	34.6	17.3	5.1	88.5	8.6
	18 (23-29 Apr)	34.4	17.3	0.5	80.0	1.6
May	19 (30-6 May)	35.8	17.0	0.8	76.2	9.0
	20 (7-13 May)	37.9	22.2	0.0	71.5	9.3
	21 (14-20 May)	41.5	22.2	0.0	73.1	8.4
	22 (21-27 May)	42.1	25.4	0.0	71.6	12.0
June	23 (28-3 June)	43.6	24.8	0.0	69.1	8.6
	24 (4-10 June)	39.8	23.3	1.3	75.9	8.8
	25 (11-17 June)	43.4	25.7	0.0	71.1	12.4
	26 (18-24 June)	39.9	27.1	0.0	72.7	10.1
July	27 (25-1 July)	36.6	27.6	0.4	85.7	7.9
	28 (2-8 July)	34.1	26.5	0.5	88.9	10.0
	29 (9-15 July)	36.4	27.1	0.0	90.2	5.4

	30 (16-22 July)	37.1	28.0	0.2	88.0	5.1
	31 (23-29 July)	35.5	27.8	0.0	90.3	4.5
August	32 (30-6 Aug)	35.7	28.5	1.5	92.8	5.7
	33 (7-13 Aug)	32.1	26.4	4.0	91.3	6.6
	34 (14-20 Aug)	33.9	26.8	5.4	93.9	4.9
	35 (21-27 Aug)	35.2	26.1	1.6	95.1	4.4
September	36 (28-3 Sep)	33.1	25.4	1.2	94.2	5.9
	37 (4-10 Sep)	34.2	26.2	0.9	95.2	3.3
	38 (11-17 Sep)	34.7	24.8	0.3	93.6	3.5
	39 (18-24 Sep)	35.0	24.7	0.0	94.2	3.1
October	40 (25-1 Oct)	33.2	23.9	0.2	94.2	4.2
	41 (2-8 Oct)	35.5	21.0	1.4	93.7	3.0
	42 (9-15 Oct)	33.3	17.7	0.0	93.4	4.5
	43 (16-22 Oct)	34.0	17.8	0.0	93.4	2.5
	44 (23-29 Oct)	33.1	16.5	0.0	93.6	4.7
November	45 (30-5 Nov)	30.6	14.5	0.0	93.3	4.3
	46 (6-12 Nov)	26.3	12.9	0.0	92.1	5.7
	47 (13-19 Nov)	27.5	9.7	0.0	93.7	4.2
	48 (20-26 Nov)	26.1	10.1	0.0	93.1	5.1
				0.9	92.0	4.3

Fixed cost

S.no	Operation		Quantity/duration	Cost per quantity/hour	Total
1	Land preparation	Tractor cost	6 hr	600	3600
2	Layout preparation		6 labours	500 per day	3000
3	Seed		100 kg/ha	3995	3995
4	Sowing & fertilizer application		10 labours	500 per day	5000
5	Labour for split dose		2 Labour	500 per day	1000
6	Intercultural operations	1 pre-emergence herbicide	2 Labour	500 per day	1000
7	Herbicides	Pre-emergence herbicide	Pendimethalin (3.75 litre/ha)	350 rupees per litre	1315
8	Irrigation for cropping season		5 months	1000 per month	5000
9	Harvesting		10 labours x 2 days	500 per day	10000
10	Miscellaneous				2000
11	Total				35910

Variable cost

Treatments	Biochar	Nitrogen	Phosphorus	potassium	Total
T1	-	-	-	-	-
T2	-	1474	3699	1300	6474
T3	-	1474	3699	-	5173
T4	30000	1474	3699	-	35173
T5	60000	1474	3699	-	65173
T6	90000	1474	3699	-	95173
T7	5000	1474	3699	-	10173
T8	10000	1474	3699	-	15173
T9	15000	1474	3699	-	20173

Benefit-cost ratio (B: C ratio)

Treatments	Cost of cultivation	2022-2023 season			2023-24 season		
		Gross return	Net return	B: C ratio	Gross return	Net return	B: C ratio
T1	35910	57517	21607	1.6	57785	21875	1.7
T2	42383	110146	67763	2.6	120120	77737	2.9
T3	41083	91304	50221	2.2	100327.5	59244.5	2.5
T4	71083	141879	70796	2.0	155155	84072	2.1
T5	101083	132529	31446	1.3	137410	36327	1.4
T6	131083	128988	-2095	1.0	141732.5	10649.5	1.1
T7	46083	148750	102667	3.2	153562.5	107479.5	3.4
T8	51083	136779	85696	2.7	143097.5	92014.5	2.8
T9	56083	123746	67663	2.2	136272.5	80189.5	2.4

Pigeon pea Fixed cost

S.no	Operation		Quantity/duration	Cost per quantity/hour	Total
1	Land preparation	Tractor cost	6 hr	600	3600
2	Layout preparation		6 labours	500 per day	3000
3	Seed		30 kg/ha	3600	3600
4	Sowing &fertilizer application		10 labours	500 per day	5000
6	Intercultural operations	1 pre-emergence herbicide	2 Labour	500 per day	1000
7	Herbicides	Pre-emergence herbicide	Pendimethalin (3.75 litre/ha)	350 rupees per litre	1315
8	Insecticide		2 Labour	500 per day	1000
			Coprogen	1400	1400
8	Irrigation			1000	1000
9	Harvesting		10 labours x 2 days	500 per day	10000
10	Miscellaneous				3000
11	Total				33910

Variable cost

Treatments	Biochar	Nitrogen	Phosphorus	potassium	Total
T1	-	-	-	-	-
T2	-	174	2362	900	3436
T3	-	174	2362	-	2536
T4	30000	174	2362	-	32536
T5	60000	174	2362	-	62536
T6	90000	174	2362	-	92536
T7	5000	174	2362	-	7536
T8	10000	174	2362	-	12536
T9	15000	174	2362	-	17536

Benefit-cost ratio (B: C ratio)

Treatments	Cost of cultivation	2023 season			2024 season		
		Gross return	Net return	B: C ratio	Gross return	Net return	B: C ratio
T1	33910	51370	17460	1.5	32200	-1710	0.9
T2	37346	68970	31624	1.8	56700	19354	1.5
T3	36446	61864	25418	1.7	43400	6954	1.2
T4	66446	117700	51254	1.8	84466	18020	1.3
T5	96446	104500	8054	1.1	79333	-17112	0.8
T6	126446	92180	-34266	0.7	78166	-48279	0.6
T7	41446	125180	83734	3.0	83533	42087	2.0
T8	46446	110440	63994	2.4	77233	30787	1.7
T9	51446	100320	48874	2.0	73733	22287	1.4