"SCREENING ONION GENOTYPES FOR GROWTH, YIELD, AND ECONOMICS OF PRODUCTION UNDER WATERLOGGED CONDITIONS AND ITS IMPACT ON PHYSICO - CHEMICAL PROPERTIES OF SOIL."

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY

in

Agronomy

By

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DECLARATION

I, **Pawar Amol Rajkumar**, bearing **Registration No. 12214270**, hereby declare that the research work embodied in the Ph.D. thesis titled **"Screening onion genotypes for growth, yield, and economics of production under waterlogged conditions and its impact on Physio - chemical properties of soil."** submitted to Lovely Professional University is the original and bonafied work carried out by me under the supervision of **Dr. Sushant Sukumar Patil**, Assistant Professor, Department of Agronomy/School of agriculture, Lovely Professional University and my co-guide Dr. A. Thangasamy, Senior Scientist and Soil Scientist at ICAR-DOGR

I further declare that:

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

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

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

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

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

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This is to certify that the work reported in the Ph. D. thesis entitled **"Screening onion genotypes for growth, yield, and economics of production under waterlogged conditions and its impact on Physio - chemical properties of soil"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the Department of Agronomy/School of agriculture is a research work carried out by **Pawar Amol Rajkumar, (12214270)**, is bonafied record of his original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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Place: LPU, Punjab
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LIST OF ABBREVIATION'S

Symbols/Abbreviation's	**Description**
W. L	Waterlogging
%	Per cent
@	At the rate
^{0}C	Degree Celsius
cm	Centimeters
et al.	Et alibi
etc.	Etcetera
Fig.	Figure
g	gram
hr.	Hour
ha	Hectare
i.e.	That is
kg	Kilogram
m	Meter
mg	Milligram
min.	Minute
ml	Milliliter
SE(m)	Standard of mean
ANOVA	Analysis of variance
CD	Critical difference
p = 0.05	Probability result due to chance is 5%
p < 0.05	Probability due to chance is less than 5%
p > 0.05	Probability due to chance is more than 5%
µg	Microgram
µmol	Micromole
m^2	Square meter
ppm	Parts per million
viz.,	Namely

vol.	Volume
wt.	Weight
DAT	Days after transplanting

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ABSTRACT

The investigation titled "Screening onion genotypes for growth, yield, and economics of production under waterlogged conditions and its impact on physio-chemical properties of soil" addresses climate-driven waterlogging as a major constraint for *kharif* onion in India and motivates genotype-based solutions to stabilize productivity under hypoxic stress. Conducted at ICAR–DOGR, Rajgurunagar (Pune) during late *kharif* 2023 and 2024, the experiment used a split-plot design with two main treatments (waterlogging vs scheduled irrigation) and eight genotypes (tolerant: Acc.1666, Acc.1630, W-355, Bhima Dark Red; sensitive: Bhima Red, Bhima Raj, Bhima Shubra, Bhima Super), imposing waterlogging at 45–55 DAT by flooding designated plots to 5 cm above soil for 72-hour periods, with uniform agronomy across genotypes and three replications to ensure robust inference. Morpho-physiological traits (plant height, leaf number, leaf area, neck thickness, dry matter, survival), biochemical indices (chlorophyll, membrane stability index, pyruvic acid, proline, antioxidant activity, protein, TSS), and post-stress soil properties (pH, EC, organic carbon, macro- and micronutrients) plus soil biological functions (SMBC; dehydrogenase, urease, acid/alkaline phosphatases) were measured at 45, 55, and 75 DAT and at harvest to capture integrated plant–soil responses. Waterlogging significantly reduced vegetative growth from 55 DAT onward through harvest, with tolerant entries (notably Acc.1666) maintaining higher plant height and canopy traits than sensitive checks, indicating superior physiological resilience under hypoxia. Bulb yield showed large main-treatment penalties and significant genotype × treatment interaction, with total mean yield decreasing from 11.12 t/ha (control) to t/ha (waterlogging) in 2023, a reduction of, and from 12.47 t/ha (control) to 10.96 t/ha (waterlogging) in 2024, a reduction of, evidencing season-dependent stress severity and differential buffering in year two. Across genotypes, Bhima Dark Red recorded the highest mean yield in 2023 t/ha while Acc.1666 led in 2024 t/ha, whereas Bhima Super consistently ranked lowest (5.79 t/ha in 2023; 9.40 t/ha in 2024), and several entries showed distinct treatment-specific responses (Acc. 1666: 14.27 vs 10.03 t/ha in 2023; 14.57 vs 13.70 t/ha in 2024), confirming a significant and agronomically meaningful genotype × waterlogging interaction that can be exploited for selection. Tolerant genotypes sustained higher chlorophyll and membrane stability with stronger osmotic (proline) and antioxidant responses, while sensitive genotypes exhibited pronounced declines in biochemical quality indices and growth, aligning with the observed yield stratification under stress. Waterlogging degraded soil chemical availability and suppressed microbial enzymes and SMBC, indicating impaired nutrient cycling that compounded plant stress, thereby linking soil-process disruption with crop performance penalties under hypoxia. Economically, waterlogging considerably reduced gross and net returns as well as benefit-cost ratios, with tolerant genotypes like Acc.1666 and Bhima Dark Red maintaining superior economic returns compared to susceptible genotypes, highlighting the direct financial impact of waterlogging and the importance of genotype selection for sustaining profitability in waterlogged conditions**.** Overall, Acc.1666 and Bhima Dark Red showed stable multi-trait resilience and superior yields under both regimes, whereas Bhima Shubra and Bhima Super were highly susceptible, supporting immediate on-farm deployment of tolerant entries and targeted breeding using these donors to enhance onion productivity in waterlogging-prone environments.

Keywords: Antioxidant**,** Available nutrient, Stress, Soil enzymes, Onion, Waterlogging, Economics.

CHAPTER I

INTRODUCTION

Commercial onion (*Allium cepa* L.) cultivation in India is a major agricultural activity, with the country producing about 20% of the world's onions second only to China and most production concentrated on the Deccan Plateau, where onions are grown rainfed during the monsoon and irrigated afterward (Gedam *et al.,* 2022). Maharashtra leads with 43% of national output, followed by Madhya Pradesh (16%), and Karnataka and Gujarat (9.0 % each), and the crop is harvested three times annually during *kharif*, Late *kharif*, and *Rabi* seasons (Press Information Bureau, 2023). Globally, the Alliaceae crop yields 98 million tons from 4.3 million hectares, while in India, onion production specifically reached 31.68 million tons in 2021-22 and stood at 30.2 million tons in 2022-23. (UN FAO, 2025). The First Advance Estimates for 2023–24 projected a sharp decline in onion production to 254.73 lakh tonnes from 302.08 lakh tonnes in the previous year, with major losses in Maharashtra, Karnataka, Andhra Pradesh, and Rajasthan. (These were the latest available official production estimates at the time of experimental planning and execution during 2023–2024) tonnes. A drop closely linked to climate change-driven increases in waterlogging during the rainy season, which severely threatens onion crops due to their shallow root systems (APEDA, 2023). Waterlogging not only reduces yields, sometimes by 50–70% but also encourages the spread of diseases such as anthracnose-twister, further limiting production, particularly in the monsoon season (Wakchaure *et al.,* 2022). These challenges are exacerbated by the broader context of natural disasters in Asia, where between 1950 and 2020, 42% of global floods occurred, impacting billions and affecting 15% of India's land, highlighting the vulnerability of onion production to both climatic and biotic stresses (EM-DAT, 2021).

Waterlogging affects a plant's delicate balance between photosynthesis and sugar used for growth and bulb development (Pan *et al.,* 2021). When soil becomes saturated, air is displaced from pore spaces. Poor oxygen levels cause anoxic root environments (Pezeshki and DeLaune, 2012). A lack of oxygen impairs root activity, reducing nutrient intake, especially nitrogen and phosphorus, which are necessary for bulb growth (Teoh *et al.,* 2022). Waterlogging can also impair water transport throughout the plant, restricting nutrient and photosynthate delivery to the development bulb (Tyagi *et al.,* 2024). These disturbances significantly reduce bulb size, weight, and number (Elzenga and Veen, 2010). Physiological and metabolic factors affect onion waterlogging at different growth stages (Vwioko *et al.,* 2017). Waterlogging in early growth phases reduces root oxygen availability and nutrient absorption notably nitrogen and phosphate causing chlorosis, delayed growth, and reduced leaf area, waterlogging during this period can impair plant growth (Gedam *et al.,* 2022). Later, inadequate oxygen delivery and poor root activity reduce food and water flow to the developing bulb, thereby decreasing bulb growth, weight, and quality (Wakchaure *et al*., 2023). Extended waterlogging can cause anaerobic conditions, disrupting metabolism and bulb development (Majeed *et al.,* 2023). Waterlogging is a major abiotic stress affecting agricultural productivity worldwide (Sharma and Chauhan, 2024). Between 2000 and 2010, about 12% of the world's irrigated land was affected by waterlogging, causing a 20% reduction in crop yields, and this problem intensified from 2010 to 2020, with an estimated 16% of arable lands worldwide impacted by waterlogging or flooding stress (Singh, 2015). Additionally, about 10-12% of the global agricultural areas faced waterlogging or severe soil drainage constraints, and roughly 20% of irrigated land worldwide was burdened by waterlogging and secondary soil salinization due to over-irrigation or poor sub-surface drainage (Patra *et al.,* 2024).

In India, floods affect an average of 7.5 million hectares of agricultural land annually, between 2015 and 2021, extreme weather events like floods damaged approximately 33.9 million hectares of India's cropped area (Sai *et al.,* 2023.). Waterlogging occurs when excess water saturates the soil for extended periods, leading to oxygen deficiency and anaerobic conditions detrimental to plant growth (Manik *et al.,* 2019). Climate change has exacerbated the frequency and intensity of waterlogging events due to unpredictable rainfall patterns and extreme weather conditions (Kumar *et al.,* 2024). This issue is particularly acute during the *kharif* season when heavy rains coincide with critical growth stages of onion crops (Mahajan, 2018). Waterlogging not only reduces crop yields but also affects bulb quality, leading to economic losses for farmers and price fluctuations in the market (Gedam *et al.,* 2023; Ghodke *et al.,* 2018). Studies have reported yield losses ranging from 25-30% under moderate waterlogging conditions to complete crop failure in severe cases (Dubey *et al.,* 2020).

Waterlogging significantly impacts soil health, nutrient dynamics, and crop productivity, particularly in clay loam soils. This phenomenon occurs when soil pores become saturated with water, leading to oxygen deficiency in the root zone (Luo *et al.,* 2024). The effects of waterlogging on soil properties and plant growth are multifaceted and interconnected, making it a complex issue in agricultural systems (Zhang *et al.,* 2025). Waterlogging significantly alters the physical characteristics of clay loam soils, increasing soil bulk density and reducing total pore volume, consequently diminishing the soil's water holding capacity (Khaerudin *et al.,* 2017). The saturation of soil pores with water reduces soil aeration leading to a decrease in oxygen concentration and an increase in carbon dioxide levels. This change in gas composition within the soil matrix has far-reaching consequences for both soil microorganisms and plant roots (Dabach, 2021). Furthermore, waterlogging affects soil structure by promoting the dispersion of soil particles which can lead to surface crusting and reduced infiltration rates. These changes in soil physical properties can persist even after the waterlogging event has subsided, potentially affecting subsequent crop cycles (Cleophas *et al.,* 2022).

Under waterlogged conditions, the soil environment shifts from aerobic to anaerobic, causing a dramatic change in microbial community composition. Aerobic microorganisms decline while anaerobic and facultative anaerobic organisms proliferate, disrupting nutrient cycling, organic matter decomposition, and overall soil health (Gschwend *et al.,* 2020; Zhang *et al.,* 2025). Consequently, nitrification is inhibited and denitrification is accelerated, leading to nitrogen losses as N_2O and N_2, while phosphorus availability decreases through the formation of insoluble iron and aluminum phosphates (Ghodke *et al.,* 2018). Furthermore, toxic levels of reduced manganese and iron may accumulate, adversely affecting plant growth (Rupngam *et al.,* 2023). For onion crops, which are particularly sensitive due to their shallow root system, these combined soil-level disruptions severely impair nutrient and water uptake, reduce growth, and lower bulb yield and quality (Ghodke *et al.,* 2018; Moleaer, 2024) The soil's nitrogen availability and cycle are significantly impacted by waterlogging (Zhang *et al.,* 2025). The microbial population changes in anaerobic circumstances to less productive anaerobic organisms, which lowers the availability of vital nutrients for onion plants, such as potassium, phosphate, and nitrogen (Barbaro *et al.,* 2025). Nutrient losses are accelerated by denitrification, which turns nitrate into gaseous nitrogen (Colmer and Voesenek, 2009). Additionally, waterlogging hinders the plant's ability to receive nutrients because of a compromised root system and decreased oxygen availability (Pan *et al.,* 2021). Nutritional imbalances driven by ethylene-induced membrane permeability changes limiting nutrient transfer and root-zone hypoxia depleting ATP for active transport cause smaller, lower-quality onion bulbs, nutrient deficits, heightened pest/disease susceptibility, and reduced yields (Gabriela *et al.,* 2025).

The impact of waterlogging on onion varies considerably depending on the growth stage at which stress is imposed. During the early vegetative state (1–20 DAT), waterlogging reduces root oxygen availability and nutrient absorption, causing chlorosis, delayed growth, and reduced leaf area, though plants at this stage may show partial recovery upon drainage (Ghodke *et al.,* 2018). However, the bulb initiation stage (20–30 DAT) is the most sensitive period, during which waterlogging causes severe reductions in plant growth, bulb formation, and overall yield (Ghodke *et al.,* 2018; Wakchaure *et al.,* 2023). Yield losses during bulb initiation can reach up to 20%, while combined stress across multiple stages results in cumulative losses of up to 60% (Wakchaure *et al.,* 2023). The bulb development and maturity stages (90–110 DAT) are comparatively less affected, with plants showing better survival and producing marketable bulbs (Ghodke *et al.,* 2018). Understanding these stage-specific responses is essential for designing targeted management strategies and selecting tolerant genotypes for waterlogging-prone environments

Despite the general understanding of plant responses to waterlogging, detailed research on its specific impact on nutrient dynamics in onion crops particularly regarding nitrate and iron uptake remains limited. This study aims to bridge that gap by evaluating waterlogging effects on nutrient uptake and onion bulb quality while analyzing prolonged soil property changes. It hypothesizes that waterlogging will reduce nutrient availability and that tolerant genotypes will exhibit distinct adaptations compared to sensitive ones, such as enhanced physiological and biochemical traits, including increased enzymatic activity. To test these hypotheses, the research employs three core objectives:

Objectives:

1. To study the effect of waterlogged conditions on growth, yield attributes and yield of onion.
2. To evaluate the effect of waterlogged conditions on available nutrient status and quality of onion.
3. To study the effect of waterlogged conditions on physical, chemical and biological properties of soil.

CHAPTER II

REVIEW OF LITERATURE

Waterlogging is a major abiotic stress that significantly affects crop growth, nutrient dynamics, and soil health, particularly in regions prone to excessive rainfall and poor drainage. The following review of literature is organized thematically around the three objectives of this study. Section 2.1 examines the existing research on the effects of waterlogging on growth, yield attributes, and yield of onion and other crops. Section 2.2 reviews the impact of waterlogged conditions on nutrient uptake and crop quality. Section 2.3 focuses on changes in soil physical, chemical, and biological properties under waterlogging. The review integrates findings from both onion-specific and broader crop studies to provide a comprehensive understanding of waterlogging stress and to identify research gaps that the present investigation seeks to address.

2.1: Effect of Waterlogged Conditions on Growth, Yield Attributes, and Yield of Onion

Watson *et al.* (1976) conducted a detailed investigation into the effects of waterlogging on wheat, barley, and oats using soils from various slope positions of a valley prone to winter waterlogging. Their experiments revealed that waterlogging whether intermittent or continuous had a significantly greater impact on plant yield than soil composition alone. Within just three days of waterlogging onset, plant growth rates declined, and prolonged exposure led to reduced root development, tiller production, and delayed reproductive development. In the first experiment, vegetative growth yield dropped by 37% under intermittent and 55% under continuous waterlogging, while wheat grain yield declined by 40% and 53%, respectively. Barley and oats showed similar sensitivity, with average grain yield reductions of 39% and 48%. The second experiment confirmed that early-stage waterlogging caused the most severe reductions in root biomass, herbage, and grain yield. Waterlogging at ear emergence further compromised plant stability and reduced grain size. Interestingly, nitrogen fertilisation at 100 kg/ha helped mitigate some of the yield losses across all three cereals, suggesting that nutrient management can partially offset the adverse effects of waterlogging.

Minchin *et al.* (1978) examined the impact of short-term waterlogging on cowpea (*Vigna unguiculata*) under simulated tropical conditions, focusing on plants reliant on either symbiotic nitrogen fixation or inorganic nitrogen sources. Their findings revealed that waterlogging significantly impaired both vegetative growth and seed production, with the severity of effects increasing when stress occurred at earlier developmental stages. Specifically, waterlogging before flowering led to a 50% reduction in vegetative growth, regardless of nitrogen source. Although nodulated plants showed some recovery in vegetative growth during reproductive development, seed yields remained 48% lower than those of unstressed controls. The reduction in yield was primarily attributed to disruptions in branch, peduncle, and flower development, resulting in fewer pods reaching maturity. Interestingly, while inorganic nitrogen enhanced vegetative growth, it did not significantly boost seed yield compared to plants relying on biological nitrogen fixation. These results underscore the vulnerability of cowpea to waterlogging, particularly during early growth stages, and highlight the limited advantage of inorganic nitrogen in mitigating yield losses under such stress.

Reddy and Mitra (1985) investigated the effects of submergence stress on rice and found that grain yield was significantly compromised under such conditions. Their study revealed that the reproductive stage, particularly flowering, was the most sensitive to submergence, with yield reductions reaching up to 58% due to impaired anthesis and elevated flower sterility. Additionally, they observed that 65–70% of spikelet's remained unfilled when submergence occurred during flowering. Yield losses were also recorded at other growth stages, with a 29% reduction under full submergence and an 18% reduction when submergence occurred at the maximum tillering stage. These findings underscore the critical vulnerability of rice during reproductive development and highlight the importance of managing water levels to mitigate yield losses during key phenological stages.

Maryam and Nasreen (2012) conducted a comprehensive literature review to examine the multifaceted effects of waterlogging on food and cash crops, focusing on physiological, anatomical, morphological, and biochemical responses. They emphasised that waterlogging defined as the saturation of soil with excess water creates anaerobic conditions that hinder normal crop growth. Under such stress, many crop varieties exhibit reduced leaf area ratio, stunted root and shoot development, and diminished photosynthetic activity. While these responses are common across various crops, certain species like wheat, cotton, and sunflower display unique adaptive traits, including aerenchyma formation, genotypic modifications for enhanced tolerance, and altered electrical conductivity. The review highlighted the critical need to identify and develop waterlogging-resistant varieties, particularly among energy and cash crops, to address global food security challenges. Genotypic adaptations were underscored as a key mechanism for survival under prolonged waterlogged conditions, reinforcing the importance of genetic research in crop resilience strategies.

Ren ***et al.*** **(2014)** conducted a two-year field study to evaluate the effects of waterlogging on the growth and yield of summer maize, focusing on different durations (3 and 6 days) and growth stages specifically the three-leaf stage (V3), six-leaf stage (V6), and 10 days after tasseling (10VT). Their findings revealed that maize yield and development were significantly influenced by both the timing and duration of waterlogging. The maize hybrid Denghai 605 (DH605) experienced yield reductions ranging from 8% to 32%, while Zhengdan 958 (ZD958) showed losses between 7% and 35%, depending on the treatment. The most severe yield declines occurred when waterlogging was imposed during the early vegetative stages (V3 and V6), indicating heightened sensitivity during these periods. In addition to yield loss, waterlogging negatively impacted plant morphology and reproductive traits, including reductions in plant height, ear height, leaf area index, grains per ear, and 1000-grain weight. The study also noted an increase in bald tip length and a shift in dry matter distribution, with more biomass allocated to stems and leaves at the expense of grain. These results underscore the critical vulnerability of maize to waterlogging during early growth stages and highlight the importance of timely drainage and water management to mitigate yield losses.

Verma ***et al.*** **(2014)** conducted a genetic diversity analysis involving 108 bread wheat accessions from India and Australia to evaluate their performance under waterlogged sodic soil conditions. The study grouped the genotypes into eleven distinct clusters, with the largest number of accessions found in cluster IV (26), followed by cluster VI (22) and cluster II (12). A key finding was that inter-cluster distances were generally greater than intra-cluster distances, indicating substantial genetic variability among the groups. The widest genetic divergence was observed between clusters VIII and IX (113.94), and between VIII and X (97.72), suggesting these groups harbor highly diverse genotypes. Cluster X exhibited the highest intra-cluster diversity (13.96) and also recorded the best performance in terms of grain yield, harvest index, and spike weight. Notably, genotypes such as Perenjori, KRL 261, and KRL 283 from cluster X, along with Gutha from cluster IX, were identified as promising candidates for use in hybridisation programs aimed at improving wheat productivity in challenging waterlogged sodic environments.

Ghodke ***et al.*** **(2018)** investigated the impact of waterlogging at different growth stages of onion (*Allium cepa* L.), focusing on the Bhima Super variety under artificial flooding conditions. Their study identified the bulb initiation stage (20–30 days after transplanting) as the most sensitive to waterlogging, resulting in severe reductions in plant growth, bulb formation, and overall yield. In contrast, the early vegetative (1–20 DAT) and bulb maturity (90–110 DAT) stages were comparatively less affected, with plants showing better survival and producing marketable bulbs. These findings highlight the critical need for targeted water management during bulb initiation to safeguard onion productivity during the *kharif* season.

Batu *et al.* (2019) conducted a comprehensive evaluation of 100 durum wheat genotypes to assess their genetic variability and performance under waterlogging conditions in Ethiopia's central highlands. The study, carried out at Debre Zeit and Chefe Donsa research sites using a 10 × 10 simple lattice design, revealed significant genotype and genotype-by-location interactions ($P \leq 0.01$) across 21 agro-morphological and quality traits. Grain yield varied widely among genotypes, ranging from 3515.25 to 7539.25 kg/ha, with an overall mean of 5788.98 kg/ha. Substantial variation was also observed in grain starch content (64.53%–68.13%) and protein content (11.43%–15.38%). Traits such as grain yield, thousand grain weight, number of kernels per spike, harvest index, and sedimentation volume exhibited high phenotypic and genotypic coefficients of variation, indicating strong genetic influence. Heritability estimates and genetic advance as a percentage of the mean ranged from 61.82% to 92.48% and 3.92% to 78.35%, respectively. Grain yield showed strong positive correlations with biomass yield, harvest index, number of effective tillers, and number of kernels per spike at both phenotypic and genotypic levels. Principal component analysis identified seven components explaining 83.7% of the total variation, and cluster analysis grouped the genotypes into four distinct clusters, with clusters II and IV being particularly notable for containing high-yielding genotypes with favorable quality traits, making them promising candidates for breeding programs under waterlogged conditions.

Manik *et al.* (2019) conducted a comprehensive scoping study addressing the persistent challenge of waterlogging in cereal production, particularly in regions characterized by high rainfall and inadequate drainage. The study emphasised that enhancing plant tolerance to waterlogging is the most cost-effective strategy for mitigating its adverse effects. However, in cases of severe waterlogging, the integration of agronomic, engineering, and genetic approaches proves to be more effective. The authors reviewed a broad spectrum of agronomic and engineering interventions currently employed by grain producers to minimise yield losses, highlighting both their benefits and limitations. Key areas identified for future research include conducting cost-benefit analyses of various drainage systems, understanding nutrient loss mechanisms under waterlogged conditions, and evaluating the impact of nutrient supplementation. Additionally, the study called for efforts to improve soil de-watering through structural and agronomic enhancements, and to explore the complex interactions between management practices and environmental variables. Most critically, the authors advocated for the development of integrated strategies that combine genetic improvements with tailored agronomic and engineering solutions to address waterlogging across diverse agro-ecological zones.

Palachai *et al.* (2019) investigated the impact of waterlogging on sugarcane productivity, focusing on the performance of 12 genotypes under varying durations of water saturation in upland (short-term) and lowland (long-term) environments. The study assessed key yield components such as cane yield, sugar yield, stalk length and diameter, millable cane count, and single stalk weight at 12 months after planting. Results revealed significant genotypic variation in response to waterlogging, with prolonged saturation notably reducing cane yield and single stalk weight. Despite these challenges, certain genotypes specifically KK3, Kps01-12, and TBy28-0941 demonstrated stable and high productivity across both waterlogging scenarios. The study identified a strong positive correlation between single stalk weight and overall cane yield, suggesting that this trait could serve as a reliable selection criterion for breeding programs targeting flood-prone areas. Additionally, the number of millable stalks emerged as a useful surrogate trait for evaluating cultivar performance under waterlogged conditions.

Blanco *et al.* (2021) investigated the potential of integrating water-saving irrigation strategies with biofertilization to enhance onion productivity under semi-arid conditions. Their study focused on an F1 2000 hybrid of *Allium cepa* L., evaluating crop performance under two irrigation regimes daily irrigation and a water deficit (WD) treatment with irrigation every three days alongside varying NPK fertilizer levels and the application of a microbial consortium (MC). Despite the reduced irrigation frequency, the WD treatment achieved a comparable yield of 36 t/ha while saving 35% of water, and significantly improved water use efficiency and modulus of elasticity by 47% and 65%, respectively. Furthermore, the use of MC under non-limiting water conditions allowed for a 50% reduction in NPK fertiliser application without compromising yield, matching the output of the fully fertilised, non-inoculated control. These findings highlight the effectiveness of combining moderate water stress with microbial biofertilization as a sustainable approach to onion cultivation, offering both resource conservation and yield stability in water-limited environments.

Dubey *et al.* (2021) investigated the impact of waterlogging on onion growth and yield, revealing that anaerobic conditions during sensitive stages particularly bulb initiation led to significant reductions in plant height, leaf number, and chlorophyll content by 30–45% compared to non-stressed plants. These physiological impairments translated into 25–40% losses in bulb diameter and weight, ultimately reducing marketable yield. The study also highlighted genotype-specific tolerance, with resilient cultivars like Acc. 1664 and RGP 5 showing higher antioxidant enzyme activity and better recovery, while sensitive genotypes such as W-344 and Bhima Red experienced up to 99% mortality. These findings emphasise the importance of selecting tolerant genotypes and optimizing agronomic strategies to mitigate waterlogging stress in onion cultivation.

Tian *et al.* (2021) conducted a comprehensive global meta-analysis to assess the impact of waterlogging on crop productivity, synthesizing data from 2,419 comparisons across 115 studies. Their findings revealed that waterlogging significantly reduced crop yield by an average of 32.9% compared to non-waterlogged conditions. This decline was attributed to reductions in key physiological and morphological traits, including 1,000-grain weight (13.67%), biomass (28.89%), plant height (10.68%), net photosynthetic rate (39.04%), and leaf area index (22.89%). The extent of yield loss varied notably among crop types, with wheat experiencing a 25.53% reduction and cotton suffering the most at 59.95%, averaging 36.81% under field conditions. Moreover, the timing and duration of waterlogging played a critical role in determining the severity of yield loss. Waterlogging during the reproductive stage led to a greater yield reduction (41.90%) than during the vegetative stage (34.75%). Prolonged waterlogging, particularly between 15 to 28 days, resulted in the most severe yield declines 53.19% in field conditions and 55.96% in potted experiments. These results underscore the complex interplay between crop type, developmental stage, and waterlogging duration in influencing crop yield outcomes.

Gedam *et al.* (2022) conducted a comprehensive screening of 100 onion genotypes under artificial waterlogging to identify tolerant lines capable of withstanding monsoon-induced stress. Based on survival, recovery, and bulb weight, genotypes were categorized as tolerant (19), intermediate (27), or highly sensitive (54). Field trials during 2018–2019 with 12 contrasting genotypes validated these findings, showing that tolerant lines such as Acc.

1666, Acc. 1622, W-355, W-208, KH-M-2, and RGP-5 exhibited superior morphological and physiological traits, including greater plant height, leaf area, chlorophyll content, membrane stability, and antioxidant activity. Principal component analysis confirmed strong associations between these traits and waterlogging tolerance, highlighting their value for breeding resilient onion cultivars.

Gedam *et al.* (2023) conducted a transcriptomic analysis to uncover the molecular basis of waterlogging tolerance in onion by comparing two contrasting genotypes: Acc. 1666 (tolerant) and W-344 (sensitive). The study identified thousands of differentially expressed genes (DEGs), with Acc. 1666 showing a distinct expression profile that included upregulation of genes involved in antioxidant defense, phytohormone biosynthesis, and energy metabolism. Key stress-responsive genes such as *ADH*, *PDC*, *PEP carboxylase*, *WRKY22*, and *Respiratory burst oxidase D* were uniquely upregulated in the tolerant genotype. Enzyme assays further confirmed higher antioxidant activity in Acc. 1666, underscoring the role of oxidative stress mitigation in waterlogging resilience. These findings provide valuable molecular targets for breeding onion varieties with improved tolerance to waterlogged conditions.

Wakchaure *et al.* (2023) highlighted the severe impact of transient waterlogging on onion (*Allium cepa* L.) during monsoon seasons, with yield losses ranging from 7% to 60% depending on the growth stage affected. Bulb initiation was identified as the most sensitive phase, followed by vegetative growth and bulb development. When waterlogging occurred across multiple stages, losses became additive, peaking at 60%. To mitigate these effects, the study demonstrated that foliar application of plant growth regulators especially potassium nitrate (20 g/L) and thiourea (600 mg/L) significantly improved marketable yield (by 10.4–23.3%) and water productivity. These treatments enhanced physiological traits such as leaf water content, chlorophyll retention, and stomatal regulation, while also restoring bulb quality and boosting biochemical attributes like total soluble solids and pyruvic acid content. The findings underscore the effectiveness of PGRs as a practical strategy to alleviate waterlogging stress in monsoon onion cultivation.

Kebede and Waltner (2024) investigated the effects of imposing moisture stress at different phenological stages of onion to identify water-saving strategies that maintain yield. Their study revealed that full irrigation produced the highest yield (21.157 t/ha), while continuous stress across all three growth stages led to the lowest yield (7.177 t/ha). However, treatments T3 and T4 where stress was applied during the second and final growth stages achieved yields statistically similar to the fully irrigated control, while saving 21.7% and 11.8% of water, respectively. In contrast, early-stage stress (T8) caused the most severe yield loss, emphasizing the importance of adequate moisture during initial growth. These findings highlight the potential of stage-specific deficit irrigation to improve water productivity in onion cultivation without significantly compromising yield.

Kekere *et al.* (2024) explored the effects of varying watering frequencies on onion growth and yield under screenhouse conditions in Nigeria, aiming to address the scarcity and high cost of onions linked to regionally constrained field production. The study evaluated six watering regimes ranging from daily irrigation (W0) to severe drought (W4) and waterlogging (W5), using onions grown in polyethylene pots. Results indicated that waterlogging (W5) had the most detrimental impact, reducing plant height and leaf number by 68.53% and 70.15%, respectively, compared to daily watering. Additionally, W5 significantly decreased shoot and root biomass, both in fresh and dry weights. Drought stress also negatively affected growth, with the most severe reductions observed under W4 (watering once every two weeks). In contrast, moderate watering frequencies three times per week (W1) and once per week (W2) produced optimal yields in terms of bulb number and size. Nutritional and proximate compositions of bulbs were also highest under W1, except for calcium and magnesium content. These findings suggest that while onions can tolerate mild drought, optimal production is achieved under consistent wet conditions, and waterlogging should be strictly avoided due to its severe impact on both growth and bulb quality.

Zhang *et al.* (2025) provided a comprehensive review of waterlogging as a critical abiotic stress that significantly impairs plant growth and productivity across both rainfed and irrigated systems. The study emphasized that the primary cause of damage under waterlogged conditions is not the excess water itself, but the resulting oxygen deficiency in the root zone. This oxygen deprivation initiates anaerobic respiration in plant roots, weakening their metabolic functions and triggering a cascade of physiological disruptions. Waterlogging was shown to adversely affect plant morphology, growth, and metabolism, often increasing ethylene production and impairing essential physiological processes. Plants respond to such stress by modifying their morphology, energy metabolism, hormone synthesis, and signal transduction pathways. The review synthesized findings from numerous studies to highlight how waterlogging reduces crop yield by disrupting hormone regulation and nutrient uptake, particularly of potassium and calcium. Morphological adaptations such as the formation of adventitious roots and aerenchyma tissues were noted as key survival strategies to facilitate oxygen transport. Zhang *et al.* (2024) also discussed several promising approaches to enhance plant tolerance to waterlogging, including improved field management, application of exogenous hormones like 6-benzylaminopurine (6-BA) and γ-aminobutyric acid (GABA), genetic interventions such as overexpression of genes like *ZmEREB180*, *HvERF2.11*, and *RAP2.6L*, and modifications to root architecture. The study concluded by identifying future research priorities, particularly the need for integrated strategies that combine physiological, genetic, and agronomic innovations to mitigate the adverse effects of waterlogging.

2.2: Effect of Waterlogged Conditions on Available Nutrient Status and Quality of Onion

Ponnamperuma (1984) provided foundational insights into how flooding alters the chemical properties of soils and nutrient availability. The study established that when soils become waterlogged, the depletion of molecular oxygen triggers a sequential reduction of electron acceptors: nitrate is reduced first through denitrification, followed by manganic manganese (Mn^{4+} to Mn^{2+}), ferric iron (Fe^{3+} to Fe^{2+}), sulphate to sulphide, and finally carbon dioxide to methane. These reductions significantly alter the available nutrient status of flooded soils. Notably, the reduction of ferric iron oxides releases adsorbed phosphate, temporarily increasing its availability, while nitrogen availability declines sharply due to denitrification losses. Furthermore, the accumulation of reduced forms of iron and manganese in soil solution may reach phytotoxic levels, adversely affecting root function and crop growth. These transformations in nutrient availability under waterlogged conditions have profound implications for crops with shallow root systems, such as onion, and underpin the rationale for studying soil nutrient dynamics under waterlogging stress.

Ashraf and Rehman (1999) explored how prolonged waterlogging influences soil available nutrient dynamics and growth in corn (*Zea mays* L.) under glasshouse conditions. Their study revealed that continuous flooding for 21 days led to complete depletion of available soil nitrate (NO_3^-), while available ammonium (NH_4^+), potassium (K), phosphorus (P), iron (Fe), and manganese (Mn) levels increased significantly. Despite these shifts in available nutrient status, calcium (Ca) and magnesium (Mg) remained largely unaffected. Waterlogging significantly reduced shoot and root biomass, and the addition of high nitrate levels further exacerbated growth inhibition. Interestingly, while leaf concentrations of N, P, and K declined under flooding, root concentrations increased, suggesting altered nutrient partitioning between plant organs. The study concluded that excessive nitrate supply under hypoxic conditions intensifies physiological stress, and that the altered soil available nutrient profile under waterlogging characterised by nitrogen depletion and iron–manganese accumulation poses a dual challenge of nutrient deficiency and potential toxicity for crop production.

Steffens *et al.* (2005) investigated whether nutrient deficiency or toxicity is the primary cause of growth inhibition in wheat and barley under waterlogged conditions. Their experiments, conducted using two contrasting soils (topsoil and subsoil), revealed that waterlogging reduced growth in the subsoil without inducing iron or manganese toxicity. Water culture experiments with anaerobic (N_2) and aerobic aeration confirmed that oxygen deficiency did not cause nutrient toxicity (Fe, Mn) but instead resulted in sub-optimum supply of essential nutrients, including nitrogen, phosphorus, potassium, manganese, copper, and zinc. In a split-root experiment with barley, sufficient potassium uptake occurred only when both potassium and oxygen were supplied to the same root compartment, demonstrating that nutrient availability alone is insufficient under hypoxic conditions. These findings suggest that the decline in available nutrient status rather than elemental toxicity is the primary mechanism through which waterlogging impairs crop growth, which is particularly relevant for onion production in waterlogging-prone regions.

Setter *et al.* (2009) conducted a comprehensive review of wheat improvement for waterlogging tolerance in Australia and India, with particular emphasis on the importance of anaerobiosis and element toxicities associated with different soil types. The review established that waterlogging-induced changes in soil available nutrient status vary substantially with soil type, pH, and organic matter content. In acidic soils, waterlogging leads to toxic accumulation of available Mn^{2+} and Fe^{2+}, whereas in alkaline soils, the primary constraints are nitrogen deficiency through denitrification and reduced availability of phosphorus and zinc. The authors demonstrated that genotypic tolerance to waterlogging involves not only morphological adaptations (such as aerenchyma formation) but also the ability to exclude or tolerate elevated levels of reduced soil elements. These findings underscore that understanding the soil-specific changes in available nutrient status under waterlogging is essential for developing crop management strategies and breeding programs, a principle equally applicable to onion cultivation in waterlogging-prone environments of the Indian subcontinent.

Elzenga and van Veen (2010) systematically analyzed how waterlogging alters key parameters influencing nutrient availability and uptake in plants, based on the nutrient uptake model by Silberbush and Barber. They found that waterlogging can both positively and negatively affect nutrient availability in the rhizosphere, depending on the specific nutrient and soil conditions. Most notably, oxygen deficiency in saturated soils impairs root function and nutrient transport, thereby reducing the effective availability of nutrients at the root surface even when soil nutrient reserves remain adequate. However, the authors highlighted several adaptive strategies that plants may employ to mitigate these effects, such as increasing root length, enhancing mycorrhizal associations, and modifying nutrient uptake kinetics. These adaptations, particularly in flooding-tolerant species, help maintain nutrient acquisition under hypoxic conditions. The study provides a theoretical framework for understanding how waterlogging alters the interface between soil available nutrient status and plant nutrient access, which is directly relevant to shallow-rooted crops such as onion.

Ren *et al.* (2017) conducted a field study to assess how waterlogging at different growth stages affects nitrogen metabolism, available nitrogen status, and yield in two maize hybrids, DengHai605 (DH605) and ZhengDan958 (ZD958). The results demonstrated that waterlogging significantly reduced soil available nitrogen accumulation, particularly when imposed at the third leaf stage (V3), with reductions of 41% in DH605 and 37% in ZD958. Nitrogen allocation to grains declined, while its proportion in stems and leaves increased, largely due to reduced dry matter accumulation and impaired nitrogen translocation from vegetative to reproductive organs. Furthermore, waterlogging suppressed the activity of key nitrogen metabolism enzymes nitrate reductase, glutamine synthetase, glutamate synthase, and glutamate dehydrogenase with the most severe reductions observed under V3 waterlogging. These disruptions in available nitrogen status and enzyme activity ultimately led to decreased maize yield, highlighting the critical sensitivity of soil nutrient availability and plant metabolic processes to waterlogging during early growth stages.

Ghodke *et al.* (2018) investigated the impact of waterlogging at different growth stages of onion (*Allium cepa* L.), focusing on the Bhima Super variety under artificial flooding conditions. Their study identified the bulb initiation stage (20–30 days after transplanting) as the most sensitive to waterlogging, resulting in severe reductions in bulb quality traits including total soluble solids, phenol content, flavonoids, pyruvic acid, and antioxidant activity. The crop growth period from 20 to 90 DAT was found to be critically sensitive to waterlogging stress, as the plants showed marked reductions in bulb quality traits and failed to produce marketable-size bulbs. In contrast, the early vegetative (1–20 DAT) and bulb maturity (90–110 DAT) stages were comparatively less affected. These findings emphasize the critical importance of maintaining adequate soil aeration and available nutrient status during the bulb initiation stage to safeguard onion quality during the *kharif* season.

Wollmer *et al.* (2018) examined how waterlogging influences micronutrient availability and plant micronutrient status in winter wheat and rapeseed, focusing on two developmental stages: DC 31 (stem elongation) and DC 51 (inflorescence emergence). Their findings revealed that early-stage waterlogging did not cause micronutrient toxicity, though it led to increased manganese (Mn) availability in rapeseed and reduced copper (Cu) and zinc (Zn) levels. In contrast, late-stage waterlogging resulted in toxic accumulations of Mn and iron (Fe) in wheat, and Mn, Cu, and Zn in rapeseed, reflecting a shift in available micronutrient status toward potentially harmful levels. These results underscore that the timing of waterlogging plays a critical role in determining whether plants experience micronutrient deficiencies or toxicities, and that soil available nutrient status is dynamically altered depending on the duration and timing of waterlogging stress.

Kaur *et al.* (2020) conducted a three-year field study to evaluate the effects of early-season waterlogging on soil nitrogen availability and corn performance under different nitrogen management strategies. The experiment assessed corn hybrids with varying flood tolerance, using pre-plant nitrogen sources including polymer-coated urea (PCU), non-coated urea (NCU), and NCU with nitrification inhibitor (NCU+NI), alongside post-waterlogging rescue nitrogen applications. Results showed that waterlogging at the V3 growth stage significantly reduced soil nitrate (NO_3^--N) concentrations by up to 69%, while ammonium (NH_4^+-N) levels remained unaffected, indicating selective depletion of available nitrogen forms through denitrification under anaerobic conditions. The study highlighted that environmental conditions influenced nitrogen availability and fertilizer efficiency, emphasising the importance of tailored nitrogen management strategies to mitigate the decline in available nutrient status under waterlogged conditions.

Gedam *et al.* (2022) conducted a comprehensive screening of 100 onion genotypes under artificial waterlogging to identify lines tolerant to monsoon-induced stress, evaluating their growth, physiological traits, and bulb quality. Genotypes were classified as tolerant (19), intermediate (27), or highly sensitive (54) based on survival, recovery, and bulb weight. Field trials during 2018–2019 with 12 contrasting genotypes validated these findings, showing that tolerant lines such as Acc. 1666, Acc. 1622, W-355, W-208, KH-M-2, and RGP-5 exhibited superior bulb quality traits including higher total soluble solids, pyruvic acid content, and antioxidant activity under stress conditions. Notably, all genotypes under stress exhibited lower TSS but higher phenol, pyruvic acid concentrations, and antioxidant activity compared to control, indicating that waterlogging triggers defensive biochemical pathways. Principal component analysis confirmed strong associations between physiological resilience traits and bulb quality parameters, highlighting the value of genotype selection for maintaining both nutrient availability and quality in onion cultivation under waterlogged conditions.

Naskar and Mallick (2023) evaluated the impact of integrated nutrient management on phosphorus (P) dynamics and rice yield under waterlogged conditions in the new alluvial zone of West Bengal. Using rice cultivar IET-4786, their two-year field study tested six treatment combinations involving varying doses of NPK, zinc (Zn), farmyard manure (FYM), and phosphate solubilizing bacteria (PSB). The treatment combining 50% recommended NPK with FYM (5 t/ha), Zn (5 kg/ha), and PSB (10 kg/ha) resulted in the highest available P content in biomass and grain, as well as the greatest P uptake and yield. The study demonstrated that integrated nutrient management can effectively enhance soil available phosphorus status under waterlogged conditions by promoting microbial P solubilization and organic matter-mediated nutrient release. These findings have implications for managing nutrient availability in waterlogged soils used for onion cultivation, where maintaining adequate available P status is critical for bulb development and quality.

Wakchaure *et al.* (2023) investigated the impact of transient waterlogging on monsoon-season onion (*Allium cepa* L.) bulb quality and evaluated the effectiveness of plant growth regulators (PGRs) in mitigating associated quality losses. Their study revealed that waterlogging at the bulb initiation stage significantly reduced bulb quality parameters, including pH (declined from 6.3 to 5.7–6.2), protein content (from 11.3 to 9.3–10.4 mg g^{-1} DW), and total phenolics (from 6.4 to 3.0–6.2 mg GA equiv. g^{-1} DW). Conversely, pyruvic acid content increased in waterlogged bulbs (90.2–103.2 μMg^{-1}) compared to control (88.4 μMg^{-1}), suggesting stress-induced pungency enhancement. TSS, recovery ratio, and bulb firmness were also adversely affected. Foliar application of PGRs particularly potassium nitrate (20 g/L) and thiourea (600 mg/L) significantly restored bulb quality attributes, including weight, firmness, and biochemical composition, and improved marketable yield by 10.4–23.3%. These findings underscore the importance of targeted agronomic interventions to maintain onion bulb quality under waterlogging stress.

Luo *et al.* (2024) investigated the effects of waterlogging stress on root development and nutrient dynamics in winter wheat during the seedling stage. Their field study revealed that waterlogging significantly altered root morphology, increasing root length, surface area, and volume, particularly in the upper 20 cm of soil. However, this was accompanied by a significant decline in available nitrogen and phosphorus content in deeper soil layers (20–60 cm), indicating disrupted nutrient distribution across the soil profile. The study also found that waterlogging led to substantial nitrogen and phosphorus losses through surface runoff, with nitrate nitrogen and soluble phosphorus comprising the majority of nutrient loss. Redundancy analysis identified available phosphorus as a key factor influencing runoff water quality, while total and dissolved phosphorus were closely linked to root growth changes. These findings highlight the dual impact of waterlogging on reducing soil available nutrient status while simultaneously increasing environmental nutrient losses.

Chand *et al.* (2025) investigated the interactive effects of waterlogging duration and nitrogen application on maize performance and soil available nutrient status using variety D-822 in a split-plot field experiment. The study revealed that prolonged waterlogging (up to 72 hours) significantly reduced key yield attributes such as cob length, cob diameter, grain rows per cob, grains per row, 100-grain weight, and both grain and stover yield. In contrast, increasing nitrogen levels from 60 to 180 kg ha^{-1} enhanced these traits and improved nutrient uptake including nitrogen, phosphorus, potassium, iron, and manganese. However, soil available nutrient status and plant nutrient uptake declined progressively with longer waterlogging durations, underscoring the detrimental impact of excess soil moisture on nutrient transformations and assimilation. These findings demonstrate that while enhanced fertilization can partially compensate for waterlogging-induced nutrient depletion, the reduction in soil available nutrient status under prolonged waterlogging remains a fundamental constraint to crop productivity.

2.3: Effect of Waterlogged Conditions on Physical, Chemical, and Biological Properties of Soil

Patrick and Mahapatra (1968) provided foundational insights into how waterlogging alters soil chemistry and nutrient availability, particularly for lowland rice cultivation. They explained that waterlogging transforms the root zone from an aerobic to an anaerobic environment, destabilizing oxidation–reduction systems. This shift leads to denitrification of nitrate nitrogen and the formation of reduced compounds like manganous manganese and ferrous iron. Under intense reduction, sulphate is converted to sulphide. While both nitrate and ammonium can be absorbed by rice, ammonium is more stable under flooded conditions, making it the preferred nitrogen form. Additionally, the reduction of ferric oxides in waterlogged soils releases phosphate, enhancing its availability to rice plants. These findings underscore the importance of understanding redox-driven nutrient transformations for optimizing fertilizers use in flooded rice systems.

Ferronato *et al.* (2018) explored how hydroperiod defined by the duration and frequency of water saturation affects soil organic matter (SOM) quality across terrestrial, intertidal, and subaqueous salt marsh ecosystems in the Baiona lagoon, Italy. Their study revealed that intertidal zones, influenced by dynamic water movements, exhibited the highest accumulation of nutrients and SOM due to strong pedoturbation effects. DRIFT spectral analysis of humic acids indicated that increased waterlogging reduced SOM aromaticity and complexity, particularly in subaqueous soils. Additionally, microbial activity, measured through microbial biomass carbon, microbial quotient, and enzyme activities, was generally higher in subsurface layers likely due to anaerobic preservation and erosion-driven redistribution. These findings underscore the pivotal role of waterlogging in shaping the chemical and biological transformation of SOM in salt marsh environments.

Ferronato *et al.* (2019) further explored how hydroperiod defined by the duration and frequency of soil water saturation affects soil organic matter (SOM) quality across terrestrial, intertidal, and subaqueous salt marsh ecosystems in the Baiona lagoon, Italy. Their findings revealed that intertidal zones, influenced by dynamic water movement, exhibited the highest accumulation of nutrients and SOM due to strong pedoturbation. DRIFT spectral analysis of humic acids showed that increased waterlogging reduced SOM aromaticity and complexity, especially in subaqueous soils. Additionally, microbial biomass carbon, microbial quotient, and enzyme activities were generally higher in subsurface layers, likely due to anaerobic preservation and erosion-driven redistribution. The study underscores the pivotal role of waterlogging in shaping SOM transformation and microbial activity in salt marsh environments.

Langan *et al.* (2022) reviewed the complexities of phenotyping for waterlogging tolerance in temperate crops, emphasising its growing importance due to climate-induced increases in flooding events. Despite advances in understanding molecular and physiological responses, phenotyping remains challenging because of the variability in waterlogging conditions such as duration, temperature, soil type, and crop growth stage. The review outlined a range of experimental approaches, from controlled hydroponic systems to field-scale screenings, and discussed phenotyping traits including survival rates, visual assessments, and photosynthetic efficiency. The authors also addressed the limitations of traditional methods and highlighted emerging trends like plant-imaging technologies. If effectively utilised to increase crop resilience to changing climates, crop phenotyping has a major role to play in global food security.

Akinyemi *et al.* (2024) evaluated the potential of rice straw biochar and its magnetic derivative both intercalated with and without urea as slow-release nitrogen fertilisers for rice cultivation under waterlogged conditions. Produced via pyrolysis at 450°C, these biochars were tested in various combinations with urea on Gleisoil soil. The study found that urea-intercalated magnetic biochar (UMRB), especially at 40 kg N ha^{-1}, significantly improved ammonium and nitrate retention, as well as rice growth parameters such as panicle number, tiller length, dry matter, and grain yield. FTIR analysis confirmed the presence of functional groups enhancing nutrient adsorption and reducing nitrate loss. These findings highlight UMRB's promise in improving nitrogen use efficiency and boosting rice productivity in flooded soils.

Pawar *et al.* (2025a) investigated the effects of waterlogging on soil physical properties, microbial activity, nutrient availability, nutrient uptake, and bulb yield in eight onion (*Allium cepa* L.) genotypes under field conditions at ICAR–Directorate of Onion and Garlic Research, Pune, India. The study employed a split-plot design with waterlogging treatments as main plots and eight onion genotypes (two tolerant and six sensitive) as sub-plots on clay loam soils during the monsoon season. Results revealed that waterlogging significantly altered soil physical properties, increasing bulk density by 5.30% and reducing infiltration rate by 76.5% compared to control plots. Soil biological indicators were severely impacted: microbial biomass carbon declined by 67.6% at 50 DAT, while dehydrogenase, urease, acid phosphatase, and alkaline phosphatase activities declined by 55.8%, 33.9%, 33.9%, and 10.2%, respectively. Available macronutrients (N, P, K, S, Ca, Mg) and micronutrients (Fe, Cu, Mn, B) were significantly reduced at 55 DAT compared to pre-waterlogging levels at 45 DAT. Post-waterlogging recovery at 55 DAT showed partial restoration of microbial biomass carbon (25.0% reduction) and phosphatase activities (12.3% reduction). Redundancy analysis revealed strong associations between soil microbial and nutrient properties and onion yield under both waterlogging and control conditions. These findings provide comprehensive evidence that waterlogging simultaneously degrades soil physical structure, suppresses biological activity, and depletes available nutrient reserves, collectively impairing onion productivity in monsoon-season cultivation.

Pawar *et al.* (2025b) evaluated the differential responses of eight onion genotypes four tolerant (Accession 1666, Bhima Dark Red Selection, Accession 1630, W-355) and four sensitive (Bhima Super, Bhima Shubra, Bhima Red, Bhima Raj) under field waterlogging conditions on clay loam soils at ICAR–DOGR, Pune, during the *kharif* season 2024. The study reported that waterlogging-induced anaerobic soil conditions significantly affected plant–soil interactions, with saturated soils displacing air from pore spaces and creating anoxic conditions that impaired root activity, water transport, and nutrient uptake. Tolerant genotype Accession 1666 exhibited minimal growth reduction under these altered soil conditions, while Bhima Dark Red Selection showed moderate declines of 17.1%, 10.6%, and 11.7% in plant height, leaf number, and total leaf area, respectively. Both tolerant genotypes maintained higher membrane stability index, relative water content, and antioxidant enzyme activities (catalase, guaiacol peroxidase, superoxide dismutase, and ascorbate peroxidase) compared to sensitive genotypes, suggesting their superior ability to cope with the oxidative stress arising from waterlogging-induced changes in soil aeration and redox conditions. The findings demonstrate that soil physical degradation under waterlogging particularly reduced aeration and altered redox potential differentially affects onion genotypes, and that genotypic selection can mitigate the adverse effects of deteriorated soil conditions on crop performance.

Salunkhe *et al.* (2025) investigated the complex interplay between waterlogging stress and anthracnose twister disease caused by *Colletotrichum gloeosporioides* in onion (*Allium cepa* L.) at ICAR–Directorate of Onion and Garlic Research, Pune, and ICAR–National Institute of Abiotic Stress Management, Baramati, India. The study established that waterlogging fundamentally alters soil physical and biological properties by creating prolonged anaerobic conditions that suppress beneficial aerobic microorganisms while promoting the proliferation of soil-borne pathogens. When onion plants were subjected to pre-infection waterlogging followed by pathogen inoculation, the disease severity was significantly higher compared to plants waterlogged after infection, suggesting that waterlogging-induced degradation of soil biological health including shifts in microbial community composition and suppression of antagonistic organisms creates a conducive environment for pathogen establishment. The study measured key physiological indicators including chlorophyll fluorescence, membrane stability index, membrane injury index, relative water content, protein content, and antioxidant enzyme activities (superoxide dismutase, ascorbate peroxidase) across different stress combinations. These findings highlight that waterlogging not only directly damages soil physical and chemical properties but also indirectly compromises soil biological health by facilitating disease establishment, representing a dual threat to onion cultivation in waterlogging-prone environments during the monsoon season.

Zhang *et al.* (2025) provided a comprehensive review of soil waterlogging impacts on soil properties, plant physiological mechanisms, and adaptive strategies. The review established that the primary effect of waterlogging on soil is the displacement of oxygen from pore spaces, transforming the root zone from an aerobic to an anaerobic environment. This oxygen depletion triggers a cascade of changes in soil physical, chemical, and biological properties: bulk density increases due to particle compaction and structural collapse; soil aggregates disperse, leading to surface crusting and reduced infiltration; and the redox potential drops sharply, initiating sequential reduction of electron acceptors including nitrate, manganese, iron, and sulphate. These chemical transformations fundamentally alter the availability of essential nutrients nitrogen is lost through denitrification, phosphorus availability temporarily increases through iron oxide reduction, while manganese and iron may accumulate to phytotoxic levels. The review further highlighted that waterlogging dramatically shifts soil microbial community composition, with aerobic populations declining and anaerobic and facultative anaerobic organisms proliferating, thereby disrupting organic matter decomposition, nutrient cycling, and overall soil biological functioning. Zhang *et al.* synthesised evidence from multiple crops and environments to conclude that the severity of soil property changes depends on soil type, waterlogging duration, temperature, and crop growth stage. The review identified that integrated strategies combining improved field management, exogenous hormone application, genetic interventions, and root architecture modifications are essential for mitigating the adverse effects of waterlogging on soil–plant systems, findings directly applicable to waterlogging-sensitive crops such as onion.

The review of literature reveals that waterlogging is a major abiotic stress that significantly reduces crop growth, yield, and quality across multiple crops, with onion being particularly vulnerable due to its shallow root system. Key findings from the reviewed literature can be summarized as follows: (i) waterlogging imposes stage-specific yield penalties, with bulb initiation being the most critical period for onion; (ii) significant genotypic variability exists in waterlogging tolerance, with accessions such as Acc. 1666 demonstrating superior morpho-physiological and molecular resilience; (iii) waterlogging disrupts soil nutrient dynamics through altered redox conditions, microbial shifts, and impaired nutrient cycling; and (iv) integrated approaches combining genetic improvement with agronomic management offer the most promising strategies for mitigation.

However, several research gaps remain. Most existing studies on waterlogging tolerance in onion have focused either on morpho-physiological responses or on molecular mechanisms in isolation, with limited integration of growth, yield, biochemical, soil, and economic parameters in a single comprehensive study. Furthermore, multi-season evaluations comparing tolerant and sensitive genotypes under field-level waterlogging stress are scarce. The impact of waterlogging on soil biological properties, particularly enzymatic activities and microbial biomass carbon, has not been adequately studied in the context of onion cultivation. Additionally, the economic implications of genotype selection under waterlogged conditions have received limited attention.

The present investigation was therefore designed to address these gaps by evaluating the morpho-physiological, biochemical, yield, soil property, and economic responses of eight contrasting onion genotypes to waterlogging stress over two consecutive seasons under field conditions."

CHAPTER III

MATERIAL METHODS

The present investigation entitled **“Screening onion genotypes for growth, yield, and economics of production under waterlogged conditions and its impact on Physio - chemical properties of soil”** was carried out at Directorate of Onion and Garlic Research, Rajgurunagar, Pune (M.H) during *kharif,* 2023-2024. This chapter deals with the concise description of the materials used and the techniques adopted during the course of investigation.

3.1 Geographical location

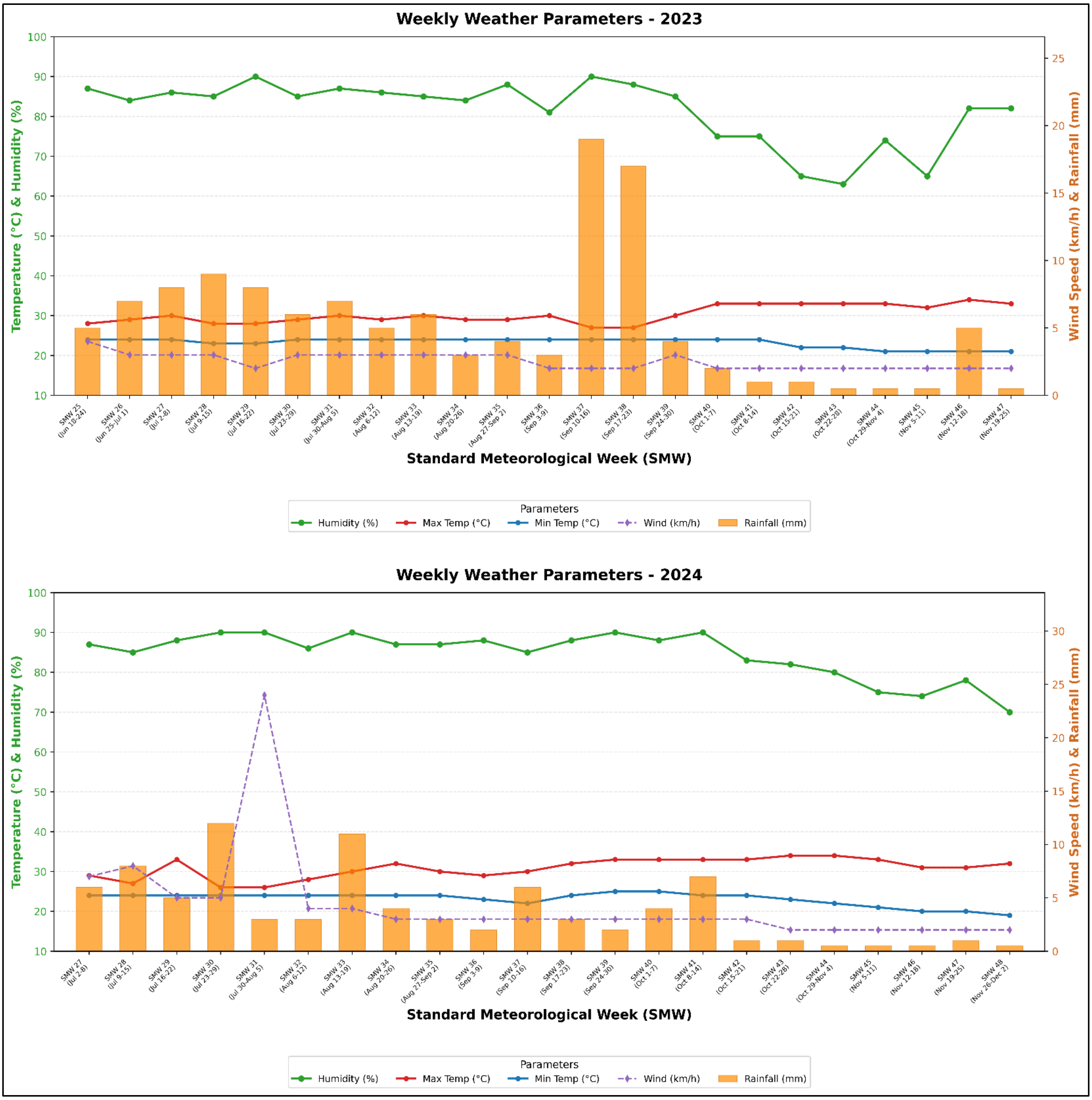
The ICAR-Directorate of onion and Garlic Research, Pune, Maharashtra, (India) is situated at 18^{0}32’North latitude and 73^{0}51’East longitude with an altitude of 553.8 m above mean sea level.

3.2 Climate

The experimental site is classified as a tropical dry and humid climate, with an average annual rainfall of (820) mm. The mean maximum air temperature ranged between 24.2°C and 39.7°C, while the mean minimum air temperature varied from (19.68) °C to (32.62) °C.

The weekly average meteorological data during the span of experimentation (2023-24) was recorded at Meteorological Observatory, DOGR, Rajgurunagar have been presented in Appendix-I and depicted in Fig. 1.

Fig.1: Weekly meteorological data of experimental site of Onion during the period from 1st Jully- 30thNov for 2023- 2024.



3.3 Soil characteristics of the experimental field

The land used in the experimental layout was fairly uniform with gentle slope. The soil was medium black with uniform texture. The detailed analyses of experimental soil:

Table 1. Initial soil status of research location based on composite soil sample

Soil properties	Value	Rating	Method used/ Reference
A. Physical composition			
Sand (%)	27	-	International Pipette Method (Black, 1965)
Silt (%)	41	-	International Pipette Method (Black, 1965)
Clay (%)	32	-	International Pipette Method (Black, 1965)
Texture	-	Clay loam	International Pipette Method (Black, 1965)
B. Chemical composition			
Soil pH	7.63	Neutral	Potentiometry (FAO GLOSOLAN, 2021)
Electrical conductivity (dS m^{-1})	0.25	Very High	Conductometry (CUTM, 2020)
Moisture (%)	28.71	-	Wet oxidation (Gravimetric soil moisture; FAO, 2019)
Soil organic carbon (mg kg^{-1})	7.51	Low	Walkley and Black, Wet oxidation (Walkley and Black, 1934)
Soil available N (kg ha^{-1})	91.47	Low	Alkaline permanganate (Subbiah and Asija, 1956)
Soil available P (kg ha^{-1})	21.05	Medium	0.5 M $NaHCO_3$ (pH 8.5) (Olsen *et al.,* 1954)
Soil available K (kg ha^{-1})	269.75	High	Neutral N NH_4OAc extract (Jackson, 1973)
Soil available S (mg kg^{-1})	10.02	Medium	0.15% $CaCl_2$ extractable (Williams and Steinbergs, 1959)
Soil available B (mg kg^{-1})	0.84	Medium	Hot water method (Bingham, 1982; Chapman and Pratt, 1961)
Soil available Fe (mg kg^{-1})	2.73	Medium	DTPA (Atomic Absorption Spectrophotometer) (Lindsay and Norvell, 1978)

Soil available Mn (mg kg^{-1})	3.73	Medium	DTPA (Atomic Absorption Spectrophotometer) (Lindsay and Norvell, 1978)
Soil available Zn (mg kg^{-1})	1.13	Medium	DTPA (Atomic Absorption Spectrophotometer) (Lindsay and Norvell, 1978)
Soil available Cu (mg kg^{-1})	4.00	High	DTPA (Atomic Absorption Spectrophotometer) (Lindsay and Norvell, 1978)
Soil available Mg (cmol kg^{-1})	0.50	Low	Ammonium acetate extract (NH_4OAc) (Jackson, 1973)

3.4 Experimental details

The experiment consisted in field condition, and one set of plant was used as waterlogging treatment and other set was as control (schedule irrigation). The experimental materials comprise of 8 onion entries including tolerant and sensitive onion genotypes. The seedlings of each genotype were raised from seeds in nursery for 45 days with recommended cultural practices and transplanted in field condition and total 408 plants for each genotype in each replication were used for evaluation.

3.4.1 Field experiment at experimental site

The experimental materials were transplanted into a flatbed for waterlogging treatment. The experiment details are given below:

Table 2: Details of field layout

Crop	Onion *(Allium cepa L.)*
Season	*kharif* 2023 and 24
Design	Split plot
Plot Size	Flatbed (3x2 m^2)
Spacing	Row to Row-15 cm; Plant to Plant- 10cm
Gross plot	6m^2
Plants per plot	400
No. of Treatment	2 treatments × 8 genotypes = 16 combinations
	• No. of Main Plot Treatments: **02 (Control and Waterlogging)** • No. of Sub-Plot Entries (Genotypes): **08**
No. of Genotypes	08
No. of Replication	03
Start of Treatment	45 DAT
End of Treatment	55 DAT

The waterlogging treatment was imposed at 45–55 DAT, coinciding with the bulb initiation and early bulb development stage, which has been identified as the most sensitive period for onion yield loss under waterlogging stress

3.4.2 Experimental materials

The following experimental materials were tested, which comprised eight onion entries, including four tolerant and four sensitive genotypes. The onion genotype materials were collected from ICAR-Directorate of Onion and Garlic Research, Pune, Maharashtra, India.

Table 3: Genotype details

Tolerant genotype	Sensitive genotypes
1. Acc.1666.	5. Bhima red
2. Acc.1630.	6. Bhima raj
3. W-355.	7. Bhima shubra
4. Bhima Dark Red.	8. Bhima super

All eight onion genotypes, both sensitive and tolerant, were cultivated using the same seed rate, spacing, recommended dose of fertilizer, plant population, and season.

Table 4: Standard agronomic practices followed for all eight onion genotypes.

Particulars	
Crop	Onion
Seed rate	8–10 kg ha^{-1}
Spacing	15 × 10 cm
Recommended dose of fertilizer	100 kg N, 50 kg P_2O_5, 60 kg K_2O ha^{-1}
Plant population	666,667 plants ha^{-1}
Season	Late *Kharif*

Fig. 2. Experimental field layout

Irrigation channel	Waterlogging	Control	Irrigation channel	Waterlogging	Control	Irrigation channel	Waterlogging	Control	Irrigation channel
	R1			R2			R3		
	W-355	Bhima Super		Bhima Red	Acc. 1630		Bhima Raj	Acc. 1666	
	Acc. 1630	Bhima Red		Acc. 355	B. D. R		W-355	Bhima Shubra	
	Bhima Raj	Acc. 1666		B. D. R	W-355		Bhima Shubra	Bhima Super	
	Bhima Shubra	B. D. R		Bhima Super	Bhima Raj		Acc. 1666	Acc. 355	
	B. D. R	Bhima Shubra		Acc. 1666	Bhima Red		B. D. R	Bhima Raj	
	Acc. 1666	Bhima Raj		Bhima Raj	Bhima Super		Acc. 1630	Bhima Red	
	Bhima Red	Acc. 1630		Acc. 1630	Bhima Shubra		Bhima Super	Acc. 1630	
	Bhima Super	W-355		Bhima Shubra	Acc. 1666		Bhima Red	B. D. R	2M

3m

3.4.2.1 Land Preparation

The investigation site prepared using tractor-pulled plough, then tractor-drawn harrow was used for harrowing in the month of August during both the first and second years. Fine tilth was obtained through repeated cross harrowing in both years. Each plot for onion transplanting was individually prepared through manual ploughing by labor to ensure precise plot-specific soil preparation. Subsequently each plot was individually leveled and flat beds were prepared. The experiment was arranged based on the layout plan shown in Fig. 2 for both years.

3.4.2.2 FYM incorporation

The farmyard manure (FYM) was applied following the standardized protocol recommended by ICAR-DOGR, ensuring that the quantity and timing of application met the crop's nutrient requirements as per the institute's guidelines. FYM was incorporated 15 days prior to seeding to allow adequate decomposition, uniform distribution, and optimal nutrient availability throughout the root zone, in line with the ICAR-DOGR standard practices for onion cultivation under waterlogged conditions. Prior to application, the nutrient concentration of FYM was analyzed in both years to ensure consistency and adequacy of nutrient supply, particularly for primary macronutrients essential for crop growth.

Table 5: Nutrient composition of FYM utilized during the experiment.

Particulars	Nutrients	Content% (2023)	Content % (2024)
FYM	N	0.5	0.5
	P	0.1	0.1
	K	0.5	0.5

3.4.3.3 Fertilizer Application

For *kharif* onion production under ICAR-DOGR standard protocols, fertilizers are applied based on the recommended dose of 100 kg nitrogen, 50 kg phosphorus (P_2O_5), and 60 kg potassium (K_2O) per hectare. At the time of transplanting, the entire quantity of phosphorus and potassium, along with 50% of the nitrogen, is applied as a basal dose using urea, single super phosphate (SSP), and muriate of potash (MOP) as nutrient sources. The remaining 50% of nitrogen is top-dressed in two equal splits at 30 and 60 days after transplanting to enhance nutrient uptake and minimize losses, particularly during the monsoon-prone *kharif* season. In accordance with integrated nutrient management practices, well-decomposed farmyard manure (FYM) is incorporated into the soil at a rate of 15–20 t/ha, fifteen days prior to transplanting, after analyzing its nutrient content to ensure uniformity and adequate decomposition. Fertilizer doses are further adjusted based on initial soil test results, with supplemental micronutrients such as zinc and sulfur provided if deficiencies are detected. This approach aligns with ICAR-DOGR's recommendations for optimizing nutrient use efficiency and supporting onion growth under waterlogging and other abiotic stresses common in the *kharif* season.

3.4.3.4 Seed priming, Nursery sowing, and Seedling management for onion under ICAR-DOGR Protocol

Certified seeds of all eight onion genotypes (tolerant: Acc.1666, Acc.1630, W-355, Bhima Dark Red; sensitive: Bhima Red, Bhima Raj, Bhima Shubra, Bhima Super) were treated with *Trichoderma viride* @ 4–5 g per kg of seeds to suppress soil-borne pathogens and enhance seedling vigor. Seeds were sown in raised nursery beds (1 m width, 15 cm height) with well-decomposed FYM (15–20 t ha^{-1}) incorporated 15 days prior, ensuring optimal drainage to mitigate waterlogging risks during germination. The seed rate was maintained at 8–10 kg ha^{-1}, sown in lines spaced 5–7 cm apart and covered with a thin soil layer.

After 45–50 days, seedlings (10–15 cm height) were hardened by reducing irrigation 7–10 days before transplanting to acclimate them to field conditions. Before transplanting, seedlings underwent root dipping in a solution of *Pseudomonas fluorescens* @ 5 g L^{-1} for 30 minutes to boost stress resilience against waterlogging. Transplanting followed ICAR-DOGR's late *kharif* schedule at 15 × 10 cm spacing.

3.4.4 Inter cultivation operations

3.4.1 Plant gaps filling

For onion under ICAR-DOGR *kharif* production protocol, gap filling was carried out approximately 10 days after transplanting by inserting healthy seedlings into vacant spots to ensure uniform plant stand across all plots. Simultaneously, excess seedlings were thinned out at around 15 days after transplanting, retaining only one vigorous seedling per hill. This practice ensures optimal plant population density and uniformity, which are critical for accurate genotype evaluation and maximizing yield potential under experimental conditions

3.4.2 Irrigation Management

For onion cultivation under ICAR-DOGR protocols during late *Kharif*, irrigation was managed to balance optimal moisture and waterlogging stress simulation. Initial irrigation was applied immediately after transplanting to ensure uniform seedling establishment. Subsequent irrigations were scheduled based on soil moisture levels, maintaining field capacity while avoiding saturation. During waterlogging treatment phases, plots designated for stress simulation were flooded to a depth of 5 cm above soil level for 72-hour periods at critical growth stages (45 -55 days after transplanting). Non-stress plots received irrigation only when soil moisture dropped below 50% of field capacity, with drainage facilities ensuring no water stagnation.

3.4.3 Weed Control Practices

Pre-emergence application of Pendimethalin (30% EC) @ 3.3 L ha^{-1} was administered 3 days after transplanting to suppress early weed germination. Three manual weeding's were performed at 20, 40, and 60 days after transplanting (DAT) to eliminate residual weeds. Mulching with paddy straw (5 t ha^{-1}) was additionally employed in all plots to inhibit weed growth and conserve soil moisture.

3.4.4 Plant Protection

Thrips control was achieved through foliar sprays of Spinosad 45% SC @ 0.3 ml L^{-1} water at 15-day intervals starting from 30 DAT. For purple blotch (*Alternaria porri*) management, Mancozeb (75% WP) @ 2 g L^{-1} was applied preventively at 45 and 75 DAT. In high-infestation scenarios, a combination of Imidacloprid (0.5 ml L^{-1}) and Hexaconazole (0.1%) was used.

3.4.5 Harvest and Post-Harvest Protocol for Onion under ICAR-DOGR *kharif* Production

Onion bulbs were harvested at physiological maturity, indicated by 70–80% neck fall and papery skin formation. Plants were manually uprooted using forks to minimize bulb damage, and border rows were excluded to maintain plot integrity. Harvested bulbs from each net plot (10 m^2) were sun-cured for 7–10 days on raised bamboo racks to reduce moisture content (12–15%) and enhance storage durability. Post-curing, roots and foliage were trimmed 2–3 cm above the bulb neck. Bulbs were graded by size (55< ,45-55,45> mm) and weight, with diseased or damaged bulbs discarded. Yield parameters equatorial diameter, polar diameter, average bulb weight (g/plant), and total yield (t ha^{-1}) were recorded per genotype and treatment**.**

3.5 Morpho-physiological observations

Plants were monitored for 30,45,55,75 and at harvest days after transplanting for various morphological observations like plant height, leaf length, number of leaves, leaf area and neck thickness. The leaf sample (4^{th} leaf) was collected at 45 and at 55 days after transplanting and used for analysis of morphological and biochemical traits (chlorophyll content, and MSI). The bulb sample were used to analyze biochemical traits (antioxidant, phenol, protein, proline and pyruvic and TSS) at harvest. The yield and associated traits like bulb yield, bulb size was done after harvesting. The recommended cultural practices, pest and disease management were done throughout the growth period.

3.5.1 Plant height (cm)

The onion plant height was measured by average of five plants from each replication. The height was measured from ground level to the tip of the longest leaf with the help of meter scale and after computing the mean and it was recorded as height of onion plant in centimeter (cm).

3.5.2 Numbers of leaves per plant

Numbers of leaves in plants were measured by average of five plants from each replication and after computing the mean, it was recorded as number of leaves in onion plant.

3.5.3 Leaf length (cm)

Leaf of the plant was measured with the help of meter scale 3rd or 4th leaf of the plant sample were plucked from the plant and taken to the laboratory with the help of plastic bags and length of three leaf of each replication were measured and average were taken as leaf length.

3.5.4 Leaf area per plant (cm2)

The plant was uprooted and separated out all the leaves from bulb neck to measure the leaf area per plant. Then, leaves were cleaned properly with the help of tissue paper and pressed under heavy material. Thereafter, leaves were run on conveyor belt of leaf area meter (Model: Biovis PSM L-3000) and the value shown by leaf area meter is expressed as cm^2.

3.5.5 Neck thickness (mm)

The neck thickness of onion plants was determined by measuring five plants from each replication using a vernier caliper, and the results are presented in millimeters (mm).

3.6 Physiological Indices

3.6.1 Leaf Area Index (LAI)

Williams (1946) proposed the term, Leaf Area Index (LAI). It is the ratio of the crop to the ground area over a period of interval of time. The value of LAI should be optimum at the maximum ground cover area at which crop canopy receives maximum solar radiation and hence, the TDMA will be high.

$$\text{LAI}=\frac{\text{Total leaf area of a plant}}{\text{Ground area occupied by the plant}}$$

3.6.2 Absolute growth rate (AGR)

Absolute growth rate AGR is the function of amount of growing material present and is influenced by the environment. It gives Absolute values of biomass between two intervals. It is mainly used for a single plant or single plant organ e.g. Leaf growth, plant weight etc.

$$\text{AGR}=\frac{h_2-h_1}{t_2-t_1}\ \text{cm day}^{-1}$$

Where, h1 and h2 are the plant height at t1 and t2 times respectively.

3.6.3 Net assimilation rate NAR

The term, NAR was used by Williams (1946). NAR is defined as dry matter increment per unit leaf area or per unit leaf dry weight per unit of time. The NAR is a measure of the average photosynthetic efficiency of leaves in a crop community.

$$\text{NAR}=\frac{(W_2-W_1)}{(t_2-t_1)}\times\frac{\log_e L_2-\log_e L_1}{(L_2-L_1)}$$

Where, W1 and W2 is dry weight of whole plant at time t1 and t2 respectively L1 and L2 are leaf weights or leaf area at t1 and t2 respectively t1-t2 are time interval in days NAR is expressed as the grams of dry weight increase per unit dry weight or area per unit time (g g $^{-1}$ day^{-1})

3.6.4 Relative Growth Rate (RGR)

The term was coined by Williams (1946). Relative Growth Rate (RGR) expresses the total plant dry weight increase in a time interval in relation to the initial weight or Dry matter increment per unit biomass per unit time or grams of dry weight increase per gram of dry weight and expressed as unit dry weight / unit dry weight / unit time (g g $^{-1}$ day^{-1})

$$\text{RGR}=\frac{\log_e W_2-\log_e W_1}{t_2-t_1}$$

Where, W1 and W2 are whole plant dry weight at t1 and t2 respectively t1 and t2 are time interval in days

3.6.5 Crop Growth Rate (CGR)

The method was suggested by Watson (1956). The CGR explains the dry matter accumulated per unit land area per unit time (g m^{-2} day^{-1})

$$CGR= \frac{(W_2-W_1)}{\rho(t_2-t_1)}$$

Where, W1 and W2 are whole plant dry weight at time $t_1 - t_2$ respectively ρ is the ground area on which W1 and W2 are recorded. CGR of a species are usually closely related to interception of solar radiation.

3.6.6 Dry matter yield (g/plot)

Five plant samples (whole plants) were collected from each treatment at different intervals at 45DAT, 55DAT and at harvest. These samples were thoroughly washed and rinsed with distilled water. The bulbs and leaves were then separated, chopped into pieces, and dried. Once air-dried, the bulb and leaf samples were further over-dried in an oven at 60°C until a constant weight was until a constant weight was reached. After reaching a constant weight, the dry weight of both the bulbs and leaves was recorded.

3.7 Biochemical parameters under waterlogging condition

The leaf samples were collected in the bags after the end of the treatment and stored in deep freezer for further analysis.

3.7.1 Chlorophyll content (mg/g fresh weight)

The chlorophyll in the leaves was estimated by using the DMSO method Hiscox and Israelstam, 1979).

Procedure

The leaves from all the sites were collected in the polythene bags and transported to the laboratory. The leaves were washed out thoroughly with distilled water. Three replicates were used for each plant. Weighted 0.05g of fresh leaf material by cutting in fragments are allowed to react with 5ml of DMSO, samples were placed in an incubator at 65°C for 4 hrs. and then after cooling to room temperature. The optical density was read at 645 nm and 663 nm wavelength on spectrophotometer. The values thus obtained were in microgram per ml of extract (solvent). Values in mg/g of fresh weight were obtained by multiplying the above values with V/W X 1000, where V is the volume of extract and W is dry weight of sample. The amount of chlorophyll content is determined using the formula given by Arnon (1949).

$$\text{Total chlorophyll content} = \frac{0.0202\ A663 + 0.00802\ A645}{1000\ X\ W} \times V$$

Were,

A_{645} = Absorbance values at 645 nm

A_{663} = Absorbance values at 663 nm

V = final volume of DMSO (ml)

W = weight of plant tissue (in grams)

3.7.2 Membrane Stability Index (MSI %)

Membrane Stability Index (MSI) was determined according to the electrolyte leakage method described by Sairam *et al.* (1997), which quantifies cellular membrane integrity based on relative electrical conductivity.

Procedure

The third leaf from each plant (both treatment and control) was collected and cut into disks of approximately 2 cm length. Leaf disks weighing 100 mg were placed in two sets of test tubes, each containing 10 mL of double-distilled water. One set of tubes was incubated at 40 °C for 30 minutes in a water bath, after which the electrical conductivity (C_1) of the solution was measured using a conductivity bridge. The second set of tubes was subsequently heated at 100 °C for 10 minutes and the electrical conductivity (C_2) was recorded.

Formula

Membrane Stability Index (MSI) was calculated using the formula:

$$MSI = [1 - (C_1/C_2)] \times 100$$

where C_1 is the conductivity after 40°C incubation and C_2 is the conductivity after 100°C incubation.

Calibration of Standard Curve

For MSI, the values for C_1 and C_2 are direct measurements from the conductivity meter, and MSI is expressed as a percentage. No external calibration standard is required; however, proper calibration of the conductivity meter should be done before measurement according to manufacturer instructions.

3.7.3 Estimation of Plant Sulphur (%) Content.

Principle:

Plant Sulphur is determined turbidimetrically after digestion of plant material. Sulphate ions react with barium chloride to form a barium sulphate suspension, the turbidity of which is measured spectrophotometrically at 440 nm.

Procedure:

The analysis begins with the digestion of 0.5 grams of finely ground, oven-dried plant material using a diacid mixture consisting of nitric acid and perchloric acid in a 9:4 ratio (HNO_3:$HClO_4$), which ensures complete oxidation of organic sulfur compounds to sulfate form5. The digest is then diluted to 100 ml with distilled water and filtered if necessary to obtain a clear extract. Five milliliters of the digested extract are pipetted into a 25 ml volumetric flask, followed by the addition of 1 gram of barium chloride crystals and 1 ml of 0.25% gum acacia solution5. The mixture is thoroughly shaken to dissolve the barium chloride completely, and the volume is made up to 25 ml with distilled water, resulting in the formation of a uniform barium sulfate suspension. The turbidity develops within 5-30 minutes and is measured at 440 nm using a spectrophotometer. A standard curve is prepared using known concentrations of the standard sulfur solution (typically 0, 1, 2, 4, 10, and 20 ppm) treated identically to the samples, and the sulfur concentration in the plant sample is determined by comparing the sample absorbance with the standard curve.

Calculation:

The Sulphur content in the plant sample is calculated using the following formula:

Sulphur (%)=

$$\frac{\text{concentration from standard curve} \times \text{Volume of extractant} \times \text{Total volume made up} \times 100}{\text{Weight of Sample} \times \text{Aliquot taken} \times 1{,}000{,}000}$$

In practice, as per the manual, the calculation can be simplified to:

Sulphur (%) = Concentration×0.05

Where "Concentration" is the value (in ppm) obtained from the standard curve.

3.7.4 Estimation of Proline ($\mu g\ g^{-1}$ FW) Content.

Principle:

Proline content in plant tissue is estimated by extracting with sulfosalicylic acid, reacting with acid ninhydrin, and measuring the chromophore formed at 520 nm. The method is based on Bates *et al.* (1973).

Procedure:

The analytical procedure begins with the homogenization of 0.5 grams of fresh plant tissue in 10 mL of 3% sulfosalicylic acid using a pre-chilled mortar and pestle to prevent enzymatic degradation of proline. The homogenate is then centrifuged at 10,000 rpm for 10 minutes at 4°C to separate cellular debris and obtain a clear supernatant containing the extracted proline. Two milliliters of the supernatant are transferred to a test tube and mixed with 2 mL of acid ninhydrin reagent and 2 mL of glacial acetic acid to create the reaction mixture. The mixture is incubated in a boiling water bath at 100°C for exactly one hour to allow complete chromophore formation, during which the characteristic red color develops. After cooling the tubes to room temperature, 4 mL of toluene is added, and the mixture is vortexed vigorously for 2 minutes to extract the chromophore into the organic phase. The toluene layer, which contains the proline-ninhydrin complex, is carefully separated and its absorbance measured at 520 nm using a spectrophotometer against a toluene blank. A standard curve is constructed using known concentrations of proline (0, 10, 20, 40, 60, 80, and 100 µg/mL) treated identically to the samples.

Calculation:

The proline content is calculated as follows:

$$\text{Proline } (\mu g\ g^{-1}\ FW) = \frac{\mu g \text{ proline (from standard curve)}}{\text{Fresh weight of sample (g)}}$$

3.7.5 Estimation of pyruvic acid (µmol/g)

Pyruvic acid or pyruvate is an important metabolic intermediate in onion bulbs as it is being directly correlated with its pungency. The spectrophotometric assay was performed for estimating pyruvic acid from onion bulb as per given by Randle and Bussard (1993).

Procedure

1 g fresh onion bulb sample was ground with 1ml of distilled water. Then the extract was filtered and collected, allowed it to stand at room temperature then got clear extract. About 0.5 ml was taken for further use, 1.5ml of 5% TCA was added and vortex vigorously. 18 ml of distilled water was added to it and again mixed it properly by vortexing. 1 ml from the above solution was taken then 1 ml water and 1 ml DNPH was added to it. The test tube was placed in water bath at temperature 37^0C for 10 minutes. Then 5 ml of 0.6 N NaOH was added and the absorbance was read at 420 nm using spectrophotometer.

The pyruvic is calculated as follows:

$$\text{Pyruvic acid } (\mu mol\ g^{-1}) = \frac{\text{Reading from standard curve} \times \text{Dilution factor}}{\text{weight of sample (g)}}$$

Calibration of standard curve

In the set of test tubes standard solution of sodium pyruvate was pipette as 0, 0.1, 0.2, 0.3, 0.4 and 1 ml having corresponding sodium pyruvate concentration of 0, 11, 22, 33, 44 and 100 µg/ml. The volume was made to 1 ml with distilled water and the color was developed. The absorbance was read at 420 nm and standard curve was prepared by plotting absorbance *V/s* concentration of the standard sodium pyruvate. The pyruvic acid measured is expressed in term of µmol of sodium pyruvate equivalent per gram of fresh weight sample.

3.7.6 Estimation of Antioxidant activity (mg/g)

The antioxidant activity is determined by Ferric Reducing Antioxidant Power (FRAP) Assay method described by Benzie and Strain (1996). The ability to reduce ferric ions was measured using the method.

Procedure

1g of sample was grind in 10ml of 80% methanol and kept it at 4^0C for 24 hours. Then centrifuged it at 10000 rpm for 20 minutes and the clear supernatant was collected. FRAP reagent was prepared freshly by mixing 25ml of 300 mM solution. Above solution was mixed well and incubated at 38^0C by kept it in water bath 37^0C temperature for 10 minutes. Then the reaction mixture was made of 3 ml by mixing, 150 µL extracted in 2850 µL FRAP reagent and allowed it to stand in dark for 30 minutes. The absorbance was read at 593 nm. The working standard was prepared of ascorbic acid concentrations (20 µg/ml). The antioxidant capacity based on the ability to reduce ferric ions of sample was calculated from the linear calibration curve.

The total antioxidant is calculated as follows:

$$\text{Total antioxidant } (\mu\text{mol AAEAn g}^{-1}\text{ FW}) = \frac{(\text{Sample absorbance - Blank absorbance})}{\text{Slope of standard curve}}$$

Calibration of standard curve

In the set of test tubes standard solution of ascorbic acid was pipette as 0, 0.01, 0.02, 0.03, 0.04 and 0.05 ml having corresponding ascorbic acid concentration of 0, 20, 40, 60, 80 and 100 µg/ml. The volume was made to 1 ml with methanol and the colour was developed. The absorbance was read at 593 nm and standard curve was prepared by plotting absorbance *V/s* concentration of the standard antioxidant activity and results were expressed as mg of ascorbic acid equivalents per gram of fresh weight sample.

3.7.7 Estimation of Protein content (%)

The total protein content in onion bulb samples was determined by the Lowry method (Lowry *et al.,* 1951), which is a widely used colorimetric assay for protein estimation based on the reduction of the Folin–Ciocalteu reagent by tyrosine and tryptophan residues in an alkaline copper-protein complex.

Procedure

One gram of fresh onion bulb tissue was ground in 5–10 mL cold 0.1 M sodium phosphate buffer (pH 7.0) using a mortar and pestle. The homogenate was centrifuged at 6000 rpm for 8 minutes at 4 °C to obtain a clear supernatant. Protein standards were prepared by diluting bovine serum albumin (BSA) stock (1 mg/mL) to obtain working solutions of 0, 40, 80, 120, 160, and 200 µg per assay tube.

For each sample and standard, 0.1 mL of supernatant or standard solution was transferred to test tubes and the volume brought to 1 mL with distilled water. Five milliliters of freshly prepared alkaline copper reagent (made by mixing 50 mL of 2% sodium carbonate in 0.1 N NaOH with 1 mL of 0.5% copper sulfate in 1% potassium sodium tartrate) was added to each tube, mixed, and allowed to stand for 10 minutes at room temperature. Subsequently, 0.5 mL of Folin–Ciocalteu reagent was added rapidly, the tubes were mixed, and incubated at room temperature for 30 minutes for color development. The absorbance of the developed blue color was measured at 660 nm using a spectrophotometer against a blank.

Formula

Protein concentration (mg/g fresh weight) was calculated using the equation:

$$\text{Protein (mg/g FW)} = (\text{Concentration from the standard curve}) \times 0.065$$

where the factor accounts for assay dilutions and sample input.

Calibration of Standard Curve

A calibration curve was constructed by plotting absorbance values at 660 nm against the corresponding concentrations of BSA standards (0–200 µg). Protein content in samples was quantified by interpolating their absorbance on this standard curve and expressed as mg of BSA equivalents per gram fresh weight.

3.7.8 Total Soluble Solid (TSS) (^{0}Brix)

The TSS of bulb were taken by using refractometer (Pocket Refractometer Pal^{-1}) Bulb from each replication of genotype were separately crushed. One drop of the onion juice was extracted from onions with a manual press and analyzed. The TSS content is expressed in ^{0}Brix.

Bulb quality parameters

3.8.1 Physical Attributes

3.8.1.1 Polar diameter (mm)

The polar diameter was measured with the help vernier calipers after harvesting. The average of 5 bulbs was used to measure the polar bulb size.

Equatorial diameter (mm)

The equatorial diameter was measured with the help of vernier calipers at harvesting. Same bulb used to measure the polar bulb size were subjected to measure the equatorial bulb size. The average value is taken as equatorial bulb size.

3.9 Yield

3.9.1 Bulb yield (tones/ha)

Bulb yield in tons per hectare was calculated based on total yield obtained from each genotype.

3.10 Soil analysis

3.10.1 Soil Chemical Analysis

3.10.1.1 Soil pH measurement (1:2 Soil: Water Suspension)

Principle:

Soil pH measured potentiometrically in a 1:2 soil-to-water suspension, reflecting hydrogen ion activity. This method follows Jackson (1973).

Procedure:

For the measurement of soil pH using the 1:2 soil-to-water suspension method, 20 grams of air-dried soil, sieved to pass through a 2 mm mesh, were weighed into a 50 mL beaker. To this, 40 mL of distilled water was added, and the mixture was stirred vigorously for 5 to 10 minutes to ensure complete dispersion of soil particles. The suspension was then allowed to equilibrate for 30 minutes, with intermittent stirring during this period to stabilize the ionic activity in the solution. Prior to measurement, the pH meter was calibrated using standard buffer solutions. The electrode was then immersed in the clear supernatant of the suspension soil, and the pH value was recorded once the reading stabilized.

3.10.1.2 Soil Electrical Conductivity (EC) *(dS/m)* measurement (1:2 Soil: Water Extract)

Principle:

EC quantifies soluble salts via conductivity in a 1:2 soil-water extract, using a calibrated conductivity meter. The method adheres to Jackson (1973).

Procedure:

For the measurement of soil electrical conductivity (EC) using the 1:2 soil-to-water extract method, 10 grams of air-dried soil sieved to ≤2 mm particle size were weighed into a 50 mL beaker. To this, 40 mL of distilled water was added to achieve a 1:2 soil-to-water ratio. The mixture was stirred thoroughly to ensure complete soil dispersion and allowed to stand undisturbed for approximately 30 minutes until a clear supernatant formed. The suspension was then filtered through Whatman No. 42 filter paper to obtain a particle-free extract. Prior to measurement, the electrical conductivity meter was calibrated using a 0.01 M potassium chloride standard solution (prepared by dissolving 0.7456 g KCl in 1L distilled water, EC = 1.41 dS/m at 25°C). The conductivity of the filtrate was measured at 24°C, and results were recorded in decisiemens per meter *(dS/m)*.

3.10.2 Soil Biological activity

3.10.2.1 Soil Microbial Biomass Carbon (SMBC) (µg C g^{-1} dry soil)

Principle:

SMBC was quantified using chloroform fumigation-extraction (Jenkinson and Powlson, 1976).

Procedure:

Fresh soil samples (10 g) were fumigated with ethanol-free chloroform in a vacuum desiccator for 24 hours at 25°C to lyse microbial cells. Concurrently, non-fumigated control samples (10 g) were processed in parallel. Both fumigated and non-fumigated samples were extracted with 40 mL of 0.5 M potassium sulfate (K_2SO_4) by shaking at 200 rpm for 30 minutes. The extracts were filtered through Whatman No. 42 filter paper to obtain clear solutions. Organic carbon in the extracts was oxidized by adding potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid, followed by 30 minutes of digestion. The residual dichromate was titrated with standardized ferrous ammonium sulfate $[(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O]$ using 1,10-phenanthroline-iron (II) sulfate complex as an indicator until a color change from blue-green to reddish-brown denoted the endpoint.

Calculation: $SMBC = \frac{EC_F - EC_{NF}}{K_{EC}}$

- EC_F: Extractable C in fumigated sample (µg/g)
- EC_{NF}: Extractable C in non-fumigated sample(µg/g)
- K_{EC}: 0.25 (extraction efficiency factor)

Units: µg C g^{-1} dry soil

3.10.3 Soil enzymatic activities

3.10.3.1 Dehydrogenase Activity (µg TPF g^{-1} dry soil h^{-1})

Principle:

Dehydrogenase activity, an indicator of microbial metabolic activity, was measured via reduction of 2,3,5-triphenyltetrazolium chloride (TTC) to triphenyl formazan (TPF) Casida *et al.* (1964).

Field-moist soil (2 g) was incubated with 2 mL of TTC solution (prepared by dissolving 1 g triphenyl tetrazolium chloride in 100 mL Tri's buffer, pH-adjusted to match the soil pH) in sterile test tubes for 24 hours at 25°C. Following incubation, formazan produced by microbial dehydrogenase activity was extracted by adding 10 mL methanol to each tube and vortexing vigorously for 1 minute. The mixture was centrifuged at 10,000 rpm for 10 minutes to pellet soil particles, and the supernatant was collected. Absorbance of the clear supernatant was measured at 485 nm using a spectrophotometer against a methanol blank.

Calculation: Dehydrogenase activity= $\frac{(C_s-C_b)\times V\times 100}{W\times DM\times t}$

- C_s: Sample TPF concentration (µg/mL)
- C_b: Blank TPF concentration (µg/mL)
- V: Extract volume (mL)
- W: Soil Weight (g)
- DM: Dry matter content
- t: Incubation time (h)

Units: µg TPF g^{-1} dry soil h^{-1}

3.10.3.2 Urease Activity (µg NH_4^+-N g^{-1} soil h^{-1})

Principle:

Urease activity was quantified by ammonium-N release from urea hydrolysis Bremner and Douglas, (1971).

Procedure:

Soil urease activity was determined by incubating 5 grams of field-moist soil with 5 mL of urea solution (10 mg urea in distilled water) in sealed containers at 37°C for 5 hours. After incubation, the reaction was terminated by adding 50 mL of 2 M potassium chloride containing phenylmercuric acetate (KCl-PMA) solution to inhibit further enzymatic activity. The mixture was shaken for 1 hour and filtered through Whatman No. 42 filter paper to obtain a clear extract. For color development, 1 mL of the filtrate was mixed with 9 mL of diacetyl monoxime-thiosemicarbazone (DAM-TSC) reagent (prepared by dissolving 0.6 g diacetyl monoxime and 0.03 g thiosemicarbazone in 100 mL distilled water) and heated in a boiling water bath for 15 minutes. The resulting red chromophore was cooled to room temperature, and its absorbance was measured at 527 nm using a spectrophotometer against a reagent blank

Calculation: Urease activity= $\frac{B-A}{W \times t}$

- B: Added urea (mg)
- A: Residual urea (mg)
- W: Dry soil weight (g)
- t: Incubation time (h)

  Units: µg NH_4^+-N g^{-1} soil h^{-1}

3.10.3.3 Acid and Alkaline Phosphatase Activities (µg PNP $g^{-1}h^{-1}$)

Principle:

Phosphatase activities were determined by p-nitrophenol (PNP) release from p-nitrophenyl phosphate Tabatabai and Bremner, (1969).

3.10.3.3.1 Acid phosphatase activity:

One gram of field-moist soil was incubated with 4 mL of modified universal buffer (MUB, pH 6.5) and 1 mL of 0.05 M *p*-nitrophenyl phosphate (pNPP) substrate solution at 37°C for 1 hour. The reaction was terminated by adding 1 mL of 0.5 M calcium chloride ($CaCl_2$) and 4 mL of 0.5 M sodium hydroxide (NaOH). The mixture was centrifuged at 8,000 rpm for 5 minutes, and the supernatant was filtered. The yellow *p*-nitrophenol (PNP) released was measured spectrophotometrically at 400 nm against a reagent blank.

3.10.3.3.2 Alkaline phosphatase activity:

The procedure was identical to acid phosphatase analysis, except the MUB was adjusted to pH 11.0 using sodium hydroxide. All other steps (incubation, termination, centrifugation, and measurement) remained consistent.

Calculation: Phosphatase activity= $\frac{C \times V}{W \times t \times SW}$

- C: PNP concentration (µg/mL)
- V: Filtrate volume (mL)
- W: Soil mass (g)
- t: Incubation time (h)
- SW: Soil moisture factor

  Units: µg PNP $g^{-1}h^{-1}$

3.10.4 Soil Nutrient analysis.

3.10.4.1 Nitrogen Available (kg ha^{-1})

Principle:

Alkaline potassium permanganate is used to oxidize organic nitrogen compounds, releasing NH_3, which is distilled and trapped in boric acid and then determined by titration.

Procedure:

- Weigh 5 g of soil (<0.5 mm sieved) into Kjeldahl tube.
- Add 25 mL of 0.32% $KMnO_4$ and a pinch of Devarda's alloy.
- Distil; collect liberated NH_3 in 20 mL of 2% boric acid with indicator.
- Titrate with standard 0.02 N H_2SO_4 to a pink endpoint.

Calculation: Alkaline $KMnO_4$ N (kg ha^{-1})=(A-B) $\times 0.02 \times 0.014 \times 2.24 \times 10^6$

where A = sample titre (mL), B = blank (mL), 0.02 = normality; 0.014 = mg N equivalent to 1 mL 1N acid; 2.24 = conversion factor to kg ha^{-1}.

Units: mg N kg^{-1} dry soil or kg N ha^{-1}

3.10.4.2 Available Phosphorus (Olsen's P) (mg kg^{-1})

Principle:

Phosphorus is extracted from soil with $NaHCO_3$ (pH 8.5). The P in extract reacts with ammonium molybdate and antimony potassium tartrate in acidic medium to form a blue complex. Intensity is read at 730 nm.

Procedure:

- Shake 5 g soil with 50 mL 0.5 M $NaHCO_3$ (pH 8.5) plus charcoal for 30 min.
- Filter: pipette aliquot, develop color with reagents as guided, make volume, read at 730 nm.

Calculation: Available P (mg kg^{-1})$=\frac{\text{Reading}\times 50\times 2.24\times 10^{6}}{\text{Aliquot taken}\times\text{Weight of soil}}$

Units: mg P kg^{-1} dry soil

3.10.4.3 Available Potassium (Ammonium Acetate method) (mg kg^{-1})

Principle:

Potassium is extracted with 1N ammonium acetate; K in extract is measured by flame photometry.

Procedure:

- Shake 5 g soil with 25 mL of 1N ammonium acetate for 5 min.
- Filter and read K in the filtrate by flame photometer.

Calculation: Available K (mg kg^{-1})$=\frac{\text{Concentration}\times\text{Total volume}\times 100}{\text{Aliquot}\times\text{Soil weight}}$

Units: mg K kg^{-1} dry soil

3.10.4.4 Available Sulphur (mg kg^{-1})

Principle:

Sulphur is extracted by 0.15% $CaCl_2$ and forms a colloidal suspension with $BaCl_2$, read calorimetrically.

Procedure:

- Shake 5 g soil with 25 mL 0.15% $CaCl_2$ for 30 min, filter.

- Take 10 mL aliquot, add $BaCl_2$ and gum acacia, make to volume, read at 440 nm.

Calculation: Available S (mg kg^{-1})=$\frac{\text{Concentration}\times 25}{\text{Soil weight}}$

Units: mg S kg^{-1} dry soil

3.10.4.5 Available Boron (mg kg^{-1})

Principle:

Boron is extracted with hot water/azomethine-H colorimetry, color intensity measured at 420 nm.

Procedure:

- Boil 20 g soil with 40 mL distilled water and 0.5 g charcoal for 5 min, filter.
- Take aliquot, add buffer and azomethine-H, wait 30 min, read absorbance.

Calculation: Available B (mg kg^{-1})=A×2

where A = ug of B from calibration curve.

Units: mg B kg^{-1} dry soil

3.10.4.6 Available Micronutrients (DTPA-extractable Fe, Mn, Zn, Cu) (mg kg^{-1})

Principle:

DTPA solution extracts Fe, Mn, Zn, and Cu, which are then measured by atomic absorption spectrophotometer.

Procedure:

- Shake 20 g air-dried soil with 40 mL DTPA extracting solution for 2 hours, filter.
- Measure content in filtrate by AAS.

Calculation: Available micronutrient (mg kg^{-1})=$\frac{\text{AAS Reading}\times 40}{20}$

Units: mg element kg^{-1} dry soil

3.10.4.7 Available Calcium and Magnesium (meq 100 g^{-1})

Principle:

Extracted with 1N ammonium acetate and determined by titration with standardized EDTA.

Procedure:

- Extract 5 g soil with ammonium acetate, filter.
- Titrate aliquot with EDTA (calcium: calcon indicator; magnesium: eriochrome black T).

Calculation: Ca (meq/100g soil) = $\frac{\text{N of EDTA} \times \text{Vol. EDTA consumed} \times 25 \times 1000}{5 \times \text{Aliquot} \times 1000}$

$$Mg = (Ca + Mg) - Ca$$

Units: meq 100 g^{-1} dry soil

3.11 Economics

3.11.1 Cost of cultivation (Rs. ha^{-1})

The COC for the cropping system in present investigation was determined by summing up all expenses incurred. This included the cost of input, expenses for mechanical operations, and labour charges. The cost of cultivation was calculated and recorded for each treatment separately.

3.11.2 Gross return (Rs. ha^{-1}) The bulb and haulm yields (kg ha^{-1}) of onion were first expressed in monetary terms (Rs) using the prevailing market prices, and treatment-wise gross returns per hectare were calculated accordingly.

3.11.3 Net return (Rs. ha^{-1}) Net monetary returns were determined by deducting cultivation cost from gross monetary returns.

3.11.4 Benefit: cost ratio: The Benefit-Cost (B:C) ratio is a measure of profitability, computed by dividing the GR by COC for a given treatment or cropping system. It indicates the economic efficiency of the investment.

$$\text{B:C ratio} = \frac{\text{Total income from crop (GR) (Rs. ha}^{-1}\text{)}}{\text{Overall input cost (COC) (Rs. ha}^{-1}\text{)}}$$

3.11.5 Statistical Analysis

Statistical analysis was performed using methods for split-plot design outlined by Gomez and

Gomez (1984). Total variance (σ^2) and degrees of freedom (n-1) were partitioned among various sources. The treatment variance was compared with the error variance to compute the F-value, which was used to test significance at the 5% level. Treatment effects were summarized in tables showing mean values for varying parameters along with the corresponding standard error (SE (m) ±) and critical difference (CD at 5% level).

3.11.6 Statistical Analysis of Soil Properties

For soil analysis data, the effects of the waterlogging treatment were evaluated using a student's t-test to compare the mean values of the waterlogging and control groups for each measured parameter. Composite soil samples were analyzed in triplicate for both the waterlogging and control treatments, and the resulting data for soil available nutrients, biological properties, and enzymatic activities were tested for statistical differences. The significance of the observed differences between the two treatment groups was determined at a 5% probability level, where a p-value of ≤ 0.05 was considered statistically significant. This approach allowed for a direct assessment of the impact of waterlogging on soil chemical and biological health indicators.

Table 6. Skeleton of analysis of variance (ANOVA) for the split-plot design

Replication (R)	$(r - 1)$	2
Main plot – Waterlogging (W)	$(a - 1)$	1
Error (a)	$(r - 1)(a - 1)$	2
Sub plot – Genotype (G)	$(b - 1)$	7
W × G interaction	$(a - 1)(b - 1)$	7
Error (b)	$a(r - 1)(b - 1)$	28
Total	$(rab - 1)$	**47**

where r *= 3 replications,* a *= 2 main-plot treatments (waterlogging and control), and* b *= 8 sub-plot genotypes. The treatment mean square was tested against the respective error mean square to compute the F-value, and significance was judged at the 5% level.*

Table 7. Skeleton of analysis of variance (ANOVA) for the soil property data (waterlogging vs. control, analyzed in triplicate)

Treatment (Waterlogging vs. Control)	$(t - 1)$	1
Error	$t(r - 1)$	4
Total	$(tr - 1)$	**5**

where t *= 2 treatments (waterlogging and control) and* r *= 3 (composite samples in triplicate). For two treatment groups this one-way analysis is equivalent to the independent-samples Student's t-test, since* $F(1, 4) = t^2(4)$*; a difference was considered significant at* $p \leq 0.05$.

CHAPTER IV

RESULT AND DISCUSSION

This chapter presents the results of a field investigation conducted to evaluate the morpho-physiological, biochemical, and yield responses of diverse onion genotypes to waterlogging stress under split-plot design at the ICAR–Directorate of Onion and Garlic Research, Pune, Maharashtra, India, during the late *kharif* seasons of 2023 and 2024. The experimental treatments included short-term waterlogging imposed at 45–55 days after transplanting (DAT) compared to scheduled irrigation control, allowing for a robust assessment of genotype-specific tolerance under hypoxic conditions in replicated plots.

The chapter provides detailed statistical analysis of key plant traits including plant height, leaf area, number of leaves, neck thickness, dry matter yield, and bulb dimensions, in addition to indices of physiological resilience such as total chlorophyll content and membrane stability index (MSI) at critical crop stages. Yield and quality parameters (bulb weight, equatorial and polar diameter, pyruvic acid, total soluble solids) and soil physicochemical properties (pH, EC, available nutrients) were measured to clarify genotype-by-environment interactions. Data are interpreted in light of relevant theoretical frameworks and previous research, with a focus on statistical significance, genotype ranking, and discussion of stress mechanisms, resilience traits, and implications for breeding and management in waterlogging-prone onion production systems; data were analyzed for main effects and genotype-by-treatment interactions with appropriate standard errors and critical differences at 5%.

4.1: Morphological Parameters.

4.1.1: Plant height (cm)

Table 6: Effect of waterlogging on plant height (cm) of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT		45 DAT		55 DAT		75 DAT		At harvest	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	29.5	34.0	36.4	40.9	26.8	30.6	33.8	38.1	37.4	41.7
Control	29.1	33.6	34.6	39.1	38.2	41.9	50.5	54.5	52.2	56.2
SEm±	0.1	0.4	0.1	0.7	0.3	0.3	0.1	0.2	0.2	0.4
CD (P ≤ 0.05)	**NS**	**NS**	**0.8**	**NS**	**1.6**	**1.8**	**0.6**	**1.3**	**1.2**	**2.1**
(Genotype)										
Acc. 1666	29.4	33.9	34.6	39.1	36.1	41.3	45.6	50.9	47.8	53.1
Acc.1630	29.3	33.8	35.7	40.2	33.9	38.5	44.1	48.7	46.9	51.6
W 355	30.1	34.6	35.9	40.4	34.3	38.3	43.4	47.4	46.5	50.5
Bhima Dark Red	30.2	34.7	36.1	40.5	34.1	38.1	44.5	48.7	47.9	52.1
Bhima Red	29.6	34.1	36.3	40.8	30.3	34.8	38.7	45.7	41.7	47.7
Bhima Raj	29.7	34.2	35.9	40.4	32.5	35.1	41.3	43.8	43.8	46.3
Bhima Shubra	27.4	31.9	33.6	38.1	29.3	32.1	38.7	41.9	41.2	44.1
Bhima Super	28.4	32.9	36.1	40.6	29.2	32	40.8	43.1	42.7	45.4
SEm±	0.6	0.7	0.8	2.0	0.5	0.7	0.6	0.7	0.5	0.6
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**1.5**	**1.9**	**1.9**	**2.1**	**1.4**	**1.7**
Interaction (Treatment*Genotype)										
Sem ±	0.9	1.0	1.1	1.5	0.7	0.9	0.9	1.1	0.7	0.8
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**2.2**	**2.7**	**2.5**	**3.0**	**1.9**	**2.3**
Interaction (Genotype*Treatment)										
Sem ±	0.9	1.0	1.0	1.5	0.7	0.9	0.8	1.0	0.7	0.8
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**2.5**	**2.9**	**2.4**	**3.0**	**2.1**	**2.9**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 6.1: Interaction effect between waterlogging treatment and genotypes on plant height (cm) at different growth stages during 2023.

Plant height (cm) 55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	32.0	40.1	36.0
Acc.1630	28.4	39.4	33.9
W-355	28.8	39.8	34.3
Bhima Dark Red	29.7	38.4	34.1
Bhima Red	24.5	36.1	30.3
Bhima Raj	24.9	40.0	32.5
Bhima Shubra	22.6	36.0	29.3
Bhima Super	23.1	35.4	29.2
Mean	26.8	38.2	
Interaction (Treatment*Genotype)			
Sem ±	0.7		
CD (P ≤ 0.05)	**2.2**		
Interaction (Genotype*Treatment)			
Sem ±	0.7		
CD (P ≤ 0.05)	**2.5**		

Plant height (cm) 75 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	40.3	51.0	45.6
Acc.1630	36.6	51.6	44.1
W-355	35.5	51.3	43.4
Bhima Dark Red	37.8	51.3	44.5
Bhima Red	29.1	48.2	38.7
Bhima Raj	32.1	50.5	41.3
Bhima Shubra	28.9	48.5	38.7
Bhima Super	30.4	51.3	40.8
Mean	33.8	50.5	
Interaction (Treatment*Genotype)			
Sem ±	0.9		
CD (P ≤ 0.05)	**2.5**		
Interaction (Genotype*Treatment)			
Sem ±	0.8		
CD (P ≤ 0.05)	**2.4**		

Plant height (cm) at harvest (2023)			
	W. L	**Control**	**Mean**
Acc.1666	43.4	52.3	47.8
Acc.1630	40.8	52.9	46.9
W-355	40.3	52.6	46.5
Bhima Dark Red	42.2	53.6	47.9
Bhima Red	31.8	51.6	41.7
Bhima Raj	34.7	52.9	43.8
Bhima Shubra	32.6	49.9	41.2
Bhima Super	33.4	52.1	42.7
Mean	37.4	52.2	
Interaction (Treatment*Genotype)			
Sem ±	0.7		
CD (P ≤ 0.05)	**2.0**		
Interaction (Genotype*Treatment)			
Sem ±	0.7		
CD (P ≤ 0.05)	**2.1**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Table 6.2: Interaction effect between waterlogging treatment and genotypes on plant height (cm) at different growth stages during 2024.

Plant height (cm) 55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	39.0	43.6	41.3
Acc.1630	33.7	43.4	38.5
W-355	32.8	43.8	38.3
Bhima Dark Red	34.4	41.9	38.1
Bhima Red	28.5	41.1	34.8
Bhima Raj	26.9	43.0	35.0
Bhima Shubra	25.1	39.0	32.1
Bhima Super	24.6	39.4	32.0
Mean	30.6	41.9	
Interaction (Treatment*Genotype)			
Sem ±	0.9		
CD (P ≤ 0.05)	**2.7**		
Interaction (Genotype*Treatment)			
Sem ±	0.9		
CD (P ≤ 0.05)	**2.9**		

Plant height (cm) 75 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	47.3	54.5	50.9
Acc.1630	41.8	55.6	48.7
W-355	39.5	55.3	47.4
Bhima Dark Red	42.6	54.8	48.7
Bhima Red	36.1	55.2	45.7
Bhima Raj	34.1	53.5	43.8
Bhima Shubra	32.4	51.5	41.9
Bhima Super	30.9	55.3	43.1
Mean	38.1	54.5	
Interaction (Treatment*Genotype)			
Sem ±	1.0		
CD (P ≤ 0.05)	**3.0**		
Interaction (Genotype*Treatment)			
Sem ±	1.0		
CD (P ≤ 0.05)	**3.0**		

Plant height (cm) at harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	50.4	55.8	53.1
Acc.1630	46.2	56.9	51.6
W-355	44.3	56.6	50.5
Bhima Dark Red	46.8	57.1	52.0
Bhima Red	38.8	56.6	47.7
Bhima Raj	36.7	55.9	46.3
Bhima Shubra	35.4	52.9	44.1
Bhima Super	34.6	56.1	45.4
Mean	41.7	56.0	
Interaction (Treatment*Genotype)			
Sem ±	0.8		
CD (P ≤ 0.05)	**2.3**		
Interaction (Genotype*Treatment)			
Sem ±	0.8		
CD (P ≤ 0.05)	**2.9**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.1.1 (a) Effect of waterlogging treatment on plant height (cm) of onion genotypes at different growth stages during 2023 and 2024.

The plant height data revealed non-significant differences at 30 and 45 DAT across waterlogging treatments, genotypes, and their interactions in both years. However, significant differences emerged from 55 DAT onwards through harvest, where the control treatment consistently produced taller plants compared to waterlogging stress conditions. Among the genotypes, Acc.1666 exhibited the highest plant height at 55 DAT (36.0 cm in 2023, 41.3 cm in 2024), 75 DAT (45.6 cm in 2023, 50.9 cm in 2024), and at harvest (47.8 cm in 2023, 53.1 cm in 2024), demonstrating superior performance under both stress and non-stress conditions (Table 6).Conversely, Bhima Shubra recorded the lowest plant height across all significant measurement stages, with values of 29.3 cm and 32.1 cm at 55 DAT, 38.7 cm and 41.9 cm at 75 DAT, and 41.2 cm and 44.1 cm at harvest during 2023 and 2024, respectively, indicating greater susceptibility to waterlogging stress and overall reduced growth potential. The sharp decline in plant height under waterlogged conditions is explained by oxygen deprivation in the root zone, which disrupts aerobic respiration, reduces energy (ATP) production, and impairs nutrient uptake (Zhang *et al.,* 2025). This leads to reduced cell division and elongation, ultimately stunting plant growth (Kavanová *et al.,* 2006). Notably, genotypes like Acc.1666, W-355, and Acc.1630 consistently maintained higher plant heights after waterlogging, suggesting they possess physiological adaptations such as enhanced root aeration or more robust antioxidant systems that mitigate the adverse effects of hypoxic stress (Gedam *et al.,* 2022). In contrast, genotypes like B. Shubra and B. Super, which showed the lowest plant heights, are likely more susceptible due to less effective stress-response mechanisms (Gedam *et al.,* 2023).

4.1.1 (b) Interaction effect between waterlogging treatment and genotypes on plant height (cm) at different growth stages during 2023-2024.

The interaction between genotype and treatment was highly significant after waterlogging (from 55 DAT onwards). The interaction effects of waterlogging treatment on plant height across different growth stages revealed significant genotypic variations in both cropping seasons (Table 6.1 and 6.2). At 55 DAT in 2023, Acc.1666 under control conditions recorded the highest plant height (40.1 cm), statistically at par with Bhima Raj (40.0 cm), Acc.1630 (39.4 cm), and W-355 (39.8 cm) under control, while Bhima Shubra under waterlogging stress exhibited the lowest height

(22.6 cm). At 75 DAT in 2023, the maximum plant height was observed in Acc.1630 under control (51.6 cm), at par with W-355 (51.3 cm), Bhima Dark Red (51.3 cm), Bhima Super (51.3 cm), Acc.1666 (51.0 cm), and Bhima Raj (50.5 cm) under control conditions, whereas Bhima Shubra under waterlogging recorded the minimum height (28.9 cm). At harvest in 2023, Bhima Dark Red under control produced the tallest plants (53.6 cm), statistically at par with Bhima Raj (52.9 cm), Acc.1630 (52.9 cm), W-355 (52.6 cm), Acc.1666 (52.3 cm), Bhima Super (52.1 cm), and Bhima Red (51.6 cm) under control, while Bhima Red under waterlogging stress showed the lowest height (31.8 cm). In 2024, at 55 DAT, Acc.1666 under control attained the highest plant height (43.6 cm), at par with W-355 (43.8 cm), Acc.1630 (43.4 cm), and Bhima Raj (43.0 cm) under control, with Bhima Super under waterlogging recording the lowest (24.6 cm). At 75 DAT in 2024, Acc.1630 under control exhibited maximum height (55.6 cm), statistically at par with W-355 (55.3 cm), Bhima Super (55.3 cm), Bhima Red (55.2 cm), Bhima Dark Red (54.8 cm), Acc.1666 (54.5 cm), and Bhima Raj (53.5 cm) under control, while Bhima Super under waterlogging showed minimum height (30.9 cm). At harvest in 2024, Bhima Dark Red under control recorded the highest plant height (57.1 cm), at par with Acc.1630 (56.9 cm), W-355 (56.6 cm), Bhima Red (56.6 cm), Bhima Super (56.1 cm), Acc.1666 (55.8 cm), and Bhima Raj (55.9 cm) under control conditions, whereas Bhima Super under waterlogging stress registered the lowest height (34.6 cm).

The observed non-significant differences in plant height during early growth stages (30 and 45 DAT) suggest that waterlogging stress had minimal impact on initial seedling establishment, likely due to shorter exposure duration and the inherent resilience of young plants (Ghodke *et al.,* 2018). However, the significant reduction in plant height under waterlogging conditions from 55 DAT onwards through harvest demonstrates the cumulative detrimental effects of prolonged anaerobic stress on vegetative growth, which restricts root respiration, nutrient uptake, and overall metabolic activity (Wakchaure *et al.,* 2023). The superior performance of Acc.1666 under both stress and non-stress conditions indicates its genetic potential for maintaining growth vigor, possibly through enhanced oxygen transport mechanisms or efficient osmotic adjustment, making it a promising candidate for waterlogging-prone areas (Gedam *et al.,* 2022). Conversely, the consistently poor performance of genotypes like Bhima Shubra, Bhima Red, and Bhima Super under waterlogging stress highlights their susceptibility to hypoxic conditions, emphasizing the critical need for genotype-specific management strategies or breeding interventions to improve waterlogging tolerance in onion cultivation. (Dubey *et al.,* 2021).

4.1.2: No. of Leaves

Table 7: Effect of waterlogging treatment on number of leaves of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT		45 DAT		55 DAT		75 DAT		At harvest	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	3.93	4.13	6.89	7.09	3.83	4.63	4.72	5.51	5.86	6.65
Control	3.94	4.14	6.91	7.11	7.76	8.68	7.86	8.78	7.92	8.77
SEm±	0.07	0.06	0.02	0.02	0.04	0.05	0.01	0.05	0.04	0.05
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.24**	**0.33**	**0.04**	**0.32**	**0.27**	**0.30**
(Genotype)										
Acc. 1666	3.63	3.83	6.64	6.84	6.63	8.43	7.06	8.86	6.54	8.34
Acc.1630	4.08	4.28	6.98	7.18	5.62	7.12	6.58	7.48	6.39	7.29
W 355	3.90	4.10	6.93	7.13	6.18	6.68	6.45	7.25	6.33	7.13
Bhima Dark Red	4.18	4.38	6.71	6.91	6.34	7.54	6.66	8.16	6.21	7.71
Bhima Red	4.01	4.21	7.20	7.40	5.01	6.21	5.75	6.87	7.42	8.37
Bhima Raj	3.59	3.79	6.59	6.79	5.39	5.61	5.84	5.85	7.33	7.55
Bhima Shubra	4.12	4.32	7.04	7.24	5.58	5.76	5.86	6.28	7.48	7.70
Bhima Super	3.95	4.15	7.13	7.33	5.60	5.85	6.12	6.43	7.42	7.63
SEm±	0.14	0.14	0.15	0.15	0.13	0.14	0.06	0.08	0.11	0.15
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**0.43**	**0.38**	**0.39**	**0.16**	**0.24**	**0.31**	**0.43**
Interaction (Treatment*Genotype)										
Sem ±	0.20	0.20	0.21	0.21	0.18	0.19	0.08	0.12	0.15	0.21
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.54**	**0.55**	**0.23**	**0.34**	**0.44**	**0.61**
Interaction (Genotype*Treatment)										
Sem ±	0.20	0.20	0.20	0.20	0.18	0.19	0.07	0.12	0.15	0.20
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.54**	**0.59**	**0.22**	**0.43**	**0.47**	**0.63**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 7.1: Interaction effect between waterlogging treatment and genotypes on number of leaves at different growth stages during 2023.

No. of leaves 55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	5.07	8.2	6.63
Acc.1630	3.42	7.82	5.62
W 355	4.72	7.65	6.18
Bhima Dark Red	5.02	7.67	6.34
Bhima Red	3.2	6.82	5.01
Bhima Raj	3.17	7.62	5.39
Bhima Shubra	3.08	8.08	5.58
Bhima Super	3	8.2	5.6
Mean	3.83	7.76	
Interaction (Treatment*Genotype)			
SE (m) ±	0.18		
CD at 5%	**0.54**		
Interaction (Genotype*Treatment)			
Sem ±	0.18		
CD (P ≤ 0.05)	**0.54**		

No. of leaves 75 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	6.57	7.55	7.06
Acc.1630	5.10	8.07	6.58
W 355	4.97	7.93	6.45
Bhima Dark Red	5.17	8.15	6.66
Bhima Red	4.23	7.27	5.75
Bhima Raj	4.07	7.62	5.84
Bhima Shubra	3.63	8.08	5.86
Bhima Super	4.03	8.2	6.12
Mean	4.72	7.86	
Interaction (Treatment*Genotype)			
SE (m) ±	0.08		
CD at 5%	**0.23**		
Interaction (Genotype*Treatment)			
Sem ±	0.07		
CD (P ≤ 0.05)	**0.22**		

No. of leaves at harvest (2023)			
	W. L	**Control**	**Mean**
Acc.1666	5.1	7.98	6.54
Acc.1630	5.00	7.78	6.39
W 355	4.77	7.88	6.33
Bhima Dark Red	4.4	8.02	6.21
Bhima Red	7.07	7.77	7.42
Bhima Raj	7.03	7.62	7.33
Bhima Shubra	6.87	8.08	7.48
Bhima Super	6.63	8.2	7.42
Mean	5.86	7.92	
Interaction (Treatment*Genotype)			
SE (m) ±	0.15		
CD at 5%	**0.44**		
Interaction (Genotype*Treatment)			
Sem ±	0.15		
CD (P ≤ 0.05)	**0.47**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Table 7.2: Interaction effect between waterlogging treatment and genotypes on number of leaves at different growth stages during 2024.

No. of leaves 55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	6.87	10.00	8.43
Acc.1630	5.52	8.72	7.12
W 355	4.92	8.45	6.68
Bhima Dark Red	5.92	9.17	7.54
Bhima Red	3.90	8.52	6.21
Bhima Raj	3.39	7.84	5.61
Bhima Shubra	3.22	8.30	5.76
Bhima Super	3.29	8.41	5.85
Mean	4.63	8.68	
Interaction (Treatment*Genotype)			
SE (m) ±	0.19		
CD at 5%	**0.55**		
Interaction (Genotype*Treatment)			
SE (m) ±	0.19		
CD at 5%	**0.59**		

No. of leaves 75 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	8.37	9.35	8.86
Acc.1630	6.00	8.97	7.48
W 355	5.77	8.73	7.25
Bhima Dark Red	6.67	9.65	8.16
Bhima Red	4.77	8.97	6.87
Bhima Raj	3.85	7.84	5.85
Bhima Shubra	4.25	8.30	6.28
Bhima Super	4.44	8.41	6.43
Mean	5.51	8.78	
Interaction (Treatment*Genotype)			
SE (m) ±	0.12		
CD at 5%	**0.34**		
Interaction (Genotype*Treatment)			
SE (m) ±	0.12		
CD at 5%	**0.43**		

No. of leaves at harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	6.90	9.78	8.34
Acc.1630	5.90	8.68	7.29
W 355	5.57	8.68	7.13
Bhima Dark Red	5.90	9.52	7.71
Bhima Red	7.77	8.97	8.37
Bhima Raj	7.25	7.84	7.55
Bhima Shubra	7.09	8.30	7.70
Bhima Super	6.84	8.41	7.63
Mean	6.65	8.77	
Interaction (Treatment*Genotype)			
SE (m) ±	0.21		
CD at 5%	**0.61**		
Interaction (Genotype*Treatment)			
SE (m) ±	0.21		
CD at 5%	**0.63**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.1.2 (a) Effect of waterlogging treatment on number of leaves of onion genotypes at different growth stages during 2023 and 2024.

Data on the number of leaves per plant was found to be non-significant at 30 and 45 DAT for main waterlogging treatments, genotypes, and their interaction (Table 7). However, significant differences were recorded from 55 DAT through harvest, where the control treatment consistently produced a higher number of leaves compared to the waterlogging treatment. Among the genotypes, Acc.1666 consistently recorded the highest number of leaves at 55 DAT (6.63 in 2023, 8.43 in 2024) and 75 DAT (7.06 in 2023, 8.86 in 2024). At harvest, the highest leaf count was observed in Bhima Shubra (7.48) in 2023 and Bhima Red (8.37) in 2024. Conversely, Bhima Red showed the lowest leaf count at 55 DAT (5.01) and 75 DAT (5.75) in 2023, while Bhima Raj recorded the lowest numbers at 55 DAT (5.61) and 75 DAT (5.85) in 2024 (Table 7), indicating their greater susceptibility to waterlogging stress.

The persistence of non-significant differences in leaf number during the early stages (30 and 45 DAT) indicates that initial vegetative growth of onion genotypes is resilient to short-term waterlogging (Ghodke *et al.,* 2018). From 55 DAT onward, the significantly higher leaf counts under control conditions reflect the cumulative negative impact of prolonged waterlogging on leaf initiation and expansion (Wakchaure *et al.,* 2023). The superior leaf production by Acc.1666 demonstrates its robust adaptive mechanisms, whereas genotypes such as Bhima Red and Bhima Raj exhibited pronounced susceptibility, underscoring the need for targeted breeding efforts to enhance waterlogging tolerance in onion (Dubey *et al.,* 2021).

4.1.2 (b) Interaction effect between waterlogging treatment and genotypes on number of leaves at different growth stages during 2023 2024.

At 55 DAT in 2023 (Table 7.1), the highest leaf number was recorded under control by Acc.1666 and Bhima Super (8.20), values statistically at par also with Bhima Shubra (8.08), Acc. 1630 (7.82), and Bhima Dark Red (7.67), while Bhima Super under waterlogging stress exhibited the lowest count (3.00). At 75 DAT in 2023, Bhima Super under control again produced the most leaves (8.20), at par with Bhima Dark Red (8.15) and Bhima Shubra (8.08), whereas Bhima Shubra under waterlogging had the fewest leaves (3.63). At harvest in 2023, control Bhima Super led with 8.20 leaves (at par with all other control treatments ≥7.76), and Bhima Dark Red under waterlogging showed the lowest leaf number (4.40). In 2024 at 55 DAT (Table 7.2), Acc.1666 under control achieved the highest count (10.00) with no other genotype within the 0.55 CD threshold, while Bhima Shubra under waterlogging recorded the fewest leaves (3.22). At 75 DAT in 2024, Bhima Dark Red under control was highest (9.65) and Bhima Raj under waterlogging the lowest (3.85). At harvest in 2024, Bhima Dark Red under control again topped the leaf count (9.52), statistically at par with Acc.1666 (9.78) and Bhima Red (8.97), whereas Bhima Dark Red under waterlogging stress had the minimum number of leaves (5.90).

The significant interaction effect highlights that onion genotypes possess distinct genetic responses to waterlogging stress. While genotypes like Acc.1666 and Bhima Super demonstrated high leaf production potential under ideal control conditions, their performance under waterlogging revealed their true tolerance levels (Pawar *et al.,* 2025). The severe reduction in leaf number for susceptible genotypes, such as Bhima Super and Bhima Shubra, under stress is indicative of physiological damage, including impaired nutrient uptake and induced leaf senescence (Dubey *et al.,* 2020). This differential response is attributed to genetic variations in coping mechanisms, such as the ability to develop aerenchyma tissue or maintain metabolic function under hypoxia (Pawar *et al.,* 2025). These findings are crucial for identifying genuinely resilient genotypes like Acc.1666 for breeding programs aimed at developing climate-resilient onion cultivars for waterlogging-prone regions.

4.1.3: Leaf area (cm^2)

Table 8: Effect of waterlogging treatment on leaf area (cm^2) of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT		**45 DAT**		**55 DAT**		**75 DAT**		**At harvest**	
(Waterlogging Treatment)	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Waterlogging	16.45	19.04	19.53	24.15	20.86	22.93	23.41	24.11	18.83	17.17
Control	17.39	18.98	19.89	21.6	26.58	28.89	26.57	28.89	22.49	20.96
SEm±	0.12	0.19	0.45	0.45	0.05	0.07	0.43	0.57	0.20	0.21
CD ($P \leq 0.05$)	**0.76**	**NS**	**NS**	**NS**	**0.3**	**0.45**	**2.63**	**3.48**	**1.22**	**1.27**
(Genotype)										
Acc. 1666	16.64	19.14	19.74	23.22	26.08	28.31	27.46	28.31	21.44	20.34
Acc.1630	17.05	18.85	19.36	22.16	25.17	26.70	26.98	25.38	21.25	20.16
W 355	17.17	19.27	19.98	22.83	24.97	26.75	26.01	25.36	19.46	18.37
Bhima Dark Red	17.31	19.31	19.72	23.42	24.86	26.64	27.52	27.17	20.66	19.56
Bhima Red	16.57	18.07	19.27	21.83	20.22	24.45	21.42	27.50	17.93	18.83
Bhima Raj	16.60	18.50	20.55	23.19	23.11	24.74	25.50	27.13	21.74	18.64
Bhima Shubra	17.23	19.63	19.83	23.46	22.36	24.99	22.88	26.41	21.42	18.32
Bhima Super	16.81	19.31	19.24	22.91	22.96	24.70	22.18	24.71	21.38	18.29
SEm±	0.45	0.47	0.52	0.60	0.54	0.61	0.62	0.71	0.52	0.52
CD ($P \leq 0.05$)	**NS**	**NS**	**NS**	**NS**	**1.57**	**1.77**	**1.81**	**2.05**	**1.52**	**1.52**
Interaction (Treatment*Genotype)										
Sem ±	0.63	0.67	0.73	0.85	0.77	0.86	0.88	1.00	0.74	0.74
CD ($P \leq 0.05$)	**NS**	**NS**	**NS**	**NS**	**2.22**	**2.53**	**2.55**	**3.00**	**NS**	**NS**
Interaction (Genotype*Treatment)										
Sem ±	**0.61**	**0.65**	**0.82**	**0.91**	**0.72**	**0.81**	**0.93**	**1.10**	**0.72**	**0.72**
CD ($P \leq 0.05$)	**NS**	**NS**	**NS**	**NS**	**2.09**	**2.37**	**3.33**	**3.29**	**NS**	**NS**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm±: Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 8.1: Interaction effect between waterlogging treatment and genotypes on leaf area (cm²) at different growth stages during 2023 and 2024.

Leaf area (cm²) 55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	24.26	27.9	26.08
Acc.1630	23.38	26.97	25.17
W 355	22.97	26.97	24.97
Bhima Dark Red	23.42	26.31	24.86
Bhima Red	16.97	23.47	20.22
Bhima Raj	18.96	27.26	23.11
Bhima Shubra	17.97	26.76	22.36
Bhima Super	18.96	26.96	22.96
Mean	20.86	26.58	
Interaction (Treatment*Genotype)			
Sem ±	0.77		
CD (P ≤ 0.05)	**2.22**		
Interaction (Genotype*Treatment)			
Sem ±	0.72		
CD (P ≤ 0.05)	**2.09**		

Leaf area (cm²) 75 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	26.70	28.21	27.46
Acc.1630	26.65	27.30	26.98
W 355	24.70	27.32	26.01
Bhima Dark Red	26.66	28.37	27.52
Bhima Red	19.94	22.89	21.42
Bhima Raj	22.71	28.30	25.50
Bhima Shubra	19.84	25.91	22.88
Bhima Super	20.11	24.25	22.18
Mean	23.41	26.57	
Interaction (Treatment*Genotype)			
Sem ±	0.88		
CD (P ≤ 0.05)	**2.55**		
Interaction (Genotype*Treatment)			
Sem ±	0.93		
CD (P ≤ 0.05)	**3.33**		

Leaf area (cm²) 55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	26.49	30.13	28.31
Acc.1630	24.91	28.5	26.7
W 355	24.7	28.8	26.75
Bhima Dark Red	25.25	28.04	26.64
Bhima Red	20.19	28.7	24.45
Bhima Raj	20.59	28.89	24.74
Bhima Shubra	21.1	28.89	24.99
Bhima Super	20.2	29.19	24.7
Mean	22.93	28.89	
Interaction (Treatment*Genotype)			
Sem ±	0.86		
CD (P ≤ 0.05)	**2.50**		
Interaction (Genotype*Treatment)			
Sem ±	0.81		
CD (P ≤ 0.05)	**2.37**		

Leaf area (cm²) 75 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	26.17	30.44	28.31
Acc.1630	21.94	28.83	25.38
W 355	21.57	29.15	25.36
Bhima Dark Red	24.24	30.10	27.17
Bhima Red	26.89	28.12	27.50
Bhima Raj	24.33	29.93	27.13
Bhima Shubra	24.78	28.04	26.41
Bhima Super	22.93	26.48	24.71
Mean	24.11	28.89	
Interaction (Treatment*Genotype)			
Sem ±	1.00		
CD (P ≤ 0.05)	3.00		
Interaction (Genotype*Treatment)			
Sem ±	1.10		
CD (P ≤ 0.05)	**3.29**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.1.3 (a) Effect of waterlogging treatment on leaf area (cm²) of onion genotypes at different growth stages during 2023 and 2024.

The leaf area data showed non-significant differences at 45 DAT across waterlogging treatments, genotypes, and interactions in both years, although the waterlogging effect was significant at 30 DAT in 2023. From 55 DAT onwards through harvest, significant differences emerged in both waterlogging treatments and genotypes, with control conditions consistently maintaining higher leaf area compared to waterlogging stress. Among the genotypes, Acc.1666 demonstrated superior performance with the highest leaf area at 55 DAT (26.08 cm² in 2023, 28.31 cm² in 2024), 75 DAT (28.31 cm² in 2024), and at harvest (21.44 cm² in 2023, 20.34 cm² in 2024), indicating its ability to maintain photosynthetic capacity under both stress and non-stress conditions. At 75 DAT in 2023, Bhima Dark Red recorded the highest leaf area (27.52 cm²). Conversely, Bhima Red exhibited the poorest performance with the lowest leaf area at 55 DAT (20.22 cm²), 75 DAT (21.42 cm²), and at harvest (17.93 cm²) in 2023, while Bhima Super recorded the lowest values at 55 DAT (24.70 cm²), 75 DAT (24.71 cm²), and at harvest (18.29 cm²) in 2024, reflecting their high susceptibility to waterlogging-induced photosynthetic impairment. The interaction effect was significant only at 55 DAT in both years and at 75 DAT in 2023.

The significant reduction in leaf area under prolonged waterlogging from 55 DAT onwards directly indicates impaired photosynthetic capacity due to root-zone hypoxia. The ability of genotypes like Acc.1666 to maintain a larger leaf area signifies a robust genetic tolerance, likely through mechanisms that mitigate stress and sustain growth. Conversely, the drastic leaf area declines in susceptible genotypes like Bhima Red and Bhima Super reflects their inability to cope, leading to premature leaf senescence and reduced biomass accumulation (Kumar *et al.,* 2015).

4.1.3 (b) Interaction effect between waterlogging treatment and genotypes on leaf area (cm²) at different growth stages during 2023 and 2024.

The interaction effect on leaf area at 55 DAT in 2023 shows that Acc.1666 under control conditions had the highest leaf area (27.90 cm²), statistically at par with Bhima Dark Red (26.31 cm²), Acc.1630 (26.97 cm²), W 355 (26.97 cm²), Bhima Raj (27.26 cm²), Bhima Shubra (26.76 cm²), and Bhima Super (26.96 cm²) under control. The lowest leaf area was recorded by Bhima Red under waterlogging (16.97 cm²). At 75 DAT in 2023, Bhima Dark Red under control led with 28.37 cm², statistically at par with Bhima Raj (28.30 cm²), Acc.1666 (28.21 cm²), Acc.1630 (27.30 cm²), W 355 (27.32 cm²), and Bhima Shubra (25.91 cm²) under control, while Bhima Red under waterlogging had the lowest leaf area (19.94 cm²). For 2024 at 55 DAT, Acc.1666 under control again had the highest leaf area (30.13 cm²), with several genotypes including Bhima Super (29.19 cm²), Bhima Raj (28.89 cm²), Bhima Shubra (28.89 cm²), and Acc.1630 (28.50 cm²) statistically at par. The lowest leaf area was observed in Bhima Red under waterlogging (20.19 cm²). These results highlight the superior performance of Acc.1666 and Bhima Dark Red under control and the pronounced susceptibility of Bhima Red to waterlogging conditions.

The pronounced interaction between waterlogging treatment and genotype on leaf area underscores the variability in stress tolerance among onion cultivars. Under control conditions, Acc.1666 consistently exhibited the largest leaf area at 55 DAT in both years and maintained par performance with top genotypes like Bhima Dark Red and Bhima Raj, indicating strong inherent vigor. In contrast, Bhima Red showed the greatest reduction under waterlogging, with the lowest leaf areas across all measured stages, reflecting its high sensitivity to hypoxic stress (Wakchaure *et al.,* 2023). The ability of genotypes such as Acc.1666 and Bhima Dark Red to sustain leaf expansion under optimal conditions suggests efficient resource allocation and potential aerenchyma formation, whereas susceptible genotypes likely suffer from impaired root function and early leaf senescence (Wakchaure *et al.,* 2023). These differential responses highlight the importance of selecting robust genotypes for waterlogged environments to ensure stable leaf area development and overall crop productivity.

4.1.4: Neck thickness (mm)

Table 9: Effect of waterlogging treatment on neck thickness (mm) of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT		**45 DAT**		**55 DAT**		**75 DAT**		**At harvest**	
(Waterlogging Treatment)	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Waterlogging	6.40	7.38	7.32	8.30	9.73	9.98	8.58	9.58	9.47	8.50
Control	6.58	7.55	7.24	8.22	8.13	9.23	11.08	10.10	12.79	11.81
SEm±	0.15	0.15	0.10	0.10	0.03	0.10	0.08	0.11	0.07	0.14
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.19**	**0.59**	**0.47**	**0.33**	**0.44**	**0.85**
(Genotype)										
Acc. 1666	6.13	7.35	6.94	8.16	10.28	10.89	10.53	10.53	12.62	11.40
Acc.1630	6.19	7.07	7.62	8.50	9.21	9.94	10.33	10.45	11.97	11.03
W 355	6.45	7.45	7.39	8.39	9.10	9.60	10.41	10.41	11.84	10.84
Bhima Dark Red	6.80	7.80	7.18	8.18	9.55	9.76	10.72	10.66	12.41	11.47
Bhima Red	6.25	6.95	7.06	7.76	7.17	9.02	8.94	8.94	10.27	9.26
Bhima Raj	7.08	8.07	7.65	8.64	8.80	9.29	9.56	9.56	10.10	9.38
Bhima Shubra	6.34	7.23	7.14	8.03	8.65	9.14	9.10	9.15	9.80	9.22
Bhima Super	6.66	7.78	7.29	8.41	8.65	9.16	9.06	9.00	10.02	8.63
SEm±	0.24	0.30	0.30	0.31	0.18	0.19	0.22	0.24	0.20	0.24
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.52**	**0.55**	**0.63**	**0.68**	**0.59**	**0.70**
Interaction (Treatment*Genotype)										
Sem ±	0.34	0.42	0.42	0.43	0.25	0.27	0.31	0.33	0.29	0.34
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.73**	**0.77**	**0.89**	**0.96**	**0.84**	**0.98**
Interaction (Genotype*Treatment)										
Sem ±	0.35	0.42	0.40	0.42	0.24	0.27	0.30	0.33	0.28	0.35
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.71**	**0.89**	**0.92**	**1.07**	**0.87**	**1.19**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 9.1: Interaction effect between waterlogging treatment and genotypes on neck thickness (mm) at different growth stages during 2023.

Neck thickness 55 DAT (2023)			
	W. L	Control	Mean
Acc.1666	11.92	8.64	10.28
Acc.1630	10.17	8.25	9.21
W 355	10.03	8.16	9.10
Bhima Dark Red	10.75	8.36	9.55
Bhima Red	7.33	7.02	7.17
Bhima Raj	9.40	8.20	8.80
Bhima Shubra	9.06	8.24	8.65
Bhima Super	9.16	8.13	8.65
Mean	9.73	8.13	
Interaction (Treatment*Genotype)			
Sem ±	0.25		
CD (P ≤ 0.05)	**0.73**		
Interaction (Genotype*Treatment)			
Sem ±	0.24		
CD (P ≤ 0.05)	**0.71**		

Neck thickness 75 DAT (2023)			
	W. L	Control	Mean
Acc.1666	10.80	10.25	10.53
Acc.1630	9.64	11.01	10.33
W 355	9.64	11.18	10.41
Bhima Dark Red	10.00	11.43	10.72
Bhima Red	7.02	10.86	8.94
Bhima Raj	7.85	11.27	9.56
Bhima Shubra	6.80	11.39	9.10
Bhima Super	6.91	11.20	9.06
Mean	8.58	11.08	
Interaction (Treatment*Genotype)			
Sem ±	0.31		
CD (P ≤ 0.05)	**0.89**		
Interaction (Genotype*Treatment)			
Sem ±	0.30		
CD (P ≤ 0.05)	**0.92**		

Neck thickness at harvest (2023)			
	W. L	Control	Mean
Acc.1666	13.30	11.94	12.62
Acc.1630	11.25	12.70	11.97
W 355	10.76	12.91	11.84
Bhima Dark Red	11.70	13.12	12.41
Bhima Red	7.77	12.77	10.27
Bhima Raj	7.23	12.96	10.10
Bhima Shubra	6.61	12.99	9.80
Bhima Super	7.15	12.89	10.02
Mean	9.47	12.79	
Interaction (Treatment*Genotype)			
Sem ±	0.29		
CD (P ≤ 0.05)	**0.84**		
Interaction (Genotype*Treatment)			
Sem ±	0.28		
CD (P ≤ 0.05)	**0.87**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Table 9.2: Interaction effect between waterlogging treatment and genotypes on neck thickness (mm) at different growth stages during 2024.

Neck thickness 55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	11.92	9.86	10.89
Acc.1630	10.75	9.13	9.94
W 355	10.03	9.16	9.60
Bhima Dark Red	10.17	9.36	9.76
Bhima Red	9.33	8.72	9.02
Bhima Raj	9.40	9.19	9.29
Bhima Shubra	9.16	9.13	9.14
Bhima Super	9.06	9.25	9.16
Mean	9.98	9.23	
Interaction (Treatment*Genotype)			
Sem ±	0.27		
CD (P ≤ 0.05)	**0.77**		
Interaction (Genotype*Treatment)			
Sem ±	0.27		
CD (P ≤ 0.05)	**0.89**		

Neck thickness 75 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	12.02	9.03	10.53
Acc.1630	10.78	10.13	10.45
W 355	10.64	10.18	10.41
Bhima Dark Red	10.88	10.43	10.66
Bhima Red	7.72	10.16	8.94
Bhima Raj	8.84	10.28	9.56
Bhima Shubra	7.80	10.50	9.15
Bhima Super	7.92	10.08	9.00
Mean	9.58	10.10	
Interaction (Treatment*Genotype)			
Sem ±	0.33		
CD (P ≤ 0.05)	**0.96**		
Interaction (Genotype*Treatment)			
Sem ±	0.33		
CD (P ≤ 0.05)	**1.07**		

Neck thickness at harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	12.08	10.72	11.40
Acc.1630	10.25	11.82	11.03
W 355	9.76	11.91	10.84
Bhima Dark Red	10.82	12.12	11.47
Bhima Red	6.45	12.07	9.26
Bhima Raj	6.78	11.97	9.38
Bhima Shubra	6.34	12.10	9.22
Bhima Super	5.49	11.77	8.63
Mean	8.50	11.81	
Interaction (Treatment*Genotype)			
Sem ±	0.34		
CD (P ≤ 0.05)	**0.98**		
Interaction (Genotype*Treatment)			
Sem ±	0.35		
CD (P ≤ 0.05)	**1.19**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.1.4 (a) Effect of waterlogging treatment on neck thickness (mm) of onion genotypes at different growth stages during 2023 and 2024.

The data on neck thickness showed non-significant differences at 30 and 45 DAT in waterlogging treatments, genotypes, and their interaction for both years. However, significant differences were observed at 55 DAT, 75 DAT, and at harvest, particularly in 2023 and 2024 for waterlogging and sub-plot genotype (Table 9). Among the genotypes, Acc.1666 exhibited the highest neck thickness at 55 DAT (10.28 mm in 2023, 10.89 mm in 2024), 75 DAT (10.53 mm in both years), and at harvest (12.62 mm in 2023, 11.40 mm in 2024) (Table 9), indicating its superior structural robustness. Conversely, Bhima Red showed the lowest neck thickness at 55 DAT (7.17 mm in 2023, 9.02 mm in 2024), 75 DAT (8.94 mm in 2023 and 2024), and at harvest (10.27 mm in 2023, 9.26 mm in 2024), reflecting vulnerability to waterlogging stress and weaker neck development (Table 9).

4.1.4 (b) Interaction effect between waterlogging treatment and genotypes on neck thickness (mm) at different growth stages during 2023-2024.

At 55 DAT in 2023, Acc.1666 under waterlogging exhibited the highest neck thickness (11.92 mm), statistically at par with Bhima Dark Red (10.75 mm), Acc. 1630 (10.17 mm), W-355 (10.03 mm), while Bhima Red under waterlogging had the lowest value (7.33 mm). At 75 DAT in 2023, Bhima Dark Red under control registered the greatest thickness (11.43 mm), at par with W-355 (11.18 mm), Acc. 1630 (11.01 mm), Bhima Shubra (11.39 mm), and Bhima Super (11.20 mm), whereas Bhima Shubra under waterlogging showed the minimum (6.80 mm). At harvest in 2023, Bhima Dark Red under control peaked at 13.12 mm, statistically similar to Bhima Shubra (12.99 mm), Bhima Super (12.89 mm), Bhima Raj (12.96 mm), Acc. 1630 (12.70 mm), and W-355 (12.91 mm), with Bhima Shubra under waterlogging the lowest (6.61 mm) (Table 9.1 and 9.2). For 2024 (Table 9.1) at 55 DAT, Acc.1666 under waterlogging again led (11.92 mm), at par with Bhima Dark Red (10.17 mm) and Acc. 1630 (10.75 mm), while Bhima Super under waterlogging was lowest (9.06 mm). At 75 DAT in 2024, Bhima Dark Red under control achieved the highest thickness (10.43 mm), statistically at par with W-355 (10.18 mm), Acc.1666 (9.03 mm), and Acc. 1630 (10.13 mm), and Bhima Super under waterlogging had the lowest (7.92 mm). At harvest in 2024, Bhima Dark Red under control recorded the maximum (12.12 mm), at par with Bhima

Shubra (12.10 mm) and Bhima Raj (11.97 mm), while Bhima Super under waterlogging had the minimum neck thickness (5.49 mm).

The significant genotypic × treatment interactions for neck thickness indicate that waterlogging stress differentially affects stem development among onion cultivars. Acc.1666 consistently maintained superior neck girth under waterlogged conditions, suggesting robust cellular integrity and possible enhanced aerenchyma formation to support turgor under hypoxia (Hendrika *et al.,* 2023). Bhima Dark Red also demonstrated strong neck thickness under control and moderate stress, highlighting its adaptive advantage. In contrast, Bhima Red and Bhima Super showed the most pronounced reductions in neck thickness under waterlogging, reflecting structural vulnerability and impaired vascular function (Tyagi *et al.,* 2024). These findings underscore the potential of cultivars like Acc.1666 and Bhima Dark Red for breeding programs aimed at improving waterlogging resilience in onion.

4.1.5: Total dry matter yield (g plant^{-1})

Table 10: Effect of waterlogging treatment on total dry matter (g plant^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT		**45 DAT**		**55 DAT**		**75 DAT**		**At harvest**	
(Waterlogging Treatment)	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Waterlogging	16.72	16.37	46.80	54.09	61.92	65.41	67.92	71.41	103.53	106.63
Control	15.99	14.84	50.66	69.88	79.19	86.73	87.81	95.35	121.93	130.45
SEm±	0.51	0.39	1.61	2.93	2.77	3.03	2.93	2.80	0.61	0.52
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**8.32**	**9.10**	**8.80**	**8.41**	**1.83**	**1.56**
(Genotype)										
Acc. 1666	15.84	15.66	50.77	69.92	78.39	90.21	86.89	98.71	119.84	134.37
Acc.1630	17.44	17.64	51.82	64.48	69.88	70.72	77.38	78.22	110.03	110.62
W 355	16.17	14.31	50.83	65.32	68.52	69.73	76.02	77.23	108.17	110.53
Bhima Dark Red	16.30	14.58	50.13	65.71	77.71	87.76	86.71	96.76	119.53	131.17
Bhima Red	17.05	15.62	48.91	59.67	66.49	70.17	72.49	76.17	110.83	112.77
Bhima Raj	16.20	16.22	48.82	56.77	68.22	73.98	74.72	80.48	112.12	117.02
Bhima Shubra	15.75	15.16	44.44	58.83	65.10	68.47	71.60	74.97	108.94	112.65
Bhima Super	16.09	15.61	44.14	55.20	70.12	77.50	77.12	84.50	112.39	119.22
SEm±	0.56	0.31	3.38	4.64	3.69	4.37	3.94	4.30	2.48	2.46
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**11.07**	**13.10**	**11.82**	**12.89**	**7.43**	**7.37**
Interaction (Treatment*Genotype)										
Sem ±	0.80	1.70	1.94	6.57	5.39	6.18	5.74	6.08	2.09	2.06
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**16.18**	**18.53**	**17.23**	**18.23**	**6.26**	**6.18**
Interaction (Genotype*Treatment)										
Sem ±	0.90	1.64	1.92	6.81	5.37	6.53	5.73	6.34	1.98	1.99
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**16.10**	**19.58**	**17.20**	**19.02**	**5.93**	**5.98**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm±: Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 10.1: Interaction effect between waterlogging treatment and genotypes on total dry matter (g plant^{-1}) at different growth stages during 2023.

Total dry matter yield (g plant^{-1})55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	77.31	79.47	78.39
Acc.1630	61.74	78.03	69.88
W-355	58.58	78.47	68.52
Bhima Dark Red	72.38	83.03	77.71
Bhima Red	56.94	76.03	66.49
Bhima Raj	56.86	79.57	68.22
Bhima Shubra	51.14	79.07	65.10
Bhima Super	60.41	79.83	70.12
Mean	61.92	79.19	
Interaction (Treatment*Genotype)			
Sem ±	5.39		
CD (P ≤ 0.05)	16.18		
Interaction (Genotype*Treatment)			
Sem ±	5.37		
CD (P ≤ 0.05)	16.10		

Total dry matter yield (g plant^{-1}) 75 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	85.31	88.47	86.89
Acc.1630	68.74	86.03	77.38
W-355	64.58	87.47	76.02
Bhima Dark Red	80.38	93.03	86.71
Bhima Red	61.94	83.03	72.49
Bhima Raj	61.86	87.57	74.72
Bhima Shubra	55.14	88.07	71.60
Bhima Super	65.41	88.83	77.12
Mean	67.92	87.81	
Interaction (Treatment*Genotype)			
Sem ±	5.74		
CD (P ≤ 0.05)	17.23		
Interaction (Genotype*Treatment)			
Sem ±	5.73		
CD (P ≤ 0.05)	17.20		

Total dry matter yield (g plant^{-1}) at harvest (2023)			
	W. L	**Control**	**Mean**
Acc.1666	114.53	125.15	119.84
Acc.1630	99.74	120.33	110.03
W-355	99.03	117.30	108.17
Bhima Dark Red	111.67	127.40	119.53
Bhima Red	101.15	120.50	110.83
Bhima Raj	101.46	122.77	112.12
Bhima Shubra	97.07	120.80	108.94
Bhima Super	103.58	121.20	112.39
Mean	103.53	121.93	112.73
Interaction (Treatment*Genotype)			
Sem ±	2.09		
CD (P ≤ 0.05)	6.26		
Interaction (Genotype*Treatment)			
Sem ±	1.98		
CD (P ≤ 0.05)	5.93		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance, Values are means of five plants per treatment per genotype.

Table 10.2: Interaction effect between waterlogging treatment and genotypes on total dry matter (g plant^{-1}) at different growth stages during 2024.

Total dry matter yield (g plant^{-1})55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	88.09	92.33	90.21
Acc.1630	62.97	78.47	70.72
W-355	58.30	81.17	69.73
Bhima Dark Red	76.29	99.23	87.76
Bhima Red	57.70	82.63	70.17
Bhima Raj	62.57	85.40	73.98
Bhima Shubra	50.07	86.87	68.47
Bhima Super	67.27	87.73	77.50
Mean	65.41	86.73	
Interaction (Treatment*Genotype)			
Sem ±	6.18		
CD (P ≤ 0.05)	18.53		
Interaction (Genotype*Treatment)			
Sem ±	6.53		
CD (P ≤ 0.05)	19.58		

Total dry matter yield (g plant^{-1})75 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	96.09	101.33	98.71
Acc.1630	69.97	86.47	78.22
W-355	64.30	90.17	77.23
Bhima Dark Red	84.29	109.23	96.76
Bhima Red	62.70	89.63	76.17
Bhima Raj	67.57	93.40	80.48
Bhima Shubra	54.07	95.87	74.97
Bhima Super	72.27	96.73	84.50
Mean	71.41	95.35	83.38
Interaction (Treatment*Genotype)			
Sem ±	6.08		
CD (P ≤ 0.05)	18.23		
Interaction (Genotype*Treatment)			
Sem ±	6.34		
CD (P ≤ 0.05)	19.02		

Total dry matter yield (g plant^{-1}) at harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	127.43	141.30	134.37
Acc.1630	99.33	121.90	110.62
W-355	98.60	122.47	110.53
Bhima Dark Red	119.47	142.87	131.17
Bhima Red	100.80	124.73	112.77
Bhima Raj	103.67	130.37	117.02
Bhima Shubra	95.17	130.13	112.65
Bhima Super	108.57	129.87	119.22
Mean	106.63	130.45	118.54
Interaction (Treatment*Genotype)			
Sem ±	2.06		
CD (P ≤ 0.05)	6.18		
Interaction (Genotype*Treatment)			
Sem ±	1.99		
CD (P ≤ 0.05)	5.98		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance, Values are means of five plants per treatment per genotype.

4.1.5 (a) Effect of waterlogging treatment on total dry matter (g plant^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

The total dry matter yield of onion genotypes showed non-significant differences between waterlogging and control at 30 and 45 DAT in both seasons, as indicated by the non-significant CD values. From 55 DAT onwards, the waterlogging treatment effect became significant, with control plants consistently recording higher dry matter than waterlogged plants at 55 DAT (79.19 vs. 61.92 in 2023; 86.73 vs. 65.41 in 2024), 75 DAT (87.81 vs. 67.92 in 2023; 95.35 vs. 71.41 in 2024), and at harvest (121.93 vs. 103.53 in 2023; 130.45 vs. 106.63 in 2024), reflecting the cumulative adverse effect of waterlogging on biomass production. Among the genotypes (sub plot), differences were non-significant up to 45 DAT in both years, while significant variation appeared from 55 DAT through harvest, with Acc.1666 recording the highest total dry matter at all later stages (78.39 and 90.21 at 55 DAT; 86.89 and 98.71 at 75 DAT; 119.84 and 134.37 at harvest in 2023 and 2024, respectively), followed closely by Bhima Dark Red and Bhima Super. In contrast, Bhima Shubra recorded the lowest dry matter at the mid-growth stages (65.10 and 68.47 at 55 DAT; 71.60 and 74.97 at 75 DAT in 2023 and 2024), and along with W-355 remained among the poorest performers at harvest (108.94 and 112.65 for Bhima Shubra; 108.17 and 110.53 for W-355 in 2023 and 2024, respectively), indicating reduced tolerance to waterlogging stress (Table X). (Table 10).

The total dry matter accumulation results clearly demonstrate the adverse impact of waterlogging stress from 55 DAT onwards, reflecting the cumulative effect of impaired physiological processes such as photosynthesis and nutrient uptake under hypoxic conditions (Pan *et al.,* 2021). Acc.1666 consistently outperformed other genotypes, maintaining higher biomass production, which indicates its superior tolerance to waterlogging, possibly through efficient metabolic adaptation (Pawar *et al.,* 2025). Bhima Dark Red and Bhima Super also showed relatively robust dry matter yields, supporting their potential for cultivation in waterlogged environments. In contrast, Bhima Shubra consistently recorded the lowest dry matter, highlighting its susceptibility and poorer growth under stress.

4.1.5 (b) Interaction effect of waterlogging treatment and onion genotype on dry matter yield (g/plot) at different growth stages during 2023-2024.

The interaction between waterlogging treatment and genotype for total dry matter was non-significant up to 45 DAT in both years but became significant from 55 DAT onwards, as supported by the CD values for the interaction terms. At 55 DAT in 2023, Bhima Dark Red under control registered the highest dry matter (83.03), which was statistically at par with Bhima Super (79.83), Bhima Raj (79.57), Acc.1666 (79.47), Bhima Shubra (79.07), W-355 (78.47), and Acc.1630 (78.03) under control, whereas Bhima Shubra under waterlogging recorded the minimum (51.14). A similar pattern was observed at 75 DAT in 2023, where Bhima Dark Red under control achieved the highest dry matter (93.03), at par with Bhima Super (88.83), Acc.1666 (88.47), Bhima Shubra (88.07), Bhima Raj (87.57), W-355 (87.47), and Acc.1630 (86.03) under control, while Bhima Shubra under waterlogging had the lowest value (55.14). At harvest in 2023, Bhima Dark Red under control recorded the maximum dry matter (127.40), statistically comparable with Acc.1666 (125.15), Bhima Raj (122.77), Bhima Super (121.20), Bhima Shubra (120.80), Bhima Red (120.50), Acc.1630 (120.33), and W-355 (117.30) under control, whereas Bhima Shubra under waterlogging produced the least dry matter (97.07). In 2024, Bhima Dark Red under control consistently maintained the highest dry matter at 55 DAT (99.23) and remained statistically at par with Acc.1666 (92.33), Bhima Super (87.73), Bhima Shubra (86.87), and Bhima Raj (85.40) under control, as well as Acc.1666 under waterlogging (88.09); Bhima Shubra under waterlogging again showed the minimum (50.07). At 75 DAT in 2024, Bhima Dark Red under control recorded the highest dry matter (109.23), at par with Acc.1666 (101.33), Bhima Super (96.73), Bhima Shubra (95.87), and Bhima Raj (93.40) under control, along with Acc.1666 under waterlogging (96.09), while Bhima Shubra under waterlogging gave the lowest value (54.07). At harvest in 2024, Bhima Dark Red under control produced the highest dry matter (142.87), statistically at par with Acc.1666 under control (141.30), whereas Bhima Shubra under waterlogging had the minimum dry matter (95.17), reaffirming its susceptibility to waterlogging (Table 10.1 and 10.2) The interaction between waterlogging treatment and genotype revealed significant variability in biomass accumulation under stress. Under waterlogging, Acc.1666 and Bhima Dark Red retained relatively higher dry matter, likely owing to efficient root aeration and sustained photosynthetic activity (Gedam *et al.,* 2023), whereas Bhima Shubra recorded the lowest dry matter, reflecting susceptibility linked to impaired root function and nutrient uptake under hypoxia (Gedam *et al.,* 2022). These findings underscore the importance of selecting genotypes with strong stress-resilience traits for sustaining productivity in waterlogged conditions.

4.2: Physiological parameters

4.2.1: Total chlorophyll (µg g^{-1})

Table 11: Effect of waterlogging treatment on total chlorophyll content (µg g^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

	45 DAT		55 DAT		75 DAT	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	3.84	3.19	4.43	3.78	5.84	5.19
Control	3.6	2.95	5.94	5.29	7.38	6.73
SEm±	0.05	0.05	0.12	0.12	0.05	0.05
CD (P ≤ 0.05)	**NS**	**NS**	**0.71**	**0.71**	**0.33**	**0.33**
(Genotype)						
Acc. 1666	3.63	2.98	7.00	6.35	8.28	7.63
Acc.1630	3.94	3.29	5.13	4.48	6.42	5.77
W 355	3.93	3.28	5.22	4.57	6.49	5.84
Bhima Dark Red	4.22	3.57	5.39	4.74	6.58	5.93
Bhima Red	4.08	3.43	4.98	4.33	6.53	5.88
Bhima Raj	3.33	2.68	4.65	4.00	6.33	5.68
Bhima Shubra	2.82	2.17	4.37	3.72	6.03	5.38
Bhima Super	3.83	3.18	4.73	4.08	6.24	5.59
SEm±	0.16	0.17	0.11	0.12	0.17	0.21
CD (P ≤ 0.05)	**0.47**	**0.48**	**0.31**	**0.34**	**0.50**	**0.61**
Interaction (Treatment*Genotype)						
Sem ±	0.23	0.24	0.15	0.17	0.25	0.30
CD (P ≤ 0.05)	**NS**	**NS**	**0.44**	**0.49**	**0.71**	**0.86**
Interaction (Genotype*Treatment)						
Sem ±	0.22	0.22	0.18	0.20	0.24	0.28
CD (P ≤ 0.05)	**NS**	**NS**	**0.76**	**0.79**	**0.73**	**0.85**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 11.1: Interaction effect between waterlogging treatment and genotypes on total chlorophyll content (µg g^{-1}) at different growth stages during 2023 and 2024.

Total chlorophyll 55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	6.82	7.18	7.00
Acc.1630	4.46	5.80	5.13
W-355	4.41	6.04	5.22
Bhima Dark Red	5.31	5.47	5.39
Bhima Red	4.05	5.91	4.98
Bhima Raj	3.80	5.49	4.65
Bhima Shubra	2.88	5.86	4.37
Bhima Super	3.67	5.79	4.73
Mean	4.43	5.94	
Interaction (Treatment*Genotype)			
SEm±	0.15		
CD (P ≤ 0.05)	**0.44**		
Interaction (Genotype*Treatment)			
SEm±	0.18		
CD (P ≤ 0.05)	**0.76**		

Total chlorophyll 75 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	7.91	8.64	8.28
Acc.1630	5.78	7.07	6.42
W-355	5.74	7.23	6.49
Bhima Dark Red	6.41	6.76	6.58
Bhima Red	5.70	7.36	6.53
Bhima Raj	5.53	7.12	6.33
Bhima Shubra	4.47	7.60	6.03
Bhima Super	5.20	7.28	6.24
Mean	5.84	7.38	
Interaction (Treatment*Genotype)			
SEm±	0.25		
CD (P ≤ 0.05)	**0.71**		
Interaction (Genotype*Treatment)			
SEm±	0.24		
CD (P ≤ 0.05)	**0.73**		

Total chlorophyll 55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	6.17	6.53	6.35
Acc.1630	3.81	5.15	4.48
W-355	3.76	5.39	4.57
Bhima Dark Red	4.66	4.82	4.74
Bhima Red	3.40	5.26	4.33
Bhima Raj	3.15	4.84	4.00
Bhima Shubra	2.23	5.21	3.72
Bhima Super	3.02	5.14	4.08
Mean	3.78	5.29	
Interaction (Treatment*Genotype)			
SE (m) ±	0.17		
CD at 5%	**0.49**		
Interaction (Genotype*Treatment)			
SEm±	0.20		
CD (P ≤ 0.05)	**0.79**		

Total chlorophyll 75 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	7.26	7.99	7.63
Acc.1630	5.13	6.42	5.77
W-355	5.09	6.58	5.84
Bhima Dark Red	5.76	6.11	5.93
Bhima Red	5.05	6.71	5.88
Bhima Raj	4.88	6.47	5.68
Bhima Shubra	3.82	6.95	5.38
Bhima Super	4.55	6.63	5.59
Mean	5.19	6.73	
Interaction (Treatment*Genotype)			
SE (m) ±	0.30		
CD at 5%	**0.86**		
Interaction (Genotype*Treatment)			
SEm±	0.28		
CD (P ≤ 0.05)	**0.85**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.1 (a) Effect of waterlogging treatment on total chlorophyll content (µg g^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

The total chlorophyll content showed non-significant differences at 45 DAT across waterlogging treatments, genotypes, and their interaction in both years. Significant treatment and genotype effects were observed at 55 DAT and 75 DAT, where Acc.1666 exhibited the highest chlorophyll levels (7.00 µg g^{-1} in 2023, 6.35 µg g^{-1} in 2024 at 55 DAT; 8.28 µg g^{-1} in 2023, 7.63 µg g^{-1} in 2024 at 75 DAT), and Bhima Shubra recorded the lowest values (4.37 µg g^{-1} and 3.72 µg g^{-1} at 55 DAT; 6.03 µg g^{-1} and 5.38 µg g^{-1} at 75 DAT) (Table 11.), reflecting its greater susceptibility to waterlogging-induced chlorophyll degradation.

The significant reductions in chlorophyll content at 55 and 75 DAT under waterlogging stress suggest that prolonged hypoxia adversely affects chlorophyll biosynthesis and stability, thereby impairing photosynthetic efficiency (Sharma *et al.,* 2022). Acc.1666 consistently maintained the highest chlorophyll levels, indicating its strong physiological resilience and ability to sustain photosynthesis under stress. Conversely, Bhima Shubra exhibited the lowest chlorophyll concentrations, highlighting its susceptibility to waterlogging-induced oxidative damage and pigment degradation (Sharma *et al.,* 2022). These findings underline the importance of selecting genotypes with robust chlorophyll retention capacity for improved tolerance and productivity in waterlogged environments.

4.2.1 (b) Interaction effect between waterlogging treatment and genotypes on total chlorophyll content (µg g^{-1}) at different growth stages during 2023 and 2024.

At 55 DAT in 2023, Acc.1666 under control showed the highest total chlorophyll content (7.18 µg g^{-1}), statistically at par with waterlogging treatment in the same genotype (6.82 µg g^{-1}). Bhima Dark Red under control (5.47 µg g^{-1}) and Bhima Red under control (5.91 µg g^{-1}) were also within the par range, while Bhima Shubra under waterlogging had the lowest content (2.88 µg g^{-1}). At 75 DAT, Acc.1666 under control again recorded the highest chlorophyll level (8.64 µg g^{-1}), statistically at par with Bhima Shubra under control (7.60 µg g^{-1}) and Bhima Red under control (7.36 µg g^{-1}), whereas Bhima Shubra under waterlogging had the lowest (4.47 µg g^{-1}) (Table 11.1). Similarly, in 2024 at 55 DAT, Acc.1666 under control had the highest chlorophyll (6.53 µg g^{-1}), alongside Bhima Dark Red (4.82 µg g^{-1}) and Bhima Red (5.26 µg g^{-1}) under control within the par range, with Bhima Shubra under waterlogging again showing the lowest (2.23 µg g^{-1}). At 75 DAT in 2024, Acc.1666 under control (7.99 µg g^{-1}) was highest on par with Bhima Shubra under control (6.95 µg g^{-1}) and Bhima Red under control (6.71 µg g^{-1}), while Bhima Shubra under waterlogging was lowest (3.82 µg g^{-1}) (Table 11.1). The results underscore Acc.1666's superior chlorophyll retention and Bhima Shubra's susceptibility under waterlogging stress.

The interaction effect of waterlogging and genotype on total chlorophyll content reveals distinct physiological responses among onion cultivars. Acc.1666 consistently maintained the highest chlorophyll levels under both control and waterlogged conditions, reflecting its enhanced ability to preserve pigment stability and photosynthetic function despite stress (Gedam *et al.,* 2023). This likely arises from effective antioxidant defense mechanisms and maintenance of chloroplast integrity under hypoxia (Sharma *et al.,* 2022). Conversely, Bhima Shubra exhibited the lowest chlorophyll content under waterlogging, indicating its susceptibility to oxidative damage and pigment degradation, which compromises photosynthesis (Tyagi *et al.,* 2024). The statistically similar chlorophyll levels in certain genotypes under control highlight inherent genetic potential, while the divergence under stress underscores the critical role of genotype-specific tolerance mechanisms (Gedam *et al.,* 2023). These findings emphasize the value of Acc.1666 for breeding programs targeting waterlogging resilience and sustained photosynthetic efficiency.

4.2.2: Membrane stability index (MSI %)

Table 12: Effect of waterlogging treatment on membrane stability index (%) of onion genotypes at different growth stages during 2023 and 2024.

	(MSI %) 45 DAT		(MSI %) 55 DAT		(MSI %) 75 DAT	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	61.75	60.75	50.43	52.43	55.74	53.74
Control	65.26	64.26	66.42	69.42	69.65	70.65
SEm±	0.36	0.39	0.18	0.33	0.22	0.29
CD (P ≤ 0.05)	**2.18**	**2.39**	**1.1**	**2.03**	**1.33**	**1.79**
(Genotype)						
Acc. 1666	65.86	64.86	65.12	67.62	70.51	70.01
Acc.1630	59.98	58.98	58.21	60.71	62.35	61.85
W 355	63.40	62.41	58.82	61.32	62.96	62.46
Bhima Dark Red	67.91	66.91	64.42	66.92	70.05	69.55
Bhima Red	64.46	63.46	57.27	59.77	60.74	60.24
Bhima Raj	64.08	63.08	55.78	58.28	59.84	59.34
Bhima Shubra	63.96	62.96	54.61	57.11	58.58	58.08
Bhima Super	58.37	57.37	53.18	55.68	56.54	56.04
SEm±	0.85	0.79	0.72	0.66	0.70	0.69
CD (P ≤ 0.05)	**2.47**	**2.29**	**2.09**	**1.92**	**2.03**	**2.01**
Interaction (Treatment*Genotype)						
Sem ±	1.20	1.12	1.02	0.94	0.99	0.98
CD (P ≤ 0.05)	**NS**	**NS**	**2.95**	**2.71**	**2.88**	**2.84**
Interaction (Genotype*Treatment)						
Sem ±	1.18	1.12	0.97	0.94	0.95	0.96
CD (P ≤ 0.05)	**NS**	**NS**	**2.92**	**3.09**	**2.92**	**3.07**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 12.1: Interaction effect between waterlogging treatment and genotypes on membrane stability index (%) at different growth stages during 2023 and 2024.

MSI % 55 DAT 2023			
	W. L	**Control**	**Mean**
Acc.1666	59.73	70.52	65.12
Acc.1630	52.22	64.20	58.21
W 355	51.19	66.45	58.82
Bhima Dark Red	58.57	70.26	64.42
Bhima Red	47.96	66.59	57.27
Bhima Raj	46.12	65.44	55.78
Bhima Shubra	42.37	66.86	54.61
Bhima Super	45.31	61.04	53.18
Mean	50.43	66.42	
Interaction (Treatment*Genotype)			
SEm±	1.02		
CD (P ≤ 0.05)	**2.95**		
Interaction (Genotype*Treatment)			
SEm±	0.97		
CD (P ≤ 0.05)	**2.92**		

MSI % 75 DAT 2023			
	W. L	**Control**	**Mean**
Acc.1666	67.27	73.75	70.51
Acc.1630	57.26	67.43	62.35
W 355	56.23	69.68	62.96
Bhima Dark Red	66.61	73.49	70.05
Bhima Red	51.65	69.83	60.74
Bhima Raj	51.00	68.68	59.84
Bhima Shubra	47.06	70.10	58.58
Bhima Super	48.81	64.28	56.54
Mean	55.74	69.65	
Interaction (Treatment*Genotype)			
SEm±	0.99		
CD (P ≤ 0.05)	**2.88**		
Interaction (Genotype*Treatment)			
SEm±	0.95		
CD (P ≤ 0.05)	**2.92**		

MSI % 55 DAT 2024			
	W. L	**Control**	**Mean**
Acc.1666	61.73	73.52	67.62
Acc.1630	54.22	67.20	60.71
W 355	53.19	69.45	61.32
Bhima Dark Red	60.57	73.26	66.92
Bhima Red	49.96	69.59	59.77
Bhima Raj	48.12	68.44	58.28
Bhima Shubra	44.37	69.86	57.11
Bhima Super	47.31	64.04	55.68
Mean	52.43	69.42	
Interaction (Treatment*Genotype)			
SEm±	0.94		
CD (P ≤ 0.05)	**2.71**		
Interaction (Genotype*Treatment)			
SEm±	0.94		
CD (P ≤ 0.05)	**3.09**		

MSI % 75 DAT 2024			
	W. L	**Control**	**Mean**
Acc.1666	65.27	74.75	70.01
Acc.1630	55.26	68.43	61.85
W 355	54.23	70.68	62.46
Bhima Dark Red	64.61	74.49	69.55
Bhima Red	49.65	70.83	60.24
Bhima Raj	49.00	69.68	59.34
Bhima Shubra	45.06	71.10	58.08
Bhima Super	46.81	65.28	56.04
Mean	53.74	70.65	
Interaction (Treatment*Genotype)			
SEm±	0.98		
CD (P ≤ 0.05)	**2.84**		
Interaction (Genotype*Treatment)			
SEm±	0.96		
CD (P ≤ 0.05)	**3.07**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.2 (a) Effect of waterlogging treatment on membrane stability index (%) of onion genotypes at different growth stages during 2023 and 2024.

The membrane stability index (MSI) data showed non-significant differences at 45 DAT for waterlogging treatments, genotypes, and their interaction in both years (Table 12). However, significant differences were recorded at 55 DAT and 75 DAT in both years for waterlogging and sub-plot effects. Among the genotypes, Bhima Dark Red and Acc.1666 consistently exhibited the highest MSI values at 55 DAT (64.42% and 65.12% in 2023; 66.92% and 67.62% in 2024) and 75 DAT (70.05% and 70.51% in 2023; 69.55% and 70.01% in 2024), reflecting better membrane integrity and stress tolerance. In contrast, Bhima Super displayed the lowest MSI across these stages, with values as low as 53.18% at 55 DAT and 56.54% at 75 DAT in 2023, and similar trends in 2024 (Table 12), indicating greater susceptibility to waterlogging-induced membrane damage.

The membrane stability index (MSI) results indicate significant impacts of waterlogging stress on cellular membrane integrity from 55 DAT onwards, demonstrating its critical role in stress tolerance. Genotypes such as Bhima Dark Red and Acc.1666 exhibited superior MSI values, reflecting their capacity to maintain membrane stability under hypoxic conditions, likely through enhanced antioxidant defense and reduced lipid peroxidation (Pan *et al.,* 2021). This membrane preservation supports better cellular function and overall plant resilience. Conversely, Bhima Super showed notably lower MSI, signifying increased membrane damage and vulnerability to stress-induced oxidative damage (Gedam *et al.,* 2023). These findings highlight the importance of selecting genotypes with robust membrane stability to improve waterlogging tolerance and sustain onion productivity under adverse conditions.

4.2.2 (b) Interaction effect between waterlogging treatment and genotypes on membrane stability index (%) at different growth stages during 2023 and 2024.

At 55 DAT in 2023, Acc.1666 under control exhibited the highest membrane stability index (MSI) of 70.52%, statistically at par with Bhima Dark Red under control (70.26%). The lowest MSI was recorded in Bhima Shubra under waterlogging (42.37%). At 75 DAT in 2023, Acc.1666 under control again led with 73.75%, at par with Bhima Dark Red under control (73.49%) and Bhima Shubra under control (70.10%), while Bhima Shubra under waterlogging had the lowest MSI (47.06%) (Table 12.1). In 2024 at 55 DAT, Acc.1666 under control was highest (73.5%), statistically similar to Bhima Dark Red under control (73.3%), with Bhima Shubra under waterlogging lowest (44.4%). At 75 DAT in 2024, Acc.1666 under control remained highest (74.8%), at par with Bhima Dark Red under control (74.5%) and Bhima Shubra under control (71.1%), and Bhima Super under waterlogging had the lowest MSI (46.8%) (Table 12.1). These results highlight Acc.1666 and Bhima Dark Red's superior membrane integrity under both stress and control, contrasting with Bhima Shubra and Bhima Super's vulnerability to waterlogging stress.

The interaction effect of waterlogging and genotype on membrane stability index (MSI) highlights significant genotypic variation in maintaining cellular integrity under stress (Pan *et al.,* 2021). Acc.1666 and Bhima Dark Red consistently showed high MSI values under both control and waterlogging conditions, indicating their strong resistance to membrane lipid peroxidation and better antioxidant defense systems (Sharma *et al.,* 2022). These genotypes likely maintain membrane fluidity and prevent leakage, which is crucial for sustaining cellular functions during hypoxic stress (Gedam *et al.,* 2022). Conversely, Bhima Shubra and Bhima Super exhibited the lowest MSI values under waterlogging, reflecting increased oxidative damage and compromised membrane integrity, leading to reduced stress tolerance. This underlines the importance of selecting genotypes with enhanced membrane stability to improve crop resilience under waterlogging conditions.

4.2.3: Leaf area index (LAI)

Table 13: Effect of waterlogging treatment on leaf area index of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT		45 DAT		55 DAT		75 DAT		At harvest	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	0.110	0.127	0.130	0.161	0.139	0.153	0.156	0.161	0.126	0.114
Control	0.116	0.127	0.133	0.144	0.177	0.193	0.177	0.193	0.150	0.140
SEm±	0.001	0.001	0.003	0.003	0.000	0.000	0.003	0.004	0.001	0.001
CD (P ≤ 0.05)	**0.005**	**NS**	**NS**	**NS**	**0.002**	**0.003**	**0.018**	**0.023**	**0.008**	**0.008**
(Genotype)										
Acc. 1666	0.111	0.128	0.132	0.155	0.174	0.189	0.183	0.189	0.143	0.136
Acc.1630	0.114	0.126	0.129	0.148	0.168	0.178	0.180	0.169	0.142	0.134
W 355	0.114	0.128	0.133	0.152	0.166	0.178	0.173	0.169	0.130	0.122
Bhima Dark Red	0.115	0.129	0.131	0.156	0.166	0.178	0.183	0.181	0.138	0.130
Bhima Red	0.110	0.120	0.128	0.146	0.135	0.163	0.143	0.183	0.120	0.126
Bhima Raj	0.111	0.123	0.137	0.155	0.154	0.165	0.170	0.181	0.145	0.124
Bhima Shubra	0.115	0.131	0.132	0.156	0.149	0.167	0.153	0.176	0.143	0.122
Bhima Super	0.112	0.129	0.128	0.153	0.153	0.165	0.148	0.165	0.143	0.122
SEm±	0.003	0.003	0.003	0.004	0.004	0.004	0.004	0.005	0.003	0.003
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.010**	**0.012**	**0.012**	**0.014**	**0.010**	**0.010**
Interaction (Treatment*Genotype)										
Sem ±	0.004	0.004	0.005	0.006	0.005	0.006	0.006	0.007	0.005	0.005
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.015**	**0.017**	**0.017**	**0.02**	**NS**	**NS**
Interaction (Genotype*Treatment)										
Sem ±	0.004	0.004	0.005	0.006	0.005	0.005	0.006	0.007	0.005	0.005
CD (P ≤ 0.05)	**NS**	**NS**	**NS**	**NS**	**0.014**	**0.016**	**0.022**	**0.022**	**NS**	**NS**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm±: Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 13.1: Interaction effect between waterlogging treatment and genotypes on leaf area index at different growth stages during 2023 and 2024.

LAI (2023)			
	W. L	**Control**	**Mean**
Acc.1666	0.162	0.186	0.174
Acc.1630	0.156	0.180	0.168
W-355	0.153	0.180	0.166
Bhima Dark Red	0.156	0.175	0.166
Bhima Red	0.113	0.156	0.135
Bhima Raj	0.126	0.182	0.154
Bhima Shubra	0.120	0.178	0.149
Bhima Super	0.126	0.180	0.153
Mean	0.139	0.177	
Interaction (Treatment*Genotype)			
SEm±	0.005		
CD (P ≤ 0.05)	**0.015**		
Interaction (Genotype*Treatment)			
SEm±	0.005		
CD (P ≤ 0.05)	**0.014**		

LAI (2023)			
	W. L	**Control**	**Mean**
Acc.1666	0.178	0.188	0.183
Acc.1630	0.178	0.182	0.180
W-355	0.165	0.182	0.173
Bhima Dark Red	0.178	0.189	0.183
Bhima Red	0.133	0.153	0.143
Bhima Raj	0.151	0.189	0.170
Bhima Shubra	0.132	0.173	0.153
Bhima Super	0.134	0.162	0.148
Mean	0.156	0.177	
Interaction (Treatment*Genotype)			
SEm±	0.006		
CD (P ≤ 0.05)	**0.017**		
Interaction (Genotype*Treatment)			
SEm±	0.006		
CD (P ≤ 0.05)	**0.022**		

LAI (2024)			
	W. L	**Control**	**Mean**
Acc.1666	0.177	0.201	0.189
Acc.1630	0.166	0.190	0.178
W-355	0.165	0.192	0.178
Bhima Dark Red	0.168	0.187	0.178
Bhima Red	0.135	0.191	0.163
Bhima Raj	0.137	0.193	0.165
Bhima Shubra	0.141	0.193	0.167
Bhima Super	0.135	0.195	0.165
Mean	0.153	0.193	
Interaction (Treatment*Genotype)			
SE (m) ±	0.006		
CD at 5%	**0.017**		
Interaction (Genotype*Treatment)			
SEm±	0.005		
CD (P ≤ 0.05)	**0.016**		

LAI (2024)			
	W. L	**Control**	**Mean**
Acc.1666	0.174	0.203	0.189
Acc.1630	0.146	0.192	0.169
W-355	0.144	0.194	0.169
Bhima Dark Red	0.162	0.201	0.181
Bhima Red	0.179	0.187	0.183
Bhima Raj	0.162	0.200	0.181
Bhima Shubra	0.165	0.187	0.176
Bhima Super	0.153	0.177	0.165
Mean	0.161	0.193	
Interaction (Treatment*Genotype)			
SE (m) ±	0.007		
CD at 5%	**0.020**		
Interaction (Genotype*Treatment)			
SEm±	0.007		
CD (P ≤ 0.05)	**0.022**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.3 (a) Effect of waterlogging treatment on leaf area index of onion genotypes at different growth stages during 2023 and 2024.

The leaf area index (LAI) data showed non-significant differences in waterlogging treatments, genotypes and interaction at 45 DAT in both years (Table 13). Significant differences were recorded at 55 DAT, 75 DAT, and at harvest, particularly in 2023. Among the genotypes, Acc.1666 exhibited the highest LAI at 55 DAT (0.174 in 2023, 0.189 in 2024), 75 DAT (0.183 in 2023, 0.189 in 2024), and at harvest (0.143 in 2023, 0.136 in 2024), maintaining values statistically at par with Bhima Dark Red and Bhima Raj at various stages. Bhima Red consistently showed the lowest LAI across these stages, with values of 0.135 at 55 DAT and 0.120 at harvest in 2023 (Table 13).

The significant reduction in leaf area index (LAI) under waterlogging stress from 55 DAT onward reflects the detrimental impact of prolonged hypoxia on leaf expansion and canopy development (Ren *et al.,* 2016). Acc.1666's consistently higher LAI, comparable to Bhima Dark Red and Bhima Raj, demonstrates its superior ability to maintain leaf growth and optimize light interception, which is critical for sustaining photosynthesis and biomass production under stress (Ren *et al.,* 2016). The poor performance of Bhima Red, with the lowest LAI values, indicates its susceptibility due to impaired water and nutrient uptake under waterlogged conditions. These differences highlight the genetic variability for stress adaptation, emphasizing the importance of selecting genotypes like Acc.1666 for environments prone to waterlogging.

4.2.3 (b) Interaction effect between waterlogging treatment and genotypes on leaf area index at different growth stages during 2023 and 2024.

At 55 DAT in 2023, Acc.1666 under control exhibited the highest leaf area index (LAI) of 0.186, statistically at par with Bhima Raj (0.182), Acc.1630 (0.180), W-355 (0.180), and Bhima Super (0.180) under control conditions, while Bhima Red under waterlogging had the lowest LAI (0.113). At 75 DAT in 2023, Bhima Dark Red under control and Bhima Raj under control both recorded the highest LAI (0.189), at par with Acc.1666 (0.188), Acc.1630 (0.182), and W-355 (0.182) under control, whereas Bhima Red under waterlogging showed the minimum LAI (0.133) (Table 13.1). In 2024 at 55 DAT, Acc.1666 under control again led with the highest LAI (0.201), at par with Bhima Super (0.195), Bhima Raj (0.193), Bhima Shubra (0.193), W-355 (0.192), Bhima Red (0.191), and Acc.1630 (0.190) under control, while Bhima Red and Bhima Super under waterlogging both had the lowest LAI (0.135). At 75 DAT in 2024, Acc.1666 under control and

Bhima Dark Red under control recorded the highest LAI (0.203 and 0.201), at par with Bhima Raj (0.200), W-355 (0.194), and Acc.1630 (0.192) under control, with Acc.1630 and W-355 under waterlogging showing the lowest LAI (0.144) (Table 13.1). These results confirm Acc.1666's superior canopy development and the vulnerability of Bhima Red under waterlogging stress.

The interaction effects reveal that Acc.1666 consistently maintains the highest leaf area index (LAI) under control conditions, indicating its superior ability to sustain canopy growth and optimize light capture for photosynthesis (Weraduwage *et al.,* 2015). This genotype's resilience likely stems from a robust root system and efficient nutrient uptake, enabling better leaf expansion even under stress. Conversely, Bhima Red shows the lowest LAI under waterlogging, reflecting its vulnerability to hypoxic stress that hampers leaf development and reduces overall canopy size (Ren *et al.,* 2016). The comparable LAI values among other genotypes under control suggest inherent genetic potential, but their marked reduction under waterlogging highlights the critical impact of stress on leaf growth (Weraduwage *et al.,* 2015). These findings underscore selecting genotypes like Acc.1666 for waterlogging tolerance to ensure stable canopy and productivity.

4.2.4: Net assimilation rate (NAR - *gm^{-2} day^{-1}*)

Table 14: Effect of waterlogging treatment on net assimilation rate (g m^{-2} day^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

Net Assimilation Rate *(gm^{-2} day^{-1})*								
	30 DAT- 45 DAT		**45 DAT -55 DAT**		**55 DAT-75 DAT**		**75 DAT- Harvest**	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	0.110	0.120	-0.074	-0.054	0.010	0.010	0.110	0.120
Control	0.120	0.180	0.124	0.076	0.020	0.020	0.090	0.090
SEm±	0.000	0.010	0.003	0.009	0.000	0.000	0.000	0.010
CD (P ≤ 0.05)	**NS**	**0.060**	**0.021**	**0.056**	**NS**	**NS**	**0.020**	**0.030**
(Genotype)								
Acc. 1666	0.130	0.170	0.046	0.025	0.020	0.020	0.090	0.100
Acc.1630	0.130	0.160	0.020	-0.005	0.010	0.010	0.090	0.090
W 355	0.120	0.160	0.030	-0.003	0.010	0.010	0.100	0.110
Bhima Dark Red	0.120	0.160	0.033	0.037	0.020	0.020	0.090	0.100
Bhima Red	0.120	0.150	0.011	0.004	0.010	0.020	0.130	0.110
Bhima Raj	0.120	0.130	0.007	0.018	0.010	0.010	0.110	0.110
Bhima Shubra	0.100	0.140	0.015	-0.004	0.010	0.010	0.120	0.120
Bhima Super	0.100	0.130	0.040	0.018	0.020	0.010	0.110	0.110
SEm±	0.010	0.010	0.009	0.015	0.000	0.010	0.000	0.010
CD (P ≤ 0.05)	**NS**	**NS**	**0.026**	**0.044**	**NS**	**NS**	**0.000**	**0.040**
Interaction (Treatment*Genotype)								
Sem ±	0.010	0.020	0.010	0.020	0.000	0.010	0.000	0.000
CD (P ≤ 0.05)	**NS**	**NS**	**0.040**	**0.060**	**NS**	**NS**	**0.010**	**0.010**
Interaction (Genotype*Treatment)								
Sem ±	NS	NS	0.013	0.022	0.003	0.010	0.001	0.014
CD (P ≤ 0.05)	**0.010**	**0.020**	**0.039**	**0.065**	**NS**	**NS**	**0.002**	**0.041**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 14.1: Interaction effect between waterlogging treatment and genotypes on net assimilation rate (g m^{-2} day^{-1}) at different growth stages during 2023 and 2024.

NAR 45 DAT -55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	-0.03	0.12	0.05
Acc.1630	-0.06	0.10	0.02
W-355	-0.04	0.10	0.03
Bhima Dark Red	-0.06	0.13	0.03
Bhima Red	-0.12	0.14	0.01
Bhima Raj	-0.09	0.10	0.01
Bhima Shubra	-0.12	0.15	0.02
Bhima Super	-0.07	0.15	0.04
Mean	-0.07	0.12	
Interaction (Treatment*Genotype)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.04**		
Interaction (Genotype*Treatment)			
SEm±	**0.01**		
CD (P ≤ 0.05)	**0.04**		

NAR 75 DAT -Harvest (2023)			
	W. L	**Control**	**Mean**
Acc.1666	0.08	0.10	0.09
Acc.1630	0.09	0.09	0.09
W-355	0.11	0.08	0.10
Bhima Dark Red	0.09	0.09	0.09
Bhima Red	0.14	0.12	0.13
Bhima Raj	0.12	0.09	0.11
Bhima Shubra	0.14	0.09	0.12
Bhima Super	0.13	0.09	0.11
Mean	0.11	0.09	
Interaction (Treatment*Genotype)			
SEm±	0.00		
CD (P ≤ 0.05)	**0.01**		
Interaction (Genotype*Treatment)			
SEm±	**0.00**		
CD (P ≤ 0.05)	**0.00**		

NAR 45 DAT -55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	-0.03	0.08	0.02
Acc.1630	-0.05	0.04	-0.01
W-355	-0.04	0.04	0.00
Bhima Dark Red	-0.04	0.12	0.04
Bhima Red	-0.06	0.07	0.00
Bhima Raj	-0.05	0.09	0.02
Bhima Shubra	-0.09	0.08	0.00
Bhima Super	-0.07	0.10	0.02
Mean	-0.05	0.08	
Interaction (Treatment*Genotype)			
SEm±	0.02		
CD (P ≤ 0.05)	**0.06**		
Interaction (Genotype*Treatment)			
SEm±	0.02		
CD (P ≤ 0.05)	0.06		

NAR 75 DAT -Harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	0.09	0.10	0.10
Acc.1630	0.10	0.09	0.09
W-355	0.12	0.09	0.11
Bhima Dark Red	0.11	0.09	0.10
Bhima Red	0.12	0.09	0.11
Bhima Raj	0.12	0.10	0.11
Bhima Shubra	0.14	0.09	0.12
Bhima Super	0.13	0.09	0.11
Mean	0.12	0.09	
Interaction (Treatment*Genotype)			
SEm±	0.00		
CD (P ≤ 0.05)	**0.01**		
Interaction (Genotype*Treatment)			
SEm±	0.01		
CD (P ≤ 0.05)	0.04		

W.L: Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.4 (a) Effect of waterlogging treatment on net assimilation rate (g m^{-2} day^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

From 30 DAT to 45 DAT, the net assimilation rate (NAR) data was found to be non-significant in the waterlogging treatments, genotypes and their interaction in both 2023 and 2024 (Table 14). Between 45 DAT to 55 DAT, data showed significant differences in both years for the waterlogging and genotype sub-plot. During this period, the highest NAR in 2023 was observed in Acc.1666 (0.046 gm m^{-2} day^{-1}), while Bhima Raj recorded the lowest (0.007 gm m^{-2} day^{-1}). In 2024, Acc.1666 again showed the highest NAR (0.025), with Acc.1630 having the lowest (-0.005). From 55 DAT to 75 DAT, the data was non-significant across all experimental factors. Between 75 DAT and harvest, significant differences occurred, with Bhima Red exhibiting the highest NAR (0.13 in 2023, 0.11 in 2024), and Acc.1630 and W-355 showing the lowest values (both 0.09 in 2023 and 2024) (Table 14).

The results indicate that waterlogging significantly impacts net assimilation rate (NAR) during the mid-growth stages (45-55 DAT and 75 DAT to harvest), reflecting the stress-induced reduction in photosynthetic efficiency (Sharma *et al.,* 2022). Acc.1666's consistently higher NAR under stress suggests its superior capacity to sustain photosynthesis, likely due to better root aeration and antioxidant defenses that mitigate hypoxic damage (Pan *et al.,* 2021). Conversely, genotypes like Bhima Raj and Acc.1630 show lower NAR values, indicating susceptibility to waterlogging's negative effects on chloroplast function and carbon fixation (Ullah *et al.,* 2024). These findings highlight the importance of selecting waterlogging-tolerant genotypes such as Acc.1666 for maintaining photosynthetic productivity under adverse conditions.

4.2.4 (b) Interaction effect between waterlogging treatment and genotypes on net assimilation rate (g m^{-2} day^{-1}) at different growth stages during 2023 and 2024.

At 45 to 55 DAT in 2023, Bhima Super under control recorded the highest net assimilation rate (NAR) at 0.15 gm m^{-2} day^{-1}, statistically at par with Bhima Shubra (0.15), Bhima Red (0.14), and Bhima Dark Red (0.13), while Bhima Red and Bhima Shubra under waterlogging had the lowest NAR at -0.12 gm m^{-2} day^{-1}. At 75 DAT to harvest in 2023, Bhima Red under waterlogging exhibited the highest NAR (0.14), statistically comparable to Bhima Shubra (0.14), Bhima Raj (0.12), and Bhima Super (0.13), whereas Acc.1630 and Bhima Dark Red under control had the lowest values (0.09) (Table 14.1). In 2024 at 45 to 55 DAT, Bhima Dark Red under control led with 0.12 gm m^{-2} day^{-1}, at par with Bhima Super (0.10) and Bhima Raj (0.09), while Bhima Shubra under waterlogging had the lowest NAR (-0.09). Between 75 DAT and harvest in 2024, Bhima Shubra under waterlogging showed the highest NAR (0.14), statistically matched by Bhima Red (0.12), Bhima Super (0.13), and Bhima Raj (0.12), with Acc.1630 under control recording the lowest (0.09) (Table 14.1). These results illustrate the variable photosynthetic recovery and efficiency among genotypes under waterlogging stress, with Bhima Red and Shubra demonstrating notable resilience during reproductive stages.

The interaction analysis revealed significant genotypic variation in net assimilation rate (NAR) under waterlogging stress, particularly during critical growth stages. Bhima Super and Bhima Shubra consistently showed high NAR under control conditions and demonstrated notable resilience under waterlogging, maintaining photosynthetic efficiency likely due to enhanced stress adaptation mechanisms such as efficient stomatal regulation and antioxidant activity (Gedam *et al.,* 2023). Conversely, Bhima Red and Bhima Shubra under waterlogging had the lowest NAR during mid-growth, reflecting temporary photoinhibition or metabolic disruption due to oxygen deficiency (Pan *et al.,* 2021). However, their recovery and higher NAR in later stages suggest compensatory photosynthetic activity during reproductive growth. Genotypes like Acc.1630 exhibited consistently lower NAR, indicating susceptibility. These findings highlight the dynamic photosynthetic responses and underscore the potential of resilient genotypes for breeding programs targeting waterlogging tolerance.

4.2.5: Crop growth rate (CGR- *gm⁻²day⁻¹*)

Table 15: Effect of waterlogging treatment on crop growth rate (g m^{-2} day^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

Crop Growth rate ($gm^{-2}day^{-1}$)								
	30 DAT- 45 DAT		**45 DAT -55 DAT**		**55 DAT-75 DAT**		**75 DAT- Harvest**	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	2.370	2.350	-0.150	-0.190	0.010	0.010	2.370	2.350
Control	2.270	2.340	0.290	0.190	0.000	0.000	2.270	2.340
SEm±	0.080	0.220	0.010	0.030	0.000	0.000	0.080	0.220
CD (P ≤ 0.05)	**NS**	**NS**	**0.050**	**0.160**	**NS**	**NS**	**NS**	**NS**
(Genotype)								
Acc. 1666	2.200	2.380	0.100	0.030	0.010	0.000	2.200	2.380
Acc.1630	2.180	2.160	0.060	-0.030	0.010	-0.010	2.180	2.160
W 355	2.140	2.220	0.050	-0.020	0.010	-0.010	2.140	2.220
Bhima Dark Red	2.190	2.290	0.100	0.060	0.010	0.000	2.190	2.290
Bhima Red	2.560	2.440	0.010	-0.020	0.010	0.020	2.560	2.440
Bhima Raj	2.490	2.440	0.060	0.010	0.010	0.010	2.490	2.440
Bhima Shubra	2.490	2.510	0.050	-0.050	0.000	0.010	2.490	2.510
Bhima Super	2.350	2.310	0.110	0.030	0.000	0.000	2.350	2.310
SEm±	0.100	0.300	0.020	0.030	0.000	0.000	0.100	0.200
CD (P ≤ 0.05)	**NS**	**NS**	**0.060**	**0.090**	**NS**	**NS**	**0.280**	**0.600**
Interaction (Treatment*Genotype)								
Sem ±	0.140	0.430	0.030	0.040	0.010	0.010	0.140	0.260
CD (P ≤ 0.05)	**NS**	**NS**	**0.090**	**0.130**	**NS**	**NS**	**0.400**	**0.770**
Interaction (Genotype*Treatment)								
Sem ±	0.153	0.455	0.029	0.047	0.006	0.007	0.153	0.355
CD (P ≤ 0.05)	**0.587**	**NS**	**0.091**	**0.181**	**NS**	**0.022**	**0.587**	**1.065**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm±: Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 15.1: Interaction effect between waterlogging treatment and genotypes on crop growth rate (g m^{-2} day^{-1}) at different growth stages during 2023 and 2024.

CGR 45 DAT -55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	-0.10	0.29	0.10
Acc.1630	-0.10	0.23	0.06
W-355	-0.13	0.23	0.05
Bhima Dark Red	-0.10	0.30	0.10
Bhima Red	-0.27	0.30	0.01
Bhima Raj	-0.13	0.25	0.06
Bhima Shubra	-0.23	0.34	0.05
Bhima Super	-0.13	0.35	0.11
Mean	-0.15	0.29	
Interaction (Treatment*Genotype)			
SEm±	0.03		
CD (P ≤ 0.05)	**0.09**		
Interaction (Genotype*Treatment)			
SEm±	0.03		
CD (P ≤ 0.05)	**0.09**		

CGR 75 DAT -Harvest (2023)			
	W. L	**Control**	**Mean**
Acc.1666	1.95	2.45	2.20
Acc.1630	2.07	2.29	2.18
W-355	2.30	1.99	2.14
Bhima Dark Red	2.09	2.29	2.19
Bhima Red	2.61	2.50	2.56
Bhima Raj	2.64	2.35	2.49
Bhima Shubra	2.80	2.18	2.49
Bhima Super	2.55	2.16	2.35
Mean	2.37	2.27	
Interaction (Treatment*Genotype)			
SEm±	0.14		
CD (P ≤ 0.05)	**0.40**		
Interaction (Genotype*Treatment)			
SEm±	0.15		
CD (P ≤ 0.05)	**0.59**		

CGR 45 DAT -55 DAT (2024)			
	W. L	**Control**	**Mean**
Acc.1666	-0.13	0.20	0.03
Acc.1630	-0.17	0.10	-0.03
W-355	-0.13	0.10	-0.02
Bhima Dark Red	-0.17	0.29	0.06
Bhima Red	-0.20	0.16	-0.02
Bhima Raj	-0.20	0.21	0.01
Bhima Shubra	-0.30	0.20	-0.05
Bhima Super	-0.20	0.25	0.03
Mean	-0.19	0.19	
Interaction (Treatment*Genotype)			
SEm±	0.04		
CD (P ≤ 0.05)	**0.13**		
Interaction (Genotype*Treatment)			
SEm±	0.05		
CD (P ≤ 0.05)	**0.18**		

CGR 75 DAT -Harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	2.09	2.66	2.38
Acc.1630	1.96	2.36	2.16
W-355	2.29	2.15	2.22
Bhima Dark Red	2.35	2.24	2.29
Bhima Red	2.54	2.34	2.44
Bhima Raj	2.41	2.46	2.44
Bhima Shubra	2.74	2.28	2.51
Bhima Super	2.42	2.21	2.31
Mean	2.35	2.34	
Interaction (Treatment*Genotype)			
SEm±	0.26		
CD (P ≤ 0.05)	**0.77**		
Interaction (Genotype*Treatment)			
SEm±	0.35		
CD (P ≤ 0.05)	**1.06**		

W.L: Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.5 (a) Effect of waterlogging treatment on crop growth rate (g m^{-2} day^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

From 30–45 DAT, crop growth rate (CGR) was non-significant in the waterlogging treatments, genotypes and their interaction in both 2023 and 2024; from 45–55 DAT, CGR was significant across waterlogging treatments, genotypes and interaction in both years, with the highest genotype values in 2023 for Bhima Super (0.11 gm^{-2} day^{-1}) and the lowest for Bhima Red (0.01), while in 2024 the highest was Bhima Dark Red (0.06) and the lowest Bhima Shubra (-0.05); from 55–75 DAT, CGR was non-significant for main, sub, and interaction in both years; from 75 DAT to harvest, the waterlogging was non-significant but sub-plot and interaction were significant in both years, with the highest genotype CGR in 2023 for Bhima Red (2.56 gm^{-2} day^{-1}) and the lowest for W-355 (2.14), and in 2024 the highest for Bhima Shubra (2.51) and the lowest for Acc.1630 (2.16) (Table 15).

The non-significant variation in CGR during early and mid-growth phases indicates uniform vegetative growth under similar environmental conditions, whereas the significant differences at 45–55 DAT and from 75 DAT to harvest suggest genotype-specific responses to resource utilization and bulb development efficiency. Higher CGR in superior genotypes may be attributed to enhanced photosynthetic rate, assimilate translocation, and better tolerance to transient stress conditions (Pawar *et al.,* 2025).

4.2.5 (b) Interaction effect between waterlogging treatment and genotypes on crop growth rate (g m^{-2} day^{-1}) at different growth stages during 2023 and 2024.

At 45 to 55 DAT in 2023, Bhima Super under control recorded the highest crop growth rate (CGR) of 0.35 gm m^{-2} day^{-1}, statistically at par with Bhima Shubra (0.34), Bhima Dark Red (0.30), and Bhima Red (0.30) under control, while Bhima Red under waterlogging had the lowest CGR (-0.27). During 75 DAT to harvest in 2023, Bhima Shubra under waterlogging exhibited the highest CGR (2.80), closely followed by Bhima Red (2.61) and Bhima Raj (2.64) under waterlogging, with W-355 under control recording the lowest CGR (1.99) (Table 15.1). In 2024 at 45 to 55 DAT, Bhima Dark Red under control led with 0.29, statistically comparable to Bhima Super (0.25) and Bhima Raj (0.21), whereas Bhima Shubra under waterlogging showed the lowest CGR (-0.30). Between 75 DAT and harvest in 2024, Bhima Shubra under waterlogging recorded the highest

CGR (2.74), statistically similar to Bhima Red (2.54) and Bhima Raj (2.41), while Acc.1630 under control had the lowest CGR (1.96) (Table 15.1).

The higher CGR in Bhima Super, Bhima Shubra, Bhima Dark Red, and Bhima Red under control conditions at 45-55 DAT likely reflects optimal physiological functioning, including efficient photosynthesis and nutrient uptake, which are disrupted under waterlogging stress (Pawar *et al.,* 2025). Waterlogging results in oxygen deficiency in the root zone, reducing root respiration and nutrient absorption, thus leading to negative or lower CGR as seen in Bhima Red and Bhima Shubra under stress (Salunkhe *et al.,* 2022). The elevated CGR during 75 DAT to harvest in some genotypes under waterlogging suggests a recovery or compensation phase possibly due to genotype-specific tolerance mechanisms that maintain carbon assimilation and support bulb development despite stress (Pawar *et al.,* 2025). The variation in CGR among genotypes highlights differential waterlogging tolerance, linked to root system resilience, anaerobic metabolism adaptation, and efficient translocation of assimilates to the bulb (Otitoloju *et al.,* 2024). These observations are consistent with literature indicating that onion, with its shallow root system, is vulnerable to waterlogging but certain genotypes can partially mitigate these effects by physiological and biochemical adjustments.

4.2.6: Relative growth rate (RGR- $gg^{-1}day^{-1}$)

Table 16: Effect of waterlogging treatment on relative growth rate (g g⁻¹ day⁻¹) of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT- 45 DAT		**45 DAT -55 DAT**		**55 DAT-75 DAT**		**75 DAT- Harvest**	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	0.070	0.080	-0.027	-0.031	0.005	0.004	0.029	0.030
Control	0.080	0.100	0.045	0.033	0.005	0.005	0.022	0.021
SEm±	0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.000
CD (P ≤ 0.05)	**NS**	**NS**	**0.008**	**0.007**	**NS**	**NS**	**0.006**	**0.002**
(Genotype)								
Acc. 1666	0.080	0.100	0.002	0.010	0.005	0.005	0.021	0.022
Acc.1630	0.070	0.090	0.004	0.004	0.005	0.005	0.024	0.026
W 355	0.080	0.100	0.006	0.000	0.005	0.005	0.024	0.020
Bhima Dark Red	0.080	0.100	0.015	0.008	0.005	0.005	0.021	0.023
Bhima Red	0.070	0.090	0.004	-0.006	0.004	0.005	0.029	0.030
Bhima Raj	0.070	0.080	0.004	-0.001	0.005	0.003	0.028	0.027
Bhima Shubra	0.070	0.090	0.023	0.000	0.005	0.004	0.029	0.028
Bhima Super	0.070	0.090	0.012	-0.007	0.005	0.004	0.026	0.029
SEm±	0.000	0.010	0.003	0.004	0.000	0.002	0.001	0.002
CD (P ≤ 0.05)	**NS**	**NS**	**0.009**	**0.012**	**NS**	**NS**	**0.004**	**0.007**
Interaction (Treatment*Genotype)								
Sem ±	0.000	0.010	0.000	0.010	0.000	0.000	0.002	0.003
CD (P ≤ 0.05)	**NS**	**NS**	**0.010**	**0.020**	**NS**	**NS**	**0.005**	**0.010**
Interaction (Genotype*Treatment)								
Sem ±	0.005	0.009	0.004	0.006	0.001	0.003	0.002	0.003
CD (P ≤ 0.05)	**NS**	**NS**	**0.014**	**0.017**	**NS**	**NS**	**0.007**	**0.009**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 16.1: Interaction effect between waterlogging treatment and genotypes on relative growth rate (g g^{-1} day^{-1}) at different growth stages during 2023 and 2024.

RGR 45 DAT -55 DAT (2023)			
	W. L	Control	Mean
Acc.1666	-0.043	0.047	0.002
Acc.1630	-0.025	0.034	0.004
W-355	-0.023	0.035	0.006
Bhima Dark Red	-0.015	0.045	0.015
Bhima Red	-0.041	0.049	0.004
Bhima Raj	-0.028	0.037	0.004
Bhima Shubra	-0.011	0.056	0.023
Bhima Super	-0.033	0.057	0.012
Mean	-0.027	0.045	
Interaction (Treatment*Genotype)			
SEm±	0.004		
CD (P ≤ 0.05)	**0.013**		
Interaction (Genotype*Treatment)			
SEm±	0.004		
CD (P ≤ 0.05)	**0.014**		

RGR 75 DAT -Harvest (2023)			
	W. L	Control	Mean
Acc.1666	0.020	0.023	0.021
Acc.1630	0.025	0.022	0.024
W-355	0.029	0.020	0.024
Bhima Dark Red	0.022	0.021	0.021
Bhima Red	0.033	0.025	0.029
Bhima Raj	0.033	0.023	0.028
Bhima Shubra	0.038	0.021	0.029
Bhima Super	0.031	0.021	0.026
Mean	0.029	0.022	
Interaction (Treatment*Genotype)			
SEm±	0.000		
CD (P ≤ 0.05)	**0.010**		
Interaction (Genotype*Treatment)			
SEm±	0.002		
CD (P ≤ 0.05)	**0.007**		

RGR 45 DAT -55 DAT (2024)			
	W. L	Control	Mean
Acc.1666	-0.012	0.033	0.010
Acc.1630	-0.022	0.030	0.004
W-355	-0.026	0.026	0.000
Bhima Dark Red	-0.018	0.035	0.008
Bhima Red	-0.044	0.033	-0.006
Bhima Raj	-0.039	0.036	-0.001
Bhima Shubra	-0.033	0.034	0.000
Bhima Super	-0.051	0.037	-0.007
Mean	-0.031	0.033	
Interaction (Treatment*Genotype)			
SEm±	0.006		
CD (P ≤ 0.05)	0.017		
Interaction (Genotype*Treatment)			
SEm±	0.006		
CD (P ≤ 0.05)	**0.017**		

RGR 75 DAT -Harvest (2024)			
	W. L	Control	Mean
Acc.1666	0.021	0.024	0.022
Acc.1630	0.028	0.023	0.026
W-355	0.026	0.014	0.020
Bhima Dark Red	0.023	0.024	0.023
Bhima Red	0.037	0.024	0.030
Bhima Raj	0.034	0.021	0.027
Bhima Shubra	0.038	0.018	0.028
Bhima Super	0.036	0.022	0.029
Mean	0.030	0.021	
Interaction (Treatment*Genotype)			
SEm±	0.003		
CD (P ≤ 0.05)	**0.010**		
Interaction (Genotype*Treatment)			
SEm±	0.003		
CD (P ≤ 0.05)	**0.009**		

W.L: Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.6 (a) Effect of waterlogging treatment on relative growth rate (g g^{-1} day^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

Effect of waterlogging treatment on relative growth rate (RGR, g g^{-1} day^{-1}) of onion genotypes From 30–45 DAT, relative growth rate (RGR) was non-significant in the waterlogging treatments, genotypes and their interaction during both 2023 and 2024, indicating similar proportional biomass increase among treatments and genotypes at early growth. From 45–55 DAT, RGR was significant at main, sub-plot, and interaction levels in both years, with higher values under control than waterlogging; in 2023, Bhima Shubra recorded the highest mean RGR (0.023 g g^{-1} day^{-1}), followed by Bhima Dark Red (0.015) and Bhima Super (0.012), while Acc.1666 showed the lowest (0.002), whereas in 2024 Bhima Shubra (0.000) and W-355 (0.000) had the lowest mean RGR and Acc.1666 the highest (0.010). From 55–75 DAT, RGR remained non-significant for main, sub-plot, and interaction in both seasons, reflecting comparable relative dry matter accumulation across genotypes and treatments. Between 75 DAT and harvest, main-plot effects were significant in both years, with control plots showing slightly higher RGR in 2023 (0.022 vs 0.029 g g^{-1} day^{-1} under waterlogging) and lower in 2024 (0.021 vs 0.030 under waterlogging), while sub-plot and interaction effects were also significant, with Bhima Red and Bhima Shubra exhibiting relatively higher RGR (0.029–0.030 g g^{-1} day^{-1}) compared with W-355 and Acc.1666 across years (Table 16).

The relative growth rate (RGR) results demonstrate that waterlogging exerts its most pronounced effect during the mid-growth stages (45 to 55 DAT and 75 DAT to harvest), reflecting the sensitivity of onion growth to hypoxic stress during critical development phases. The significant reductions in RGR during these intervals suggest impaired cell division and expansion due to oxygen deficiency, which disrupts energy metabolism and nutrient uptake (Ullah *et al.,* 2024). Genotypes like Bhima Shubra and Bhima Red, which showed higher RGR during these stages, likely possess adaptive traits such as enhanced anaerobic metabolism or better root aeration, enabling them to sustain growth under stress (Pan *et al.,* 2021). In contrast, Acc.1666's consistently lower RGR in these periods may indicate a strategic conservation of resources or slower growth under adverse conditions. The non-significant differences in early and mid-late growth stages highlight that waterlogging impacts are more limited outside these sensitive periods. These findings emphasize the importance of targeting genotypes with resilience during mid and late growth stages for breeding programs aimed at improving waterlogging tolerance in onions.

4.2.6 (b) Interaction effect between waterlogging treatment and genotypes on relative growth rate (g g^{-1} day^{-1}) at different growth stages during 2023 and 2024.

At 45–55 DAT in 2023, all genotypes under waterlogging exhibited negative RGR, with Bhima Shubra (−0.011 g g^{-1} day^{-1}) being the least affected and Bhima Red (−0.041) and Acc.1666 (−0.043) showing the most pronounced decline, whereas under control Bhima Super registered the highest RGR (0.057 g g^{-1} day^{-1}), closely followed by Bhima Shubra (0.056), Bhima Red (0.049), and Acc.1666 (0.047) (Table 16.1). During 75 DAT to harvest in 2023, RGR values were positive under both waterlogging and control, with Bhima Shubra under waterlogging achieving the highest RGR (0.038 g g^{-1} day^{-1}), followed by Bhima Red and Bhima Raj (0.033), whereas the lowest values were recorded by W-355 under control (0.020) and Acc.1666 under waterlogging (0.020). In 2024, a similar pattern was observed at 45–55 DAT, where all genotypes under waterlogging showed negative RGR, with the most severe reduction in Bhima Super (−0.051 g g^{-1} day^{-1}) and Bhima Red (−0.044), while under control, Acc.1666 (0.033), Bhima Dark Red (0.035), and Bhima Super (0.037) recorded the highest RGR. Between 75 DAT and harvest in 2024, Bhima Shubra under waterlogging maintained the highest RGR (0.038 g g^{-1} day^{-1}), followed by Bhima Red (0.037) and Bhima Super (0.036), whereas the lowest RGR occurred in W-355 under control (0.014) and Bhima Raj under control (0.021) (Table 16.1).

The interaction effects on relative growth rate (RGR) reveal significant genotypic differences in response to waterlogging stress, especially during the critical mid-growth stages. Bhima Shubra and Bhima Super under control consistently showed the highest RGR, reflecting their potential for vigorous growth when unstressed. However, under waterlogging, genotypes such as Acc.1666, Acc. 1630, and Bhima Red exhibited the lowest RGR, indicating sensitivity to hypoxic conditions which may impair cell division and expansion (Sharma *et al.,* 2022). Interestingly, Bhima Shubra, Bhima Red, and Bhima Super demonstrated recovery and higher RGR during the reproductive phase under waterlogging, suggesting adaptive physiological mechanisms that facilitate growth compensation (Ren *et al.,* 2016). The variation in RGR highlights the importance of genotype-specific traits for waterlogging tolerance and underscores the potential of select genotypes for improving crop resilience under adverse conditions.

4.2.7: Absolute growth rate (AGR- *gday*$^{-1}$)

Table 17: Effect of waterlogging treatment on absolute growth rate (g day^{-1}) of onion genotypes at different growth stages during 2023 and 2024.

	30 DAT- 45 DAT		45 DAT -55 DAT		55 DAT-75 DAT		75 DAT- Harvest	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	2.01	2.52	-1.51	-1.38	0.30	0.36	2.37	2.35
Control	2.31	3.67	2.85	2.02	0.43	0.49	2.27	2.34
SEm±	0.07	0.22	0.06	0.09	0.03	0.05	0.08	0.22
CD (P ≤ 0.05)	**NS**	**NS**	**0.35**	**0.55**	**NS**	**NS**	**NS**	**NS**
(Genotype)								
Acc. 1666	2.33	3.62	1.19	1.10	0.43	0.43	2.20	2.38
Acc.1630	2.29	3.12	0.43	-0.09	0.38	0.37	2.18	2.16
W 355	2.31	3.40	0.56	-0.08	0.38	0.38	2.14	2.22
Bhima Dark Red	2.26	3.41	1.15	0.98	0.45	0.45	2.19	2.29
Bhima Red	2.12	2.94	0.21	0.12	0.30	0.50	2.56	2.44
Bhima Raj	2.18	2.70	0.39	0.34	0.33	0.63	2.49	2.44
Bhima Shubra	1.91	2.91	0.41	-0.07	0.33	0.33	2.49	2.51
Bhima Super	1.87	2.64	1.04	0.30	0.35	0.35	2.35	2.31
SEm±	0.11	0.13	0.19	0.21	0.04	0.14	0.10	0.07
CD (P ≤ 0.05)	**0.31**	**0.39**	**0.55**	**0.64**	**NS**	**NS**	**0.28**	**0.21**
Interaction (Treatment*Genotype)								
Sem ±	0.15	0.41	0.27	0.29	0.05	0.04	0.14	0.15
CD (P ≤ 0.05)	**NS**	**NS**	**0.78**	**0.88**	**NS**	**NS**	**0.40**	**0.46**
Interaction (Genotype*Treatment)								
Sem ±	0.16	0.44	0.26	0.46	0.06	0.05	0.15	0.25
CD (P ≤ 0.05)	**0.58**	**NS**	**0.79**	**NS**	**NS**	**NS**	**0.59**	**0.76**

DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 17.1: Interaction effect between waterlogging treatment and genotypes on absolute growth rate (g day^{-1}) at different growth stages during 2023 and 2024.

AGR 45 DAT -55 DAT (2023)			
	W. L	**Control**	**Mean**
Acc.1666	-0.53	2.92	1.19
Acc.1630	-1.40	2.25	0.43
W-355	-1.20	2.32	0.56
Bhima Dark Red	-0.70	3.00	1.15
Bhima Red	-2.53	2.95	0.21
Bhima Raj	-1.70	2.48	0.39
Bhima Shubra	-2.60	3.41	0.41
Bhima Super	-1.40	3.49	1.04
Mean	-1.51	2.85	
Interaction (Treatment*Genotype)			
SEm±	0.27		
CD (P ≤ 0.05)	**0.78**		
Interaction (Genotype*Treatment)			
SEm±	0.26		
CD (P ≤ 0.05)	**0.79**		

AGR 75 DAT -Harvest (2023)			
	W. L	**Control**	**Mean**
Acc.1666	1.95	2.45	2.20
Acc.1630	2.07	2.29	2.18
W-355	2.30	1.99	2.14
Bhima Dark Red	2.09	2.29	2.19
Bhima Red	2.61	2.50	2.56
Bhima Raj	2.64	2.35	2.49
Bhima Shubra	2.80	2.18	2.49
Bhima Super	2.55	2.16	2.35
Mean	2.37	2.27	
Interaction (Treatment*Genotype)			
SEm±	0.14		
CD (P ≤ 0.05)	**0.4**		
Interaction (Genotype*Treatment)			
SEm±	0.15		
CD (P ≤ 0.05)	**0.59**		

AGR 45 DAT -55 DAT			
	W. L	**Control**	**Mean**
Acc.1666	-0.60	2.79	1.10
Acc.1630	-1.30	1.13	-0.09
W-355	-1.20	1.04	-0.08
Bhima Dark Red	-1.07	3.02	0.98
Bhima Red	-1.30	1.55	0.12
Bhima Raj	-1.47	2.15	0.34
Bhima Shubra	-2.13	1.99	-0.07
Bhima Super	-1.93	2.54	0.30
Mean	-1.38	2.02	
Interaction (Treatment*Genotype)			
SEm±	0.29		
CD (P ≤ 0.05)	**0.88**		
Interaction (Genotype*Treatment)			
SEm±	0.46		
CD (P ≤ 0.05)	**1.39**		

AGR 75 DAT -Harvest (2024)			
	W. L	**Control**	**Mean**
Acc.1666	2.09	2.66	2.38
Acc.1630	1.96	2.36	2.16
W-355	2.29	2.15	2.22
Bhima Dark Red	2.35	2.24	2.29
Bhima Red	2.54	2.34	2.44
Bhima Raj	2.41	2.46	2.44
Bhima Shubra	2.74	2.28	2.51
Bhima Super	2.42	2.21	2.31
Mean	2.35	2.34	
Interaction (Treatment*Genotype)			
SEm±	0.15		
CD (P ≤ 0.05)	**0.46**		
Interaction (Genotype*Treatment)			
SEm±	0.25		
CD (P ≤ 0.05)	**0.76**		

W.L: Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

4.2.7 (a) Interaction effect between waterlogging treatment and genotypes on absolute growth rate (g day^{-1}) at different growth stages during 2023 and 2024.

From 30 to 45 DAT, the absolute growth rate (AGR) data was found to be non-significant in the waterlogging treatments, genotypes and their interaction in both 2023 and 2024 (Table 17). Between 45 and 55 DAT, significant differences were recorded in both years for the waterlogging treatments and genotypes. In 2023, Acc.1666 exhibited the highest AGR (1.19 g day^{-1}), statistically similar to Bhima Dark Red (1.15 g day^{-1}), while Bhima Red recorded the lowest AGR (0.21 g day^{-1}). In 2024, Acc.1666 again showed the highest AGR (1.10 g day^{-1}), with Acc.1630 having the lowest AGR (-0.09 g day^{-1}). The growth period from 55 to 75 DAT was non-significant for all factors. From 75 DAT to harvest, data was non-significant in main plot, but significant in sub-plot effects with Bhima Red showing the highest AGR (2.56 g day^{-1} in 2023, 2.44 g day^{-1} in 2024), and W-355 recording the lowest AGR (2.14 g day^{-1} in 2023, 2.22 g day^{-1} in 2024) (Table 17). This highlights the differential impact of waterlogging stress on growth rates, with Acc.1666 and Bhima Red demonstrating robust growth under stress conditions.

4.2.7 (b) Interaction effect of waterlogging treatment and genotypes on absolute growth rate (AGR- *gday*$^{-1}$) at key growth stages.

During 45 to 55 DAT in 2023, Bhima Shubra under waterlogging recorded the highest absolute growth rate (AGR) of 0.41 g day^{-1}, statistically at par with Bhima Red (0.21) and Bhima Raj (0.39) (Table 17.1). Conversely, Acc.1666 and Acc. 1630 exhibited the lowest AGRs of –1.40 and –1.70, indicating severe growth suppression due to waterlogging. In 2024, from 45 to 55 DAT, Bhima Shubra again showed the highest AGR (0.41), with Bhima Red (0.12) and Bhima Raj (0.34) also performing relatively well, while Acc.1666 and Acc.1630 showed the lowest values of –1.30 and –1.47. Between 75 DAT and harvest in 2023, Bhima Shubra and Bhima Red reached high AGRs of 2.80 and 2.54, respectively, with Bhima Red showing the highest. In 2024, similar patterns were observed with Bhima Shubra and Bhima Red again showing the highest AGRs of 2.74 and 2.54, while Acc.1666 and Acc.1630 recorded the lowest AGRs (Table 17.1), indicating that waterlogging severely affects growth in some genotypes, but others like Bhima Shubra and Bhima Red tend to recover or sustain higher growth rates during later stages.

The interaction results reveal that waterlogging differentially impacts absolute growth rate (AGR) among onion genotypes. Bhima Shubra demonstrated a remarkable capacity to sustain growth under waterlogging stress during 45 to 55 DAT, possibly due to more efficient anaerobic metabolism or superior root adaptations facilitating continued nutrient uptake (Masato *et al.,* 2021). Bhima Red and Bhima Raj also showed resilience with relatively higher AGRs, suggesting some tolerance mechanisms that mitigate oxygen deficiency effects. Conversely, Acc.1666 and Acc. 1630 experienced severe growth suppression, indicating sensitivity to hypoxia. Despite initial setbacks, genotypes like Bhima Shubra and Bhima Red recovered during the 75 DAT to harvest stage, maintaining high AGRs, which likely reflects compensatory growth later in the season. These findings stress the importance of selecting genotypes with strong adaptive growth responses for enhanced waterlogging tolerance in onions.

4.3: Biochemicals

Table 18: Effect of waterlogging treatment on biochemical parameters of onion bulb at harvest during 2023 and 2024.

	Pyruvic (μ mol g^{-1})		Proline (μ mol g^{-1})		Antioxidant (mg TE kg^{-1})		Protein (%)		TSS (°Brix)	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	5.99	6.88	1.41	1.38	406.23	322.33	3.41	3.50	9.97	10.84
Control	6.58	7.45	2.07	2.05	427.04	386.05	3.68	3.71	11.92	12.79
SEm±	0.08	0.08	0.10	0.03	2.76	3.59	0.03	0.05	0.08	0.08
CD (P ≤ 0.05)	**0.47**	**0.46**	**0.59**	**0.21**	**16.78**	**21.85**	**0.09**	**0.15**	**0.51**	**0.51**
(Genotype)										
Acc. 1666	7.45	9.00	2.38	2.36	546.18	637.28	4.32	4.48	11.35	12.35
Acc.1630	6.21	8.00	1.64	1.61	577.18	468.28	3.95	3.84	11.66	12.66
W 355	6.23	6.83	1.54	1.50	408.51	299.61	3.36	3.47	11.34	12.33
Bhima Dark Red	6.16	7.74	2.57	2.54	483.45	524.55	3.85	4.12	10.86	11.85
Bhima Red	6.70	6.78	1.22	1.19	529.57	233.42	3.31	3.35	10.36	10.35
Bhima Raj	6.40	6.01	1.58	1.55	357.20	298.30	3.07	3.12	11.21	12.20
Bhima Shubra	5.77	6.34	1.90	1.87	151.18	121.73	3.17	3.11	10.64	11.63
Bhima Super	5.38	6.62	1.08	1.06	279.78	250.33	3.32	3.35	10.15	11.14
SEm±	0.24	0.50	0.14	0.16	8.37	9.64	0.05	0.15	0.20	0.20
CD (P ≤ 0.05)	**0.71**	**1.44**	**0.42**	**0.48**	**24.24**	**27.92**	**0.15**	**0.42**	**0.58**	**0.58**
Interaction (Treatment*Genotype)										
Sem ±	0.35	0.70	0.20	0.23	11.83	13.63	0.08	0.21	0.28	0.28
CD (P ≤ 0.05)	**1.00**	**2.04**	**0.59**	**0.67**	**34.28**	**39.48**	**0.22**	**0.60**	**0.82**	**0.82**
Interaction (Genotype*Treatment)										
Sem ±	0.33	0.66	0.21	0.22	11.41	13.24	0.08	0.22	0.28	0.28
CD (P ≤ 0.05)	**1.02**	**1.95**	**0.76**	**0.66**	**35.17**	**41.47**	**0.26**	**0.78**	**0.89**	**0.89**

TSS: Total soluble solids; DAT: Days After Transplanting, B.T. (45 DAT): Before Waterlogging Treatment, A.T (55 DAT): After Waterlogging Treatment, SEm± : Standard Error of Mean, CD at 5%: Critical Difference (5% significance), NS: Not Significant.

Table 18.1: Interaction effect between waterlogging treatment and genotypes on biochemical parameters of onion bulb at harvest during 2023.

Pyruvic (µ mol g^{-1}) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	8.91	5.99	7.45
Acc.1630	6.43	5.98	6.21
W-355	6.27	6.20	6.23
Bhima Dark Red	6.96	5.36	6.16
Bhima Red	5.62	7.78	6.70
Bhima Raj	5.01	7.80	6.40
Bhima Shubra	4.5	7.04	5.77
Bhima Super	4.24	6.52	5.38
Mean	5.99	6.58	
Interaction (Treatment*Genotype)			
SEm±	0.35		
CD (P ≤ 0.05)	**1.05**		
Interaction (Genotype*Treatment)			
SEm±	0.33		
CD (P ≤ 0.05)	**1.02**		

Proline (µ mol g^{-1}) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	2.21	2.55	2.38
Acc.1630	1.49	1.78	1.64
W-355	1.53	1.55	1.54
Bhima Dark Red	1.75	3.39	2.57
Bhima Red	1.00	1.44	1.22
Bhima Raj	0.97	2.19	1.58
Bhima Shubra	1.34	2.46	1.90
Bhima Super	0.98	1.19	1.08
Mean	1.41	2.07	
Interaction (Treatment*Genotype)			
SEm±	0.19		
CD (P ≤ 0.05)	**0.59**		
Interaction (Genotype*Treatment)			
SEm±	0.21		
CD (P ≤ 0.05)	**0.76**		

Antioxidant (mg TE kg^{-1}) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	708.48	383.87	546.18
Acc.1630	590.92	563.44	577.18
W-355	459.15	357.87	408.51
Bhima Dark Red	613.50	353.41	483.45
Bhima Red	339.43	719.71	529.57
Bhima Raj	297.56	416.85	357.20
Bhima Shubra	120.63	181.72	151.18
Bhima Super	120.14	439.43	279.78
Mean	406.23	427.04	
Interaction (Treatment*Genotype)			
SEm±	11.83		
CD (P ≤ 0.05)	**34.28**		
Interaction (Genotype*Treatment)			
SEm±	11.41		
CD (P ≤ 0.05)	**35.17**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Table 18.2: Interaction effect between waterlogging treatment and genotypes on biochemical parameters of onion bulb at harvest during 2024.

Pyruvic (µ mol g-1) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	8.90	9.10	9.00
Acc.1630	8.40	7.59	8.00
W-355	7.34	6.32	6.83
Bhima Dark Red	8.50	6.98	7.74
Bhima Red	5.76	7.80	6.78
Bhima Raj	5.45	6.57	6.01
Bhima Shubra	5.30	7.38	6.34
Bhima Super	5.38	7.85	6.62
Mean	6.88	7.45	
Interaction (Treatment*Genotype)			
SEm±	0.7		
CD (P ≤ 0.05)	**2.04**		
Interaction (Genotype*Treatment)			
SEm±	0.66		
CD (P ≤ 0.05)	**1.95**		

Proline (µ mol g^{-1}) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	2.19	2.54	2.36
Acc.1630	1.45	1.77	1.61
W-355	1.49	1.52	1.50
Bhima Dark Red	1.73	3.36	2.54
Bhima Red	0.96	1.41	1.19
Bhima Raj	0.94	2.16	1.55
Bhima Shubra	1.31	2.43	1.87
Bhima Super	0.94	1.18	1.06
Mean	1.38	2.05	
Interaction (Treatment*Genotype)			
SEm±	0.23		
CD (P ≤ 0.05)	**0.67**		
Interaction (Genotype*Treatment)			
SEm±	0.22		
CD (P ≤ 0.05)	**0.66**		

Antioxidant (mg TE kg^{-1}) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	649.58	624.97	637.28
Acc.1630	432.02	504.54	468.28
W-355	300.25	298.97	299.61
Bhima Dark Red	554.60	494.51	524.55
Bhima Red	162.73	304.11	233.42
Bhima Raj	238.66	357.95	298.3
Bhima Shubra	120.63	122.82	121.73
Bhima Super	120.14	380.53	250.33
Mean	322.33	386.05	
Interaction (Treatment*Genotype)			
SEm±	13.63		
CD (P ≤ 0.05)	**39.48**		
Interaction (Genotype*Treatment)			
SEm±	13.24		
CD (P ≤ 0.05)	**41.47**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Table 18.3: Interaction effect between waterlogging treatment and genotypes on biochemical parameters of onion bulb at harvest during 2023 and 2024.

Protein (%) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	4.31	4.34	4.32
Acc.1630	4.08	3.82	3.95
W-355	3.50	3.22	3.36
Bhima Dark Red	4.20	3.49	3.85
Bhima Red	2.88	3.74	3.31
Bhima Raj	2.82	3.32	3.07
Bhima Shubra	2.69	3.64	3.17
Bhima Super	2.77	3.86	3.32
Mean	3.41	3.68	
Interaction (Treatment*Genotype)			
SEm±	0.08		
CD (P ≤ 0.05)	**0.22**		
Interaction (Genotype*Treatment)			
SEm±	0.08		
CD (P ≤ 0.05)	**0.26**		

TSS (°Brix) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	10.91	11.80	11.35
Acc.1630	10.30	13.03	11.66
W-355	10.01	12.67	11.34
Bhima Dark Red	10.75	10.97	10.86
Bhima Red	9.95	10.77	10.36
Bhima Raj	9.72	12.70	11.21
Bhima Shubra	9.44	11.83	10.64
Bhima Super	8.69	11.60	10.15
Mean	9.97	11.92	
Interaction (Treatment*Genotype)			
SEm±	0.28		
CD (P ≤ 0.05)	**0.82**		
Interaction (Genotype*Treatment)			
SEm±	0.28		
CD (P ≤ 0.05)	**0.89**		

Protein (%) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	4.63	4.34	4.48
Acc.1630	4.15	3.53	3.84
W-355	3.51	3.44	3.47
Bhima Dark Red	4.59	3.65	4.12
Bhima Red	2.89	3.8	3.35
Bhima Raj	2.95	3.29	3.12
Bhima Shubra	2.68	3.55	3.11
Bhima Super	2.63	4.07	3.35
Mean	3.5	3.71	
Interaction (Treatment*Genotype)			
SEm±	0.21		
CD (P ≤ 0.05)	**0.6**		
Interaction (Genotype*Treatment)			
SEm±	0.22		
CD (P ≤ 0.05)	**0.78**		

TSS (°Brix) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	11.9	12.79	12.35
Acc.1630	11.29	14.03	12.66
W-355	11.01	13.66	12.33
Bhima Dark Red	11.74	11.96	11.85
Bhima Red	9.95	10.76	10.35
Bhima Raj	10.71	13.69	12.2
Bhima Shubra	10.44	12.83	11.63
Bhima Super	9.68	12.59	11.14
Mean	10.84	12.79	
Interaction (Treatment*Genotype)			
SEm±	0.28		
CD (P ≤ 0.05)	**0.82**		
Interaction (Genotype*Treatment)			
SEm±	0.28		
CD (P ≤ 0.05)	**0.89**		

TSS: Total soluble solids; W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Figure 3: Interaction effect between waterlogging treatment and genotypes on biochemical parameters (pyruvic acid, proline, antioxidant activity, protein, and TSS) of onion bulb at harvest during 2023.

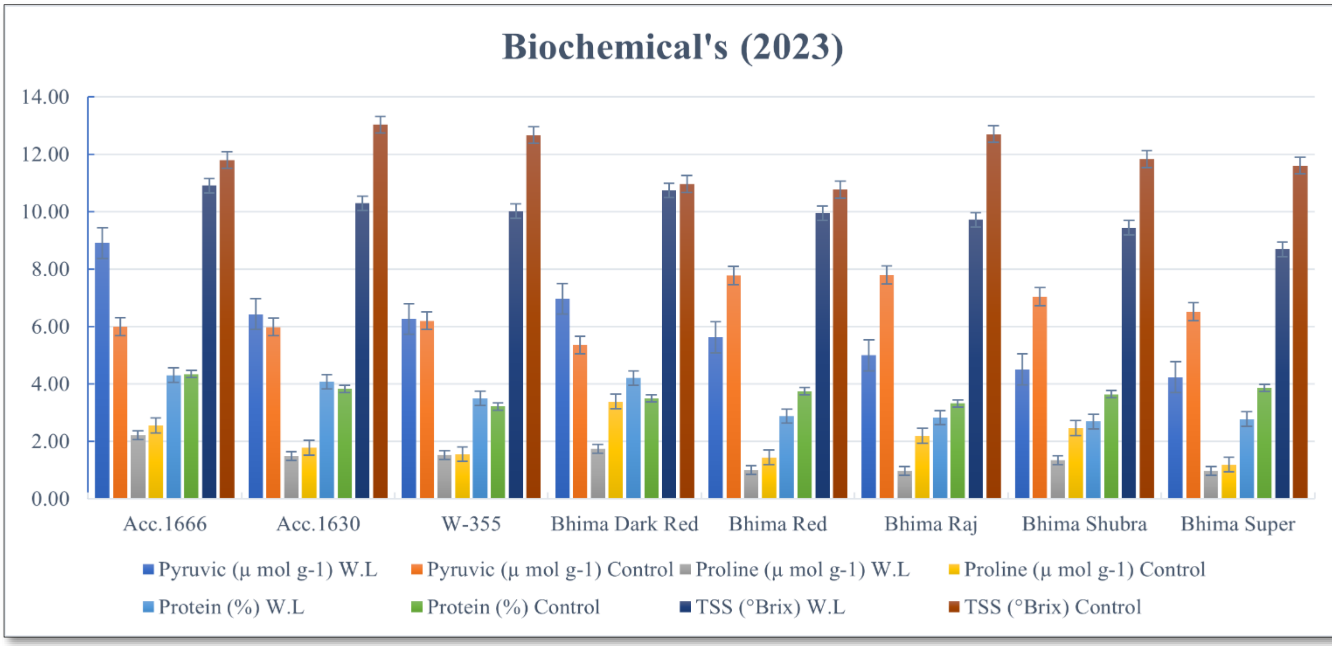
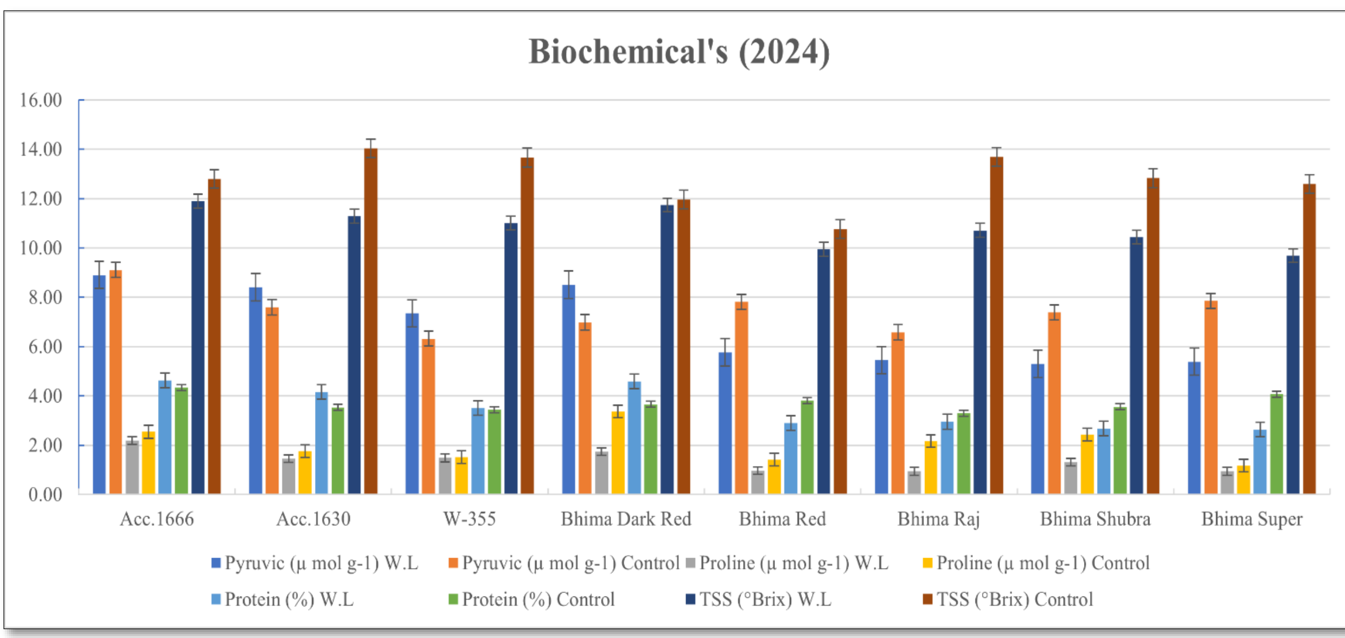


Figure 3.1: Interaction effect between waterlogging treatment and genotypes on biochemical parameters (pyruvic acid, proline, antioxidant activity, protein, and TSS) of onion bulb at harvest during 2024



4.3 (a) Effect of waterlogging treatment on biochemical parameters of onion bulb at harvest during 2023 and 2024.

The biochemical analysis at harvest stage revealed significant differences in all measured parameters between waterlogging treatments and genotypes in both 2023 and 2024. Waterlogging significantly reduced pyruvic content, proline accumulation, antioxidant activity, protein percentage, and total soluble solids (TSS) compared to control treatments, highlighting the stress-induced biochemical alterations in onions. Among genotypes, Acc.1666 exhibited the highest pyruvic content (7.45 µmol g^{-1} in 2023; 9.00 µmol g^{-1} in 2024), proline content (2.38 and 2.36 µmol g^{-1}), antioxidants (546.18 and 637.28 mg TE kg^{-1}), protein percentage (4.32% and 4.48%), and TSS (11.35°Brix and 12.35°Brix) (Table 18), reflecting superior biochemical quality and stress resilience. In contrast, Bhima Shubra and Bhima Super recorded the lowest antioxidant activities and protein percentages across both years, indicating weaker biochemical defense under waterlogging stress. The significant genotype differences and waterlogging treatment effects demonstrate variability in biochemical adaptation, emphasizing the potential of genotypes like Acc.1666 for improving waterlogging tolerance and bulb quality in onion cultivation.

The significant reduction in biochemical parameters under waterlogging stress reflects impaired metabolic activity due to hypoxia, which disrupts enzyme function and energy-dependent biosynthesis processes (Xu *et al.,* 2024). Acc.1666's superior performance in pyruvic acid, proline, antioxidants, protein, and TSS indicates its ability to maintain metabolic stability and osmotic adjustment under stress, likely through enhanced antioxidant systems and efficient carbon and nitrogen metabolism (Wakchaure *et al.,* 2023). In contrast, Bhima Shubra and Bhima Super's lower values suggest poor stress adaptation, with reduced capacity to accumulate protective compounds and store nutrients (Gedam *et al.,* 2023). These findings highlight the importance of selecting genotypes with robust biochemical responses to sustain bulb quality and stress resilience in waterlogged environments.

4.3 (b) Interaction effect between waterlogging treatment and genotypes on biochemical parameters of onion bulb at harvest during 2023 and 2024.

4.3.1 Pyruvic Content (µmol g^{-1})

In 2023 (Figure 3), Acc.1666 under control exhibited the highest pyruvic content of 5.99 µmol g^{-1}, statistically at par with Acc.1630 under control (5.98 µmol g^{-1}) and Bhima Dark Red under control (5.36 µmol g^{-1}), while Bhima Super under waterlogging recorded the lowest at 4.24 µmol g^{-1} (Table 18.1). In 2024 (Figure 3.1), Acc.1666 under both waterlogging and control showed the highest values (9.10 and 9.00 µmol g^{-1}, respectively), at par with Acc.1630 under waterlogging (8.40 µmol g^{-1}) and Bhima Dark Red under waterlogging (8.50 µmol g^{-1}), whereas Bhima Raj under waterlogging had the lowest at 5.45 µmol g^{-1} (Table 18.1). These interaction effects underscore Acc.1666's robust pyruvic accumulation under stress, contributing to enhanced flavor and quality in waterlogged conditions (Gedam *et al.,* 2023).

4.3.2 Proline Content (µmol g^{-1})

For proline in 2023 (Figure 3), Bhima Dark Red under control achieved the highest content of 3.39 µmol g^{-1}, statistically at par with Acc.1666 under control (2.55 µmol g^{-1}) and Bhima Shubra under control (2.46 µmol g^{-1}), while Bhima Super under waterlogging was lowest at 0.98 µmol g^{-1} (Table 18.1). In 2024, (Figure 3.1) Bhima Dark Red under control led with 3.36 µmol g^{-1}, at par with Acc.1666 under control (2.54 µmol g^{-1}) and Bhima Shubra under control (2.43 µmol g^{-1}), with Bhima Super under waterlogging recording the lowest at 0.94 µmol g^{-1} (Table 18.1). The interaction highlights Bhima Dark Red's superior proline synthesis as an Osmo protectant under non-stress, but reduced accumulation under waterlogging indicates genotypic limits in stress-induced osmoregulation (Wakchaure *et al.,* 2023).

4.3.3 Antioxidant Activity (mg TE kg^{-1})

Antioxidant activity in 2023 (Figure 3) showed Acc.1666 under waterlogging with the highest at 708.48 mg TE kg^{-1}, statistically at par with Acc.1630 under waterlogging (590.92 mg TE kg^{-1}) and Bhima Dark Red under waterlogging (613.50 mg TE kg^{-1}), while Bhima Shubra under waterlogging had the lowest at 120.63 mg TE kg^{-1} (Table 18.1). In 2024, (Figure 3.1) Acc.1666 under control reached the peak of 624.97 mg TE kg^{-1}, at par with Acc.1666 under waterlogging (649.58 mg TE kg^{-1}) and Bhima Dark Red under waterlogging (554.60 mg TE kg^{-1}), with Bhima Shubra under waterlogging lowest at 120.63 mg TE kg^{-1} (Table 18.1). This interaction reveals

Acc.1666's exceptional antioxidant defense under waterlogging, aiding in scavenging reactive oxygen species for better stress tolerance (Weraduwage *et al.,* 2015).

4.3.4 Protein Content (%)

In 2023, (Figure 3) Acc.1666 under waterlogging displayed the highest protein content of 4.31%, statistically at par with Acc.1666 under control (4.34%) and Acc.1630 under waterlogging (4.08%), whereas Bhima Raj under waterlogging was lowest at 2.82% (Table 18.1). For 2024, (Figure 3.1) Bhima Dark Red under waterlogging led with 4.59%, at par with Acc.1666 under waterlogging (4.63%) and Acc.1630 under waterlogging (4.15%), with Bhima Shubra under waterlogging recording the lowest at 2.68% (Table 18.1). The interaction effects indicate that waterlogging generally suppresses protein synthesis, but genotypes like Acc.1666 and Bhima Dark Red maintain higher levels, likely due to efficient nitrogen assimilation and reduced proteolysis under hypoxia (Gedam *et al.,* 2023).

4.3.5 Total Soluble Solids (TSS, °Brix)

TSS in 2023 (Figure 3) was highest in Acc.1630 under control at 13.03 °Brix, statistically at par with Acc.1666 under control (11.80 °Brix) and Bhima Raj under control (12.70 °Brix), while Bhima Super under waterlogging had the lowest at 8.69 °Brix (Table 18.1). In 2024, (Figure 3.1) Acc.1630 under control achieved the peak of 14.03 °Brix, at par with Acc.1666 under control (12.79 °Brix) and Bhima Raj under control (13.69 °Brix), with Bhima Red under waterlogging lowest at 9.95 °Brix (Table 18.1). These interactions demonstrate that control conditions enhance TSS accumulation for better bulb quality, with Acc.1630 showing resilience, while waterlogging diminishes soluble carbohydrate storage in susceptible genotypes like Bhima Super (Pawar *et al.,* 2025).

The interaction analysis shows that waterlogging depresses all key biochemical traits at harvest, but the magnitude depends strongly on genotype, evidencing true treatment × genotype effects. Acc.1666 consistently sustains high pyruvic acid under both control and stress, indicating preserved sulfur–amino acid metabolism and glycolytic flux that underpin pungency and carbon turnover despite hypoxia (Pawar *et al.,* 2025). Proline peaks in Bhima Dark Red under control and remains comparatively high in Acc.1666, reflecting superior osmotic adjustment and membrane protection; by contrast, very low proline in Bhima Super under waterlogging signals limited stress acclimation (Gedam *et al.,* 2023). Antioxidant capacity remains exceptionally high in Acc.1666 (notably even under waterlogging), suggesting robust ROS-scavenging systems that mitigate oxidative damage common in flooded tissues (Wakchaure *et al.,* 2023). Protein content is also maintained better by Acc.1666 and Bhima Dark Red, implying more efficient nitrogen assimilation and reduced proteolysis under oxygen deficit. TSS is maximized under control, especially in Acc.1630, showing that carbohydrate accumulation benefits from unstressed photosynthesis and source–sink continuity; waterlogging depresses TSS in susceptible types like Bhima Super and Bhima Red, consistent with curtailed carbon fixation and translocation (Pawar *et al.,* 2025). Together, these coordinated advantages (Osmo protection, antioxidant defense, nitrogen economy, and carbon storage) explain Acc.1666's biochemical resilience and bulb quality under stress. Conversely, Bhima Shubra and Bhima Super exhibit weak antioxidant and protein responses, marking them as biochemically vulnerable to flooding. These genotype-specific biochemical signatures provide actionable criteria for selecting parents and cultivars suited to waterlogged environments.

4.3.6 Bulb Sulphur (%) content.

Table 19: Effect of waterlogging treatment on sulphur content (%) of onion bulb at different growth stages during 2023 and 2024.

Bulb Sulphur (%)						
	45 DAT		55 DAT		Harvest	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	0.35	0.35	0.27	0.27	0.39	0.39
Control	0.29	0.29	0.29	0.29	0.39	0.40
SEm±	0.01	0.01	0.00	0.00	0.00	0.01
CD (P ≤ 0.05)	**0.04**	**0.05**	**0.01**	**0.00**	**NS**	**NS**
(Genotype)						
Acc. 1666	0.23	0.23	0.29	0.30	0.44	0.44
Acc.1630	0.36	0.36	0.25	0.26	0.45	0.46
W 355	0.31	0.35	0.27	0.27	0.43	0.43
Bhima Dark Red	0.34	0.32	0.29	0.29	0.43	0.44
Bhima Red	0.28	0.28	0.32	0.33	0.25	0.26
Bhima Raj	0.30	0.32	0.26	0.26	0.40	0.40
Bhima Shubra	0.36	0.36	0.25	0.26	0.38	0.39
Bhima Super	0.34	0.33	0.27	0.28	0.35	0.35
SEm±	0.03	0.03	0.00	0.01	0.00	0.01
CD (P ≤ 0.05)	**0.08**	**0.08**	**0.01**	**0.03**	**0.01**	**0.04**
Interaction (Treatment*Genotype)						
Sem ±	0.04	0.04	0.01	0.01	0.01	0.02
CD (P ≤ 0.05)	**NS**	**NS**	**0.02**	**0.04**	**0.02**	**0.05**
Interaction (Genotype*Treatment)						
Sem ±	0.03	0.04	0.01	0.01	0.01	0.02
CD (P ≤ 0.05)	**NS**	**NS**	**0.02**	**0.04**	**0.02**	**0.07**

SE (m): Standard Error of Mean, CD at 5%: Critical Difference at 5% significance; DAT: Days after transplanting; B.T (45 DAT): Before Treatment; A.T (55 DAT): After Treatment.

Table 19.1: Interaction effect between waterlogging treatment and genotypes on sulphur content (%) of onion bulb at different growth stages during 2023 and 2024.

Sulphur (%) 55 DAT (2023)			
	W. L	Control	Mean
Acc.1666	0.37	0.22	0.29
Acc.1630	0.31	0.20	0.25
W-355	0.29	0.25	0.27
Bhima Dark Red	0.34	0.24	0.29
Bhima Red	0.25	0.39	0.32
Bhima Raj	0.22	0.30	0.26
Bhima Shubra	0.18	0.32	0.25
Bhima Super	0.17	0.37	0.27
Mean	0.27	0.29	
Interaction (Treatment*Genotype)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.02**		
Interaction (Genotype*Treatment)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.02**		

Sulphur (%) at harvest (2023)			
	W. L	Control	Mean
Acc.1666	0.49	0.39	0.44
Acc.1630	0.44	0.47	0.45
W-355	0.44	0.41	0.43
Bhima Dark Red	0.45	0.42	0.43
Bhima Red	0.23	0.27	0.25
Bhima Raj	0.39	0.41	0.40
Bhima Shubra	0.37	0.39	0.38
Bhima Super	0.31	0.39	0.35
Mean	0.39	0.39	
Interaction (Treatment*Genotype)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.02**		
Interaction (Genotype*Treatment)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.02**		

Sulphur (%) 55 DAT (2024)			
	W. L	Control	Mean
Acc.1666	0.37	0.22	0.30
Acc.1630	0.32	0.19	0.26
W-355	0.28	0.25	0.27
Bhima Dark Red	0.34	0.24	0.29
Bhima Red	0.26	0.39	0.33
Bhima Raj	0.22	0.30	0.26
Bhima Shubra	0.19	0.32	0.26
Bhima Super	0.18	0.37	0.28
Mean	0.27	0.29	
Interaction (Treatment*Genotype)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.04**		
Interaction (Genotype*Treatment)			
SEm±	0.01		
CD (P ≤ 0.05)	**0.04**		

Sulphur (%) at harvest (2024)			
	W. L	Control	Mean
Acc.1666	0.48	0.39	0.44
Acc.1630	0.45	0.47	0.46
W-355	0.44	0.42	0.43
Bhima Dark Red	0.45	0.42	0.44
Bhima Red	0.23	0.28	0.26
Bhima Raj	0.39	0.41	0.40
Bhima Shubra	0.38	0.39	0.39
Bhima Super	0.31	0.39	0.35
Mean	0.39	0.40	
Interaction (Treatment*Genotype)			
SEm±	0.02		
CD (P ≤ 0.05)	**0.05**		
Interaction (Genotype*Treatment)			
SEm±	0.02		
CD (P ≤ 0.05)	**0.07**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Figure 4: Effect of sulphur % of waterlogging treatment on onion (bulb) genotypes at 55 DAT and at harvest during 2023 season.

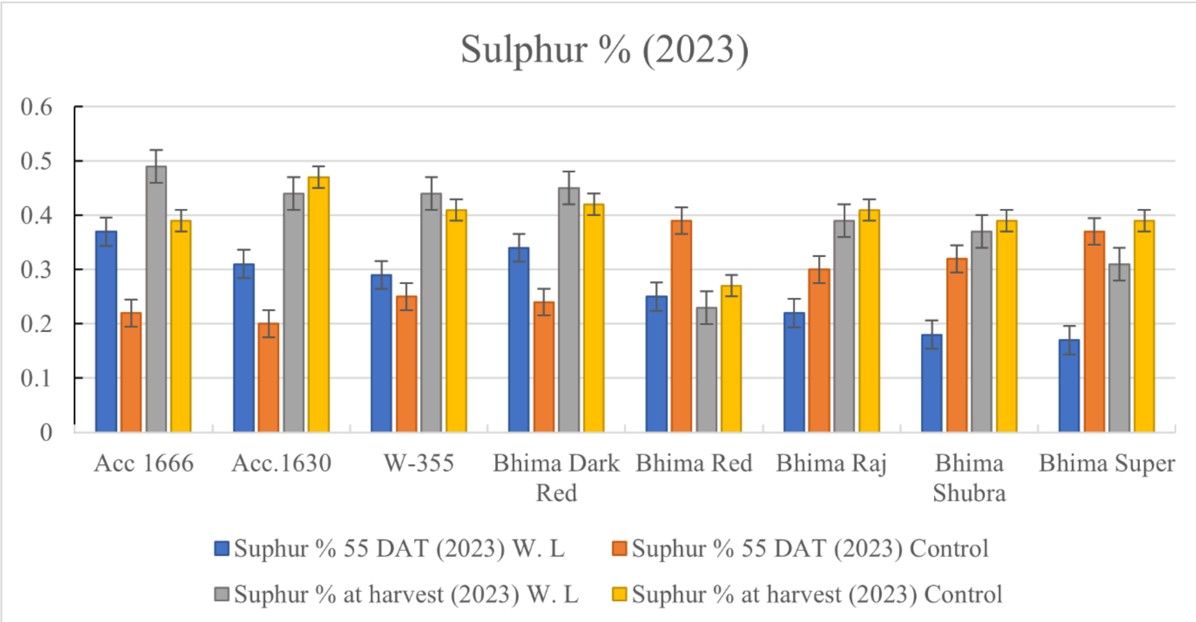
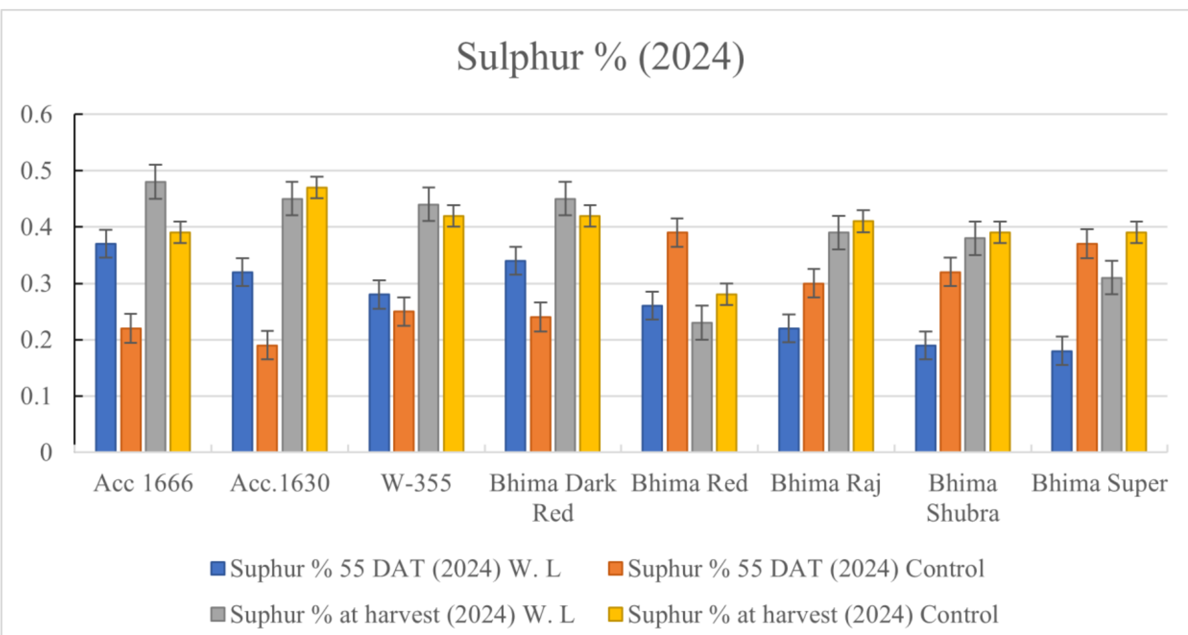


Figure 4.1: Effect of sulphur % of waterlogging treatment on onion (bulb) genotypes at 55 DAT and at harvest during 2024 season.



4.3.6 (a) Effect of waterlogging treatment on sulphur content (%) of onion bulb at different growth stages during 2023 and 2024.

In both the 2023 and 2024 cropping seasons, the effects of waterlogging stress and control on bulb sulphur percentage were analyzed at key growth stages (45 DAT before treatment, 55 DAT after treatment, and at harvest) across waterlogging treatments and genotypes. At 45 DAT and 55 DAT, the difference in mean bulb sulphur (%) between waterlogged and control treatments was statistically significant, with the highest value at 45 DAT recorded for Acc.1630 (0.36%) and the lowest for Acc.1666 (0.23%) in both years at 45 DAT interaction was found to be non-significant. At 55 DAT, Bhima Red under control showed the highest sulphur (0.33% in 2024), while Bhima Shubra and Bhima Raj under waterlogging had the lowest (0.25% in 2023) (Table 19). At harvest, differences between treatments and genotypes were not significant (NS) for either the waterlogging or genotypes in both years, indicating that initial waterlogging effects diminished by maturity and at 55 DAT and at harvest interaction was significant.

The significant treatment differences at 45–55 DAT indicate an early, transient disruption of sulphur assimilation under hypoxia, with genotypic contrasts showing Bhima Red retaining higher S under control while Bhima Shubra/Raj declined most under waterlogging at 55 DAT, and Acc.1630 leading at 45 DAT in both years. By harvest, non-significant differences suggest physiological recovery and re-equilibration of sulphur metabolism as drainage and plant maturation progressed, dampening early waterlogging effects (Gedam *et al.,* 2022). The consistent strength of Acc.1666 under stress aligns with known tolerance traits (better antioxidant status, sustained photosynthesis) that can stabilize nutrient uptake and S-containing metabolite synthesis after initial shock (Pawar *et al.,* 2025). These dynamics imply that mid-season S perturbations are critical for diagnosis, whereas end-season convergence reflects resilience and compensatory uptake once hypoxia subsides.

4.3.6 (b) Interaction effect between waterlogging treatment and genotypes on sulphur content (%) of onion bulb at different growth stages during 2023 and 2024.

Across both seasons and stages (Table 19.1), sulphur (%) in bulbs showed clear genotype-specific responses without using means: at 55 DAT in 2023 (Figure 4) under waterlogging, the highest value was in Acc.1666 (0.37%) and the lowest in Bhima Super (0.17%), at harvest in 2023 under waterlogging, Acc.1666 was highest (0.49%) and Bhima Red lowest (0.23%), at 55 DAT in 2024 under waterlogging, Acc.1666 again was highest (0.37%) and Bhima Super lowest (0.18%), at harvest in 2024 under waterlogging, Acc.1666 remained highest (0.48%) and Bhima Red lowest (0.23%) (Figure 4.1).

Waterlogging-by-genotype interactions for bulb sulphur consistently favored Acc.1666 under stress, indicating superior sulphur acquisition/retention during hypoxia, whereas Bhima Super and Bhima Red repeatedly showed the lowest values under waterlogging at mid-season and harvest, respectively, reflecting poorer sulphur uptake or assimilation under inundation. Sustained sulphur in Acc.1666 across seasons and stages suggests more resilient root function and metabolism under low oxygen, aligning with known waterlogging-tolerance traits that stabilize nutrient status through maintained photosynthesis and antioxidant capacity (Pawar *et al.,* 2025). The convergence of patterns across both 2023 and 2024 strengthens the inference that sulphur dynamics are a reliable discriminator of genotype response to waterlogging, with Acc.1666 a robust performer and Bhima Red/Super more susceptible under stress. Practically, these results highlight Acc.1666 as a promising donor for breeding programs targeting nutrient stability and quality under monsoon waterlogging, while management for susceptible cultivars should prioritize drainage and sulphur nutrition to mitigate mid-season declines.

4.4: Bulb morphology

Table 20: Effect of waterlogging treatment on equatorial and polar diameter (mm) of onion genotypes at harvest during 2023 and 2024.

	Equatorial diameter (mm)		**Polar Diameter (mm)**	
(Waterlogging Treatment)	**2023**	**2024**	**2023**	**2024**
Waterlogging	38.93	40.77	33.78	36.44
Control	48.00	52.42	40.46	45.36
SEm±	0.80	0.88	0.69	1.07
CD (P ≤ 0.05)	2.39	2.65	2.08	3.20
(Genotype)				
Acc. 1666	51.07	54.72	42.26	45.08
Acc.1630	45.07	49.80	41.87	41.94
W 355	44.39	47.81	38.82	41.59
Bhima Dark Red	51.91	54.15	41.30	44.47
Bhima Red	32.98	40.76	26.57	39.73
Bhima Raj	41.05	41.64	33.43	35.95
Bhima Shubra	37.64	42.87	37.47	39.45
Bhima Super	43.59	41.02	35.23	39.01
SEm±	0.78	1.11	0.55	1.15
CD (P ≤ 0.05)	**2.27**	**3.20**	**1.59**	**3.35**
Interaction (Treatment*Genotype)				
Sem ±	1.11	1.56	0.77	1.63
CD (P ≤ 0.05)	**3.22**	**4.53**	**2.24**	**4.73**
Interaction (Genotype*Treatment)				
Sem ±	1.31	1.54	0.74	1.86
CD (P ≤ 0.05)	**5.34**	**4.94**	**2.28**	**7.34**

SEm±: Standard Error of Mean, CD at 5%: Critical Difference at 5% significance; mm: millimeter.

Table 20.1: Interaction effect between waterlogging treatment and genotypes on equatorial and polar diameter (mm) at harvest during 2023 and 2024.

Equatorial diameter (mm) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	46.41	55.74	51.07
Acc.1630	38.76	51.38	45.07
W 355	38.51	50.27	44.39
Bhima Dark Red	48.22	55.61	51.91
Bhima Red	27.86	38.10	32.98
Bhima Raj	40.29	41.80	41.05
Bhima Shubra	34.18	41.09	37.64
Bhima Super	37.18	50.01	43.59
Mean	38.93	48	
Interaction (Treatment*Genotype)			
SEm±	1.11		
CD (P ≤ 0.05)	**3.22**		
Interaction (Genotype*Treatment)			
SEm±	1.31		
CD (P ≤ 0.05)	**5.34**		

Polar diameter (mm) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	41.21	43.30	42.26
Acc.1630	37.34	46.40	41.87
W 355	34.37	43.26	38.82
Bhima Dark Red	38.92	43.68	41.3
Bhima Red	23.14	30.01	26.57
Bhima Raj	29.97	36.88	33.43
Bhima Shubra	34.44	40.49	37.47
Bhima Super	30.82	39.64	35.23
Mean	33.78	40.46	
Interaction (Treatment*Genotype)			
SEm±	0.77		
CD (P ≤ 0.05)	**2.24**		
Interaction (Genotype*Treatment)			
SEm±	0.74		
CD (P ≤ 0.05)	**2.28**		

Equatorial diameter (mm) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	51.47	57.97	54.72
Acc.1630	43.19	56.41	49.8
W 355	43.19	52.42	47.81
Bhima Dark Red	49.70	58.60	54.15
Bhima Red	36.95	44.57	40.76
Bhima Raj	34.37	48.91	41.64
Bhima Shubra	36.92	48.82	42.87
Bhima Super	30.37	51.68	41.02
Mean	40.77	52.42	
Interaction (Treatment*Genotype)			
SEm±	1.56		
CD (P ≤ 0.05)	**4.69**		
Interaction (Genotype*Treatment)			
SEm±	1.54		
CD (P ≤ 0.05)	**4.94**		

Polar diameter (mm) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	44.42	45.74	45.08
Acc.1630	37.65	46.23	41.94
W 355	37.09	46.10	41.59
Bhima Dark Red	40.55	48.40	44.47
Bhima Red	37.49	41.98	39.73
Bhima Raj	31.43	40.47	35.95
Bhima Shubra	33.76	45.14	39.45
Bhima Super	29.17	48.85	39.01
Mean	36.44	45.36	
Interaction (Treatment*Genotype)			
SEm±	1.63		
CD (P ≤ 0.05)	**4.90**		
Interaction (Genotype*Treatment)			
SEm±	1.86		
CD (P ≤ 0.05)	**7.34**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Figure 5: Effect of waterlogging treatment on equatorial and polar diameter (mm) of onion genotypes at harvest during 2023.

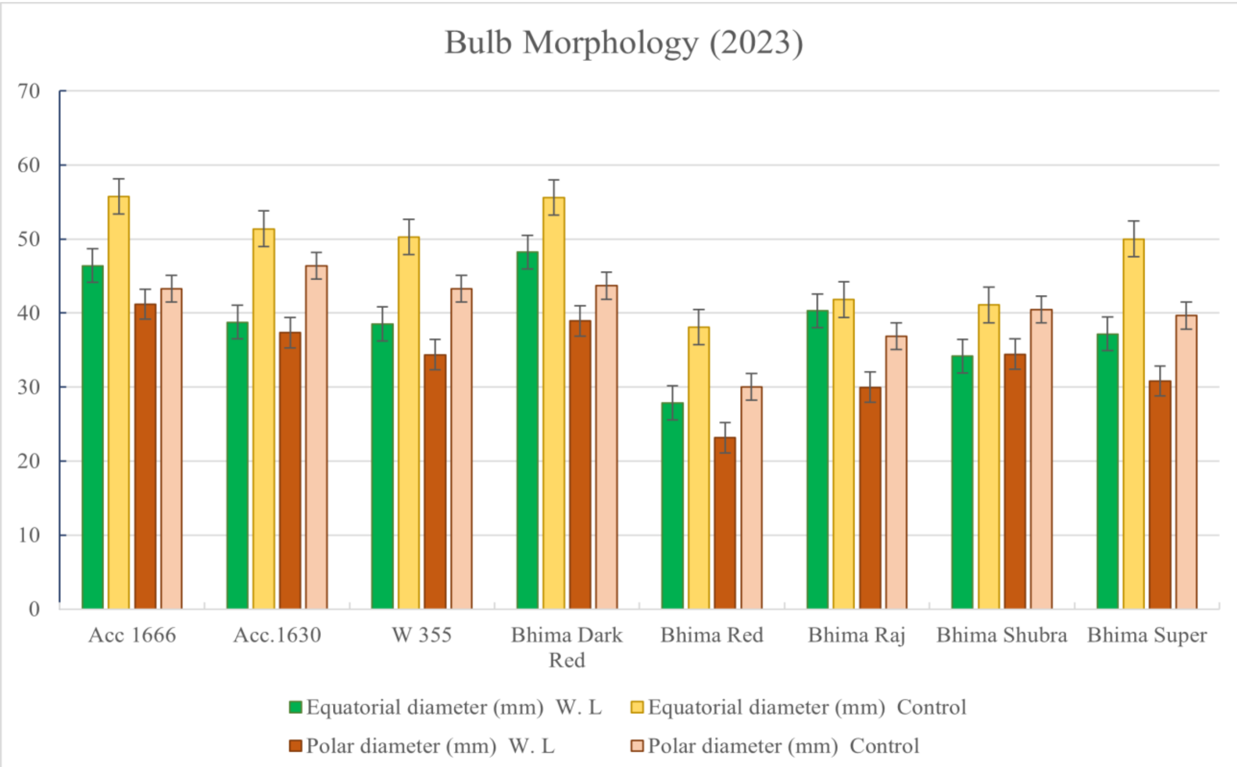
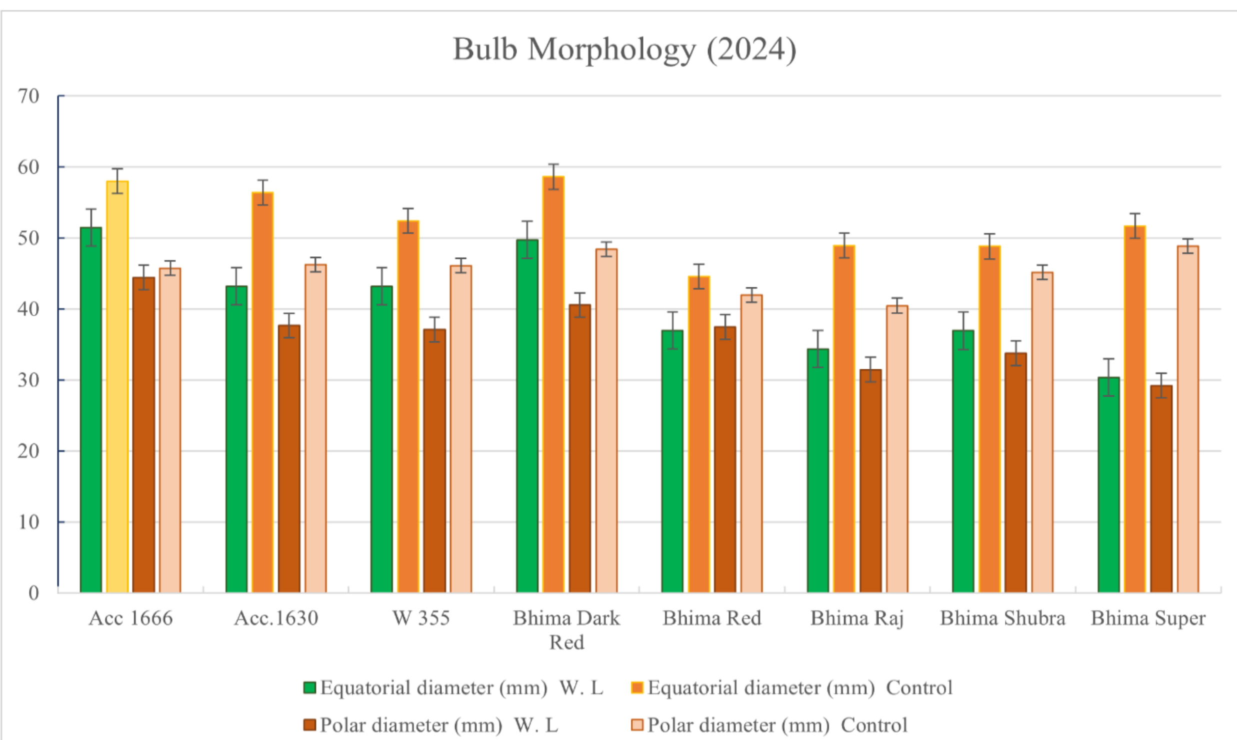


Figure 5.1: Effect of waterlogging treatment on equatorial and polar diameter (mm) of onion genotypes at harvest during 2023.



4.4 (a) Effect of waterlogging treatment on equatorial and polar diameter (mm) of onion genotypes at harvest during 2023 and 2024.

The results for yield attributing parameters indicate significant effects of waterlogging stress and genotype on onion bulb size in both 2023 and 2024 (Table 20). The waterlogging treatment effect was significant for both Equatorial and polar diameter in both years, with control plants having significantly larger bulbs than waterlogged ones (Equatorial diameter: 48.00 mm vs. 38.93 mm in 2023 and 52.42 mm vs. 40.77 mm in 2024; polar diameter: 40.46 mm vs. 33.78 mm in 2023 and 45.36 mm vs. 36.44 mm in 2024). The genotype effect was also significant, where Acc.1666 showed the highest Equatorial diameter (51.07 mm in 2023 and 54.72 mm in 2024) and polar diameter (42.26 mm in 2023 and 45.08 mm in 2024), while Bhima Red recorded the lowest Equatorial diameter (32.98 mm in 2023 and 40.76 mm in 2024) and polar diameter (26.57 mm in 2023 and 39.73 mm in 2024). The interaction between waterlogging treatment and genotype was significant for both parameters, suggesting genotypic variation in response to water stress. These results emphasize the importance of selecting genotypes like Acc.1666 for maintaining bulb size and yield under waterlogging conditions.

Waterlogging-induced hypoxia restricts cell division and expansion in onion bulbs, leading to significantly smaller Equatorial and polar diameters under stress. The superior performance of Acc.1666, which maintained the largest bulb dimensions under both waterlogged and control conditions, likely reflects its robust root aeration and efficient water–nutrient uptake that sustain turgor-driven growth (Pawar *et al.,* 2025). Bhima Dark Red's comparable performance under control further underscores the role of genetic traits in maintaining cell expansion (Wakchaure *et al.,* 2023). In contrast, Bhima Red's markedly reduced bulb size under waterlogging indicates a limited capacity for maintaining osmotic balance and cell wall extensibility under low-oxygen conditions (Gedam *et al.,* 2023). These findings highlight the necessity of breeding for traits that enhance root resilience and maintain turgor-driven enlargement to secure yield under waterlogging stress.

4.4 (b) Interaction effect between waterlogging treatment and genotypes on equatorial and polar diameter (mm) at harvest during 2023 and 2024.

The interaction effects on Equatorial and polar diameters of onion genotypes reveal significant genotypic differences under waterlogging and control conditions for both 2023 and 2024 (Table 20.1). In 2023, Bhima Dark Red under control recorded the highest Equatorial diameter of 55.61 mm, closely followed by Acc.1666 under control (55.74 mm), while Bhima Red under waterlogging presented the lowest Equatorial diameter at 27.86 mm. For the polar diameter in 2023, Acc.1666 exhibited the highest under control (43.30 mm) and waterlogging (41.21 mm), whereas Bhima Red under waterlogging showed the lowest polar diameter of 23.14 mm (Figure 5). Similarly, in 2024, Acc.1666 under control led with the highest Equatorial diameter of 57.97 mm, statistically at par with Bhima Dark Red under control (58.60 mm), while Bhima Super under waterlogging had the lowest at 30.37 mm. For 2024 polar diameter, Acc.1666 again showed the maximum under control (45.74 mm), followed by Bhima Dark Red under control (48.40 mm), while Bhima Super under waterlogging recorded the lowest diameter of 29.17 mm (Figure 5.1). These results emphasize Acc.1666 and Bhima Dark Red's superior potential in maintaining bulb size under both waterlogged and favorable conditions, while Bhima Red and Bhima Super are most adversely affected by waterlogging stress.

The interaction results indicate significant genotypic variation in bulb size parameters under waterlogging and control conditions. Acc.1666 and Bhima Dark Red consistently exhibited the largest Equatorial and polar diameters, reflecting their superior ability to maintain cell expansion and turgor under both normal and stress conditions (Ma *et al.,* 2020). This may be attributed to their efficient root systems and better water and nutrient uptake, which help sustain growth despite hypoxic stress (Ma *et al.,* 2020). Conversely, Bhima Red and Bhima Super showed the smallest bulb dimensions under waterlogging, indicating higher sensitivity likely due to impaired osmotic regulation and cell wall loosening under stress (Xu *et al.,* 2024). These findings highlight the importance of selecting genotypes with strong physiological traits for maintaining yield and bulb quality in waterlogged environments.

4.5: Yield

Table 21: Effect of waterlogging treatment on bulb yield (t ha⁻¹) of onion genotypes at harvest during 2023 and 2024.

Yield t/ha			
(Waterlogging Treatment)	**2023**	**2024**	**Pooled**
Waterlogging	7.15	10.96	9.06
Control	11.12	12.47	11.79
SEm±	0.03	0.02	0.02
CD (P ≤ 0.05)	**0.19**	**0.09**	**0.07**
(Genotype)			
Acc. 1666	12.15	14.13	13.14
Acc.1630	10.28	10.78	10.53
W 355	7.61	11.10	9.36
Bhima Dark Red	14.52	13.25	13.88
Bhima Red	8.29	9.95	9.12
Bhima Raj	8.54	13.28	10.91
Bhima Shubra	5.92	11.80	8.86
Bhima Super	5.79	9.40	7.60
SEm±	0.46	0.09	0.23
CD (P ≤ 0.05)	**1.33**	**0.25**	**0.66**
Interaction (Treatment*Genotype)			
Sem ±	0.65	0.12	0.33
CD (P ≤ 0.05)	**1.88**	**0.36**	**0.94**
Interaction (Genotype*Treatment)			
Sem ±	0.61	0.12	0.31
CD (P ≤ 0.05)	**1.77**	**0.35**	**0.88**

SE (m): Standard Error of Mean, CD at 5%: Critical Difference at 5% significance.

Table 21.1: Interaction effect between waterlogging treatment and genotypes on bulb yield ($t\ ha^{-1}$) at harvest during 2023 and 2024.

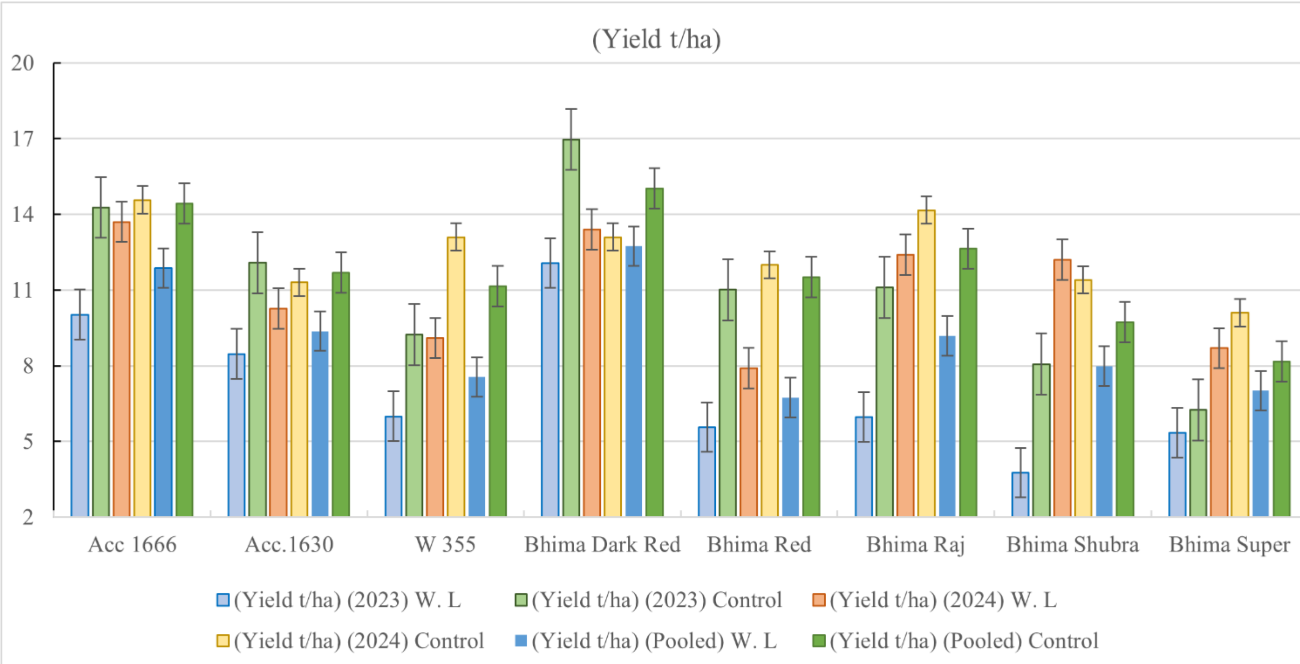
(Yield t/ha) (2023)			
	W. L	**Control**	**Mean**
Acc.1666	10.03	14.27	12.15
Acc.1630	8.47	12.08	10.28
W 355	6.00	9.23	7.61
Bhima Dark Red	12.07	16.96	14.52
Bhima Red	5.57	11.01	8.29
Bhima Raj	5.97	11.10	8.54
Bhima Shubra	3.77	8.07	5.92
Bhima Super	5.34	6.25	5.79
Mean	7.15	11.12	
Interaction (Treatment*Genotype)			
SEm±	0.65		
CD (P ≤ 0.05)	**1.88**		
Interaction (Genotype*Treatment)			
SEm±	0.61		
CD (P ≤ 0.05)	**1.77**		

(Yield t/ha) (2024)			
	W. L	**Control**	**Mean**
Acc.1666	13.70	14.57	14.13
Acc.1630	10.27	11.30	10.78
W 355	9.10	13.10	11.10
Bhima Dark Red	12.40	13.10	12.75
Bhima Red	7.90	12.00	9.95
Bhima Raj	12.40	14.17	13.28
Bhima Shubra	12.20	11.40	11.80
Bhima Super	8.70	10.10	9.40
Mean	10.96	12.47	
Interaction (Treatment*Genotype)			
SEm±	0.23		
CD (P ≤ 0.05)	**0.68**		
Interaction (Genotype*Treatment)			
SEm±	0.12		
CD (P ≤ 0.05)	**0.35**		

(Yield t/ha) Pooled			
	W. L	**Control**	**Mean**
Acc.1666	11.86	14.42	13.14
Acc.1630	9.37	11.69	10.53
W 355	7.55	11.16	9.36
Bhima Dark Red	12.55	15.03	13.79
Bhima Red	6.74	11.51	9.12
Bhima Raj	9.19	12.64	10.91
Bhima Shubra	7.99	9.73	8.86
Bhima Super	7.02	8.18	7.60
Mean	9.06	11.79	
Interaction (Treatment*Genotype)			
SEm±	0.33		
CD (P ≤ 0.05)	**0.94**		
Interaction (Genotype*Treatment)			
SEm±	0.31		
CD (P ≤ 0.05)	**0.88**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance.

Figure 6: Effect of waterlogging treatment on (Yield t/ha) of onion genotypes at harvest during 2023–24 and pooled.



4.5 (a) Effect of waterlogging treatment on bulb yield (t ha⁻¹) of onion genotypes at harvest during 2023 and 2024.

The yield data revealed significant differences in both waterlogging and genotype effects across 2023 and 2024 (Table 21), indicating the substantial impact of waterlogging stress and genotypic variation on onion productivity. The waterlogging treatment effect was significant in both years, with control plants yielding substantially higher than waterlogged plants (11.12 t/ha vs. 7.15 t/ha in 2023 and 12.47 t/ha vs. 10.96 t/ha in 2024), demonstrating the detrimental effect of waterlogging on bulb yield. The sub-plot genotype effect was also significant, where Bhima Dark Red recorded the highest yield in 2023 (14.52 t/ha), while Acc.1666 exhibited the highest yield in 2024 (14.13 t/ha). Conversely, Bhima Super showed the lowest yield in 2023 (5.79 t/ha), and Bhima Super again recorded the lowest in 2024 (9.40 t/ha). In the pooled data, control treatment (11.79 t/ha) maintained a clear advantage over waterlogging (9.06 t/ha), confirming the consistent reduction in yield under stress across both years. Among genotypes, Bhima Dark Red (13.88 t/ha) and Acc.1666 (13.14 t/ha) recorded the highest pooled yields, while Bhima Super (7.60 t/ha) exhibited the lowest, indicating stable superiority of tolerant genotypes under combined seasonal effects. The interaction between waterlogging treatment and genotypes was significant for both years, suggesting differential genotypic responses to waterlogging stress. These findings underscore the importance of selecting high-yielding, waterlogging-tolerant genotypes like Bhima Dark Red and Acc.1666 for maximizing onion productivity under adverse environmental conditions.

The significant yield reduction under waterlogging stress reflects the cumulative effect of hypoxia-induced metabolic disruptions, including impaired root respiration, reduced nutrient uptake, and compromised photosynthetic efficiency, all of which limit bulb development and final productivity (Pawar *et al.,* 2025). Genotypes like Bhima Dark Red and Acc.1666 demonstrated superior yields under both waterlogged and control conditions, indicating their ability to maintain physiological functions through enhanced root aeration, efficient antioxidant systems, and sustained carbon assimilation that support bulb growth despite oxygen deficiency (Pawar *et al.,* 2025; Gedam *et al.,* 2023). The lower yields observed in Bhima Super and Bhima Shubra reflect their inability to adapt metabolically to waterlogging, with reduced leaf area, lower net assimilation rates, and poor bulb expansion contributing to diminished productivity (Gedam *et al.,* 2023). The significant interaction effects confirm that yield response to waterlogging is genotype-dependent, emphasizing genetic variability in stress tolerance mechanisms. These findings highlight that breeding programs should prioritize genotypes with robust physiological resilience and compensatory growth capacity to ensure stable yields under waterlogged conditions. Selection of high-performing genotypes like Acc.1666 and Bhima Dark Red is critical for sustainable onion production in flood-prone areas.

4.5 (b) Interaction effect between waterlogging treatment and genotypes on bulb yield (t ha^{-1}) at harvest during 2023 and 2024.

In 2023, (Figure 6) the highest yielding genotype under control was Bhima Dark Red at 16.96 t/ha, closely followed by Acc.1666 at 14.27 t/ha, while under waterlogging Acc.1666 led at 10.03 t/ha and the lowest yield occurred in Bhima Shubra at 3.77 t/ha (also low were Bhima Red at 5.57 t/ha and Bhima Raj at 5.97 t/ha) (Table 21.1). In 2024, the highest yield under control was recorded by Acc.1666 at 14.57 t/ha, with Bhima Raj next at 14.17 t/ha, whereas under waterlogging the top performer was Acc.1666 at 13.70 t/ha and the lowest was W 355 at 9.10 t/ha (followed by Bhima Super at 8.70 t/ha) (Table 21.1). Overall, Acc.1666 consistently ranked among the top under both treatments across years, while Bhima Shubra (2023) and W 355 (2024) were the most adversely affected under waterlogging. In pooled data, control plants produced a mean yield of 11.79 t/ha compared to 9.06 t/ha under waterlogging. Among genotypes, Bhima Dark Red (15.03 t/ha under control and 12.74 t/ha under waterlogging) and Acc.1666 (14.42 t/ha under control and 11.86 t/ha under waterlogging) maintained superior yields, indicating stable tolerance to waterlogging stress. In contrast, Bhima Super and Bhima Red remained the lowest yielders under pooled conditions, reflecting their susceptibility to waterlogging.

The interaction results show clear genotype-dependent yield responses to waterlogging, with Acc.1666 consistently maintaining the smallest yield penalty across years due to likely superior root aeration, osmotic adjustment, and antioxidant capacity that preserve assimilation and bulb filling under hypoxia (Pawar *et al.,* 2025). Bhima Dark Red excelled under control in 2023, indicating strong intrinsic vigor and sink strength when stress is absent, while still remaining competitive under waterlogging, reflecting balanced source–sink coordination (Pawar *et al.,* 2025). Conversely, Bhima Shubra (2023) and W 355 (2024) suffered the greatest yield losses under waterlogging, suggesting poor tolerance marked by impaired nutrient uptake, lower canopy efficiency, and reduced translocation to bulbs. The stability of Acc.1666 under both environments highlights desirable resilience traits for flood-prone areas. Practically, deploying Acc.1666 (and Bhima Dark Red where drainage is reliable) can safeguard productivity against episodic waterlogging.

4.6: Soil analysis

4.6.1: Soil physiochemical properties

Table 22: Effect of waterlogging treatment on soil available nutrient status and chemical properties at 45 DAT (pre-treatment) and 55 DAT (post-treatment) during 2023 and 2024.

	Year 2023						Year 2024					
Available nutrients	45 DAT		P = 0.05	55 DAT		P = 0.05	45 DAT		P = 0.05	55 DAT		P = 0.05
	Control	W. L		Control	W. L		Control	W. L		Control	W. L	
Soil pH	7.75	7.72	**0.83**	7.35	7.11	**0.0244***	7.71	7.68	**0.553**	7.39	7.16	**0.0118***
Soil EC (dS m^{-1})	0.25	0.25	**0.34**	0.26	0.23	**0.0005***	0.24	0.25	**0.643**	0.26	0.25	**0.0009****
Soil available N (kg ha^{-1})	99.29	98.17	**0.642**	104.55	65.31	**0.0002****	100.10	99.05	**0.630**	105.20	66.40	**0.0003****
Soil available P (kg ha^{-1})	21.47	21.88	**0.674**	20.76	15.80	**0.0418***	21.80	22.05	**0.680**	21.05	16.10	**0.0395***
Soil available K (kg ha^{-1})	370.31	367.68	**0.631**	377.99	306.83	**0.004***	372.50	369.40	**0.640**	380.10	309.20	**0.0042***
Soil available S (mg kg^{-1})	17.23	17.14	**0.938**	16.25	13.26	**0.007***	17.40	17.30	**0.940**	16.40	13.45	**0.0069***
Soil available Fe (mg kg^{-1})	3.97	4.00	**0.867**	4.40	2.73	**0.003***	4.05	4.08	**0.870**	4.48	2.80	**0.0031***
Soil available Mn (mg kg^{-1})	5.13	5.13	**0.505**	5.67	3.44	**0.002***	5.20	5.19	**0.510**	5.75	3.52	**0.0021***
Soil available Zn (mg kg^{-1})	1.76	1.80	**0.890**	3.14	3.04	**0.7190**	1.80	1.84	**0.895**	3.20	3.12	**0.715**
Soil available cu (mg kg^{-1})	6.02	6.07	**0.816**	5.70	4.73	**0.002***	6.10	6.14	**0.820**	5.80	4.82	**0.0023***
Soil available Ca (cmol kg^{-1})	1.18	1.17	**0.700**	1.40	1.02	**0.003***	1.20	1.19	**0.705**	1.42	1.04	**0.0032***
Soil available Mg (cmol kg^{-1})	0.67	0.64	**0.877**	0.80	0.41	**0.011***	0.69	0.66	**0.880**	0.82	0.42	**0.0108***
Soil available B (mg kg^{-1})	0.92	0.94	**0.102**	0.92	0.62	**0.0003****	0.93	0.95	**0.105**	0.93	0.63	**0.0004****
Organic carbon (mg kg^{-1})	6.70	6.39	**0.112**	10.21	6.18	**0.0007****	6.80	6.48	**0.115**	10.35	6.25	**0.0008****

DAT: Days after transplanting; W.L: Waterlogging treatment; p = 0.05: Significance Level; *: 0.01 < 0.05 Significant difference; **: $0.001 \le p < 0.01$ Highly significant difference.

4.6.1.1 Soil pH

At 45 DAT during both 2023 and 2024, soil pH did not differ significantly between control and waterlogging treatments, with values ranging from 7.72–7.75 in 2023 and 7.68–7.71 in 2024, indicating similar baseline reaction before stress. At 55 DAT, waterlogging significantly reduced pH compared with the control in 2023 (7.11 vs. 7.35) and 2024 (7.16 vs. 7.39), reflecting a shift towards slight acidity under saturated conditions (Table 22). This post-treatment acidification under waterlogging likely results from enhanced microbial activity and anaerobic processes that release organic acids and hydrogen ions into the soil solution (Manik *et al.,* 2019).

4.6.1.2 Soil electrical conductivity (EC) (dS m^{-1})

Soil EC remained statistically similar between treatments at 45 DAT in both years, with values around 0.24–0.25 dS m^{-1}. By 55 DAT, EC declined significantly under waterlogging in 2023 (0.23 vs. 0.26 dS m^{-1}) and 2024 (0.25 vs. 0.26 dS m^{-1}), suggesting dilution and leaching of soluble salts due to prolonged flooding (Table 22). These reductions may be attributed to dilution effects from water saturation and potential leaching of soluble salts under prolonged flooding (Abrol, Yadav, and Massoud, 1988).

4.6.1.3 Soil available nitrogen (kg ha^{-1})

Available N showed no significant difference between control and waterlogging at 45 DAT in 2023 (99.29 vs. 98.17 kg ha^{-1}) and 2024 (100.10 vs. 99.05 kg ha^{-1}), indicating uniform pre-treatment status. In contrast, waterlogging markedly reduced N at 55 DAT in both years, from 104.55 to 65.31 kg ha^{-1} in 2023 and from 105.20 to 66.40 kg ha^{-1} in 2024, highlighting substantial N loss under anaerobic conditions (Table 22). primarily due to denitrification and volatilization processes accelerated by anaerobic conditions, which convert nitrate to gaseous forms and reduce plant availability (Cameron *et al.,* 2013).

4.6.1.4 Soil available phosphorus (kg ha^{-1})

At 45 DAT, P availability remained comparable between treatments in 2023 (21.47 vs. 21.88 kg ha^{-1}) and 2024 (21.80 vs. 22.05 kg ha^{-1}). However, at 55 DAT waterlogging significantly decreased P in 2023 (15.80 vs. 20.76 kg ha^{-1}) and 2024 (16.10 vs. 21.05 kg ha^{-1}), reflecting reduced P availability under saturated soil conditions (Table 22), attributable to fixation with iron and aluminum under reduced oxygen, forming insoluble phosphates that limit crop uptake (Amery and Smolders, 2012).

4.6.1.5 Soil available potassium (kg ha^{-1})

Potassium did not differ significantly between control and waterlogging at 45 DAT in 2023 (370.31 vs. 367.68 kg ha^{-1}) and 2024 (372.50 vs. 369.40 kg ha^{-1}). By 55 DAT, K declined significantly under waterlogging, from 377.99 to 306.83 kg ha^{-1} in 2023 and from 380.10 to 309.20 kg ha^{-1} in 2024, indicating K depletion in flooded plots (Table 22), likely resulting from increased leaching and reduced root uptake efficiency in saturated soils, exacerbating potassium deficiency in waterlogged conditions (Manik *et al.,* 2019).

4.6.1.6 Soil available sulfur (mg kg^{-1})

Available S was statistically similar between treatments at 45 DAT in both years, with values around 17.1–17.4 mg kg^{-1}. At 55 DAT, waterlogging significantly reduced S to 13.26 mg kg^{-1} compared with 16.25 mg kg^{-1} in 2023 and to 13.45 mg kg^{-1} compared with 16.40 mg kg^{-1} in 2024, demonstrating a consistent decline under waterlogged conditions (Table 22), owing to enhanced microbial reduction of sulfate to hydrogen sulfide under anaerobic environments, which volatilizes and diminishes soil sulfur reserves (Lara *et al.,* 2019)

4.6.1.7 Soil available iron (mg kg^{-1})

Iron availability showed no significant differences at 45 DAT in 2023 (3.97 vs. 4.00 mg kg^{-1}) and 2024 (4.05 vs. 4.08 mg kg^{-1}). After waterlogging, Fe decreased significantly at 55 DAT, from 4.40 to 2.73 mg kg^{-1} in 2023 and from 4.48 to 2.80 mg kg^{-1} in 2024, indicating reduced Fe availability under prolonged saturation (Table 22), possibly due to precipitation as insoluble ferric oxides upon re-aeration or competition with other reduced species in flooded soils (Barczok *et al.,* 2023).

4.6.1.8 Soil available manganese (mg kg^{-1})

At 45 DAT, Mn remained unaffected by waterlogging in both years, with closely similar values (5.13 mg kg^{-1} in 2023 and about 5.2 mg kg^{-1} in 2024). At 55 DAT, Mn levels declined significantly under waterlogging from 5.67 to 3.44 mg kg^{-1} in 2023 and from 5.75 to 3.52 mg kg^{-1} in 2024, showing consistent depletion due to flooding (Table 22), as anaerobic conditions promote reduction to soluble Mn^{2+} followed by leaching or immobilization upon oxidation (Haque *et al.,* 2015).

4.6.1.9 Soil available zinc (mg kg^{-1})

Zinc concentrations did not differ significantly between treatments at 45 DAT in either 2023 (1.76 vs. 1.80 mg kg^{-1}) or 2024 (1.80 vs. 1.84 mg kg^{-1}). Similarly, at 55 DAT, Zn remained statistically unchanged under waterlogging in 2023 (3.14 vs. 3.04 mg kg^{-1}) and 2024 (3.20 vs. 3.12 mg kg^{-1}), indicating that Zn availability was relatively stable under waterlogged conditions (Table 22), suggesting zinc's relative stability under waterlogging, possibly due to its low mobility and association with soil organic matter.

4.6.1.10 Soil available copper (mg kg^{-1})

Available Cu showed no significant treatment effect at 45 DAT in 2023 (6.02 vs. 6.07 mg kg^{-1}) or 2024 (6.10 vs. 6.14 mg kg^{-1}). At 55 DAT, waterlogging significantly reduced Cu from 5.70 to 4.73 mg kg^{-1} in 2023 and from 5.80 to 4.82 mg kg^{-1} in 2024, revealing a consistent decline in Cu availability after flooding (Table 22), likely from adsorption onto soil particles or formation of insoluble sulfides in reduced environments (Pan *et al.,* 2015).

4.6.1.11 Soil available calcium (cmol kg^{-1})

Calcium levels were statistically similar between treatments at 45 DAT in 2023 (1.18 vs. 1.17 cmol kg^{-1}) and 2024 (1.20 vs. 1.19 cmol kg^{-1}). By 55 DAT, waterlogging significantly decreased Ca from 1.40 to 1.02 cmol kg^{-1} in 2023 and from 1.42 to 1.04 cmol kg^{-1} in 2024, suggesting loss of exchangeable Ca under saturated soil conditions (Table 22), attributed to leaching from displaced exchange sites and reduced root cation exchange capacity under flooding (UNE, 2023).

4.6.1.12 Soil available magnesium (cmol kg^{-1})

At 45 DAT, Mg did not differ significantly between control and waterlogging in either year, with values around 0.64–0.69 cmol kg^{-1}. At 55 DAT, Mg decreased sharply under waterlogging from 0.80 to 0.41 cmol kg^{-1} in 2023 and from 0.82 to 0.42 cmol kg^{-1} in 2024, indicating substantial reductions in available Mg in flooded plots (Table 22), due to enhanced leaching and competition with other cations like ammonium in anaerobic soils (Piirainen *et al.,* 2009)

4.6.1.13 Soil available boron (mg kg^{-1})

Boron availability was unaffected at 45 DAT, with non-significant differences between treatments in 2023 (0.92 vs. 0.94 mg kg^{-1}) and 2024 (0.93 vs. 0.95 mg kg^{-1}). After waterlogging, B declined significantly at 55 DAT from 0.92 to 0.62 mg kg^{-1} in 2023 and from 0.93 to 0.63 mg kg^{-1} in 2024, indicating sensitive leaching or redistribution of B under saturated conditions (Table 22), primarily through leaching in saturated conditions, as boron's anionic form increases mobility under flooding (Sá and Ernani, 2016).

4.6.1.14 Organic carbon (mg kg^{-1})

Organic carbon did not vary significantly between control and waterlogging at 45 DAT in 2023 (6.70 vs. 6.39 mg kg^{-1}) and 2024 (6.80 vs. 6.48 mg kg^{-1}), reflecting comparable initial C status. At 55 DAT, waterlogging significantly reduced organic carbon from 10.21 to 6.18 mg kg^{-1} in 2023 and from 10.35 to 6.25 mg kg^{-1} in 2024, demonstrating strong depletion of soil C under prolonged waterlogging (Table 22), resulting from accelerated microbial decomposition under anaerobic conditions, which mineralizes carbon more rapidly without sufficient oxygen for balanced humification (Huang and Hall, 2017).

4.6.2: Soil enzymatic and biological activities

Table 23: Effect of waterlogging on soil enzymatic activities and microbial biomass carbon at different growth stages during 2023 and 2024.

	45 DAT (2023)			45 DAT (2024)			55 DAT (2023)			55 DAT (2024)		
Enzymatic Activities	**Control**	**W. L**	**p = 0.05**	**Control**	**W. L**	**p = 0.05**	**Control**	**W. L**	**p = 0.05**	**Control**	**W. L**	**p = 0.05**
Dehydrogenase (μg TPF g^{-1} h^{-1})	46.6	46.4	**0.95**	45.10	44.90	**0.53**	42.9	19.5	**0.000053****	44.8	20.6	**0.00014****
Acid-Phosphatase (μg PNP g^{-1} h^{-1})	87.7	86.3	**0.55**	86.80	85.60	**0.61**	101.0	83.7	**0.00068****	102.4	88.2	**0.00091****
Alkaline-Phosphatase (μg PNP g^{-1} h^{-1})	97.2	97.5	**0.94**	98.80	97.00	**0.58**	111.6	85.5	**0.0127***	116.7	86.2	**0.0267***
Urease (μg NH4-N g^{-1} soil h^{-1})	73.1	72.5	**0.77**	74.30	71.20	**0.77**	90.7	66.9	**0.000253****	92.6	64.5	**0.00074****
SMBC (μg g^{-1} soil)	62.8	62.9	**0.99**	60.2	60.4	**0.55**	57.7	20.4	**0.0000337****	60.2	21.5	**0.00014****

DAT: Days after transplanting; W.L: Waterlogging treatment; SMBC: Soil microbial biomass carbon; P = 0.05: Significance Level; *: 0.01 < 0.05 Significant difference; **: 0.001 < 0.01 Highly significant difference.

4.6.2.1 Dehydrogenase (µg TPF g^{-1} h^{-1})

At 45 DAT in 2023 and 2024, differences between control (46.6; 45.10) and waterlogging (46.4; 44.90) were non-significant, indicating similar baseline oxidative microbial activity before stress. At 55 DAT, waterlogging caused a highly significant decline in both 2023 and 2024: control 42.9 vs waterlogging 19.5 in 2023, and control 44.8 vs waterlogging 20.6 in 2024 (Table 23), evidencing strong suppression of microbial respiratory enzymes under flooding.

4.6.2.2 Acid phosphatase (µg PNP g^{-1} h^{-1})

At 45 DAT in 2023 and 2024, differences were non-significant (2023: 87.7 vs 86.3; 2024: 86.80 vs 85.60). At 55 DAT, waterlogging led to a highly significant reduction in both 2023 and 2024: control 101.0 vs waterlogging 83.7 in 2023, and control 102.4 vs waterlogging 88.2 in 2024 (Table 23), reflecting constrained organic P mineralization under anaerobic conditions.

4.6.2.3 Alkaline phosphatase (µg PNP g^{-1} h^{-1})

At 45 DAT in 2023 and 2024, differences were non-significant (2023: 97.2 vs 97.5; 2024: 98.80 vs 97.00). At 55 DAT, waterlogging produced a significant decrease in both 2023 and 2024: control 111.6 vs waterlogging 85.5 in 2023, and control 116.7 vs waterlogging 86.2 in 2024 (Table 23), indicating reduced phosphomonoesterase activity in saturated soils.

4.6.2.4 Urease (µg NH4-N g^{-1} soil h^{-1})

At 45 DAT in 2023 and 2024, differences were non-significant (2023: 73.1 vs 72.5; 2024: 74.30 vs 71.20). At 55 DAT, waterlogging induced a highly significant decline in both 2023 and 2024: control 90.7 vs waterlogging 66.9 in 2023, and control 92.6 vs waterlogging 64.5 in 2024 (Table 23), consistent with inhibited N-cycling enzyme activity under hypoxia.

4.6.2.5 Soil microbial biomass carbon (SMBC, µg g^{-1})

At 45 DAT in 2023 and 2024, differences were non-significant (2023: 62.8 vs 62.9; 2024: 60.2 vs 60.4), indicating comparable microbial standing biomass pre-stress. At 55 DAT, waterlogging caused a highly significant reduction in both 2023 and 2024: control 57.7 vs waterlogging 20.4 in 2023, and control 60.2 vs waterlogging 21.5 in 2024 (Table 23), showing sharp losses in microbial biomass under prolonged saturation.

The results demonstrate that waterlogging significantly suppresses soil enzymatic and microbial activities critical for nutrient cycling and soil health. Initially, at 45 DAT, similar values under control and waterlogging indicate stable baseline microbial functions before flooding stress. However, by 55 DAT, prolonged waterlogging induced highly significant declines in dehydrogenase, acid and alkaline phosphatases, urease activities, and soil microbial biomass carbon, reflecting impaired microbial metabolism and enzymatic processes under hypoxic conditions (Gu *et al.,* 2019). These reductions are primarily due to oxygen deprivation that limits aerobic microbial respiration and the breakdown of organic matter, consequently disrupting phosphorus and nitrogen mineralization crucial for plant nutrition (Pan *et al.,* 2021). The sharp decrease in microbial biomass further evidences microbial mortality or dormancy triggered by anaerobic stress (Yu *et al.,* 2022). Collectively, these findings highlight the detrimental impact of waterlogging on soil biological functions, undermining nutrient availability and ecosystem sustainability in onion cultivation.

4.7 Economics

Table 24: Effect of waterlogging treatment on economics of production of onion genotypes during 2023 and 2024.

Economics								
Main plot	**COC**		**Gross Return**		**Net Return**		**BC Ratio**	
	2023	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Waterlogging	167266	167266	307599	504083	140333	336817	1.84	3.01
Control	153778	153778	478220	573467	324442	419689	3.11	3.73
SEm±	-	-	1340	1717	1340	1717	-	-
CD (P ≤ 0.05)	-	-	**8152**	**5151**	**8152**	**5151**	-	-
Sub-plot								
Acc 1666	160522	160522	522450	650133	361928	489611	3.28	4.06
Acc.1630	160522	160522	441825	496033	281303	335511	2.78	3.10
W 355	160522	160522	327397	510600	166875	350078	2.06	3.21
Bhima Dark Red	160522	160522	624217	609500	463695	448978	3.92	3.80
Bhima Red	160522	160522	356542	457700	196020	297178	2.26	2.88
Bhima Raj	160522	160522	367148	611033	206626	450511	2.32	3.82
Bhima Shubra	160522	160522	254536	542800	94014	382278	1.61	3.38
Bhima Super	160522	160522	249161	432400	88639	271878	1.56	2.71
SEm±	-	-	19776	14036	19776	14036	-	-
CD (P ≤ 0.05)	-	-	**57288**	**42108**	**57288**	**57288**	-	-
Main x sub-Interaction (T*G)								
SEm±	-	-	27967	25708	27967	25708	-	-
CD (P ≤ 0.05)	-	-	**81017**	**77124**	**81017**	**77124**	-	-
Main x sub-Interaction (G*T)								
SEm±	-	-	26195	25387	26195	25387	-	-
CD (P ≤ 0.05)	-	-	**76103**	**76161**	**76103**	**76161**	-	-

COC: Cost of cultivation; B:C: Benefit–cost ratio; SEm±: Standard Error of Mean; CD at 5%: Critical Difference at 5% significance; All monetary values in ₹ ha^{-1}.

Table 25: Interaction effect between waterlogging treatment and genotypes of onion on economic during 2023 and 2024.

Gross Return (2023)			
	W. L	**Control**	**Mean**
Acc 1666	431194	613706	522450
Acc.1630	364306	519344	441825
W-355	258000	396794	327397
Bhima Dark Red	519106	729328	624217
Bhima Red	239606	473478	356542
Bhima Raj	256806	477491	367148
Bhima Shubra	162206	346867	254536
Bhima Super	229572	268750	249161
Mean	307599	478220	
Interaction (Treatment*Genotype)			
Sem ±	27967		
CD (P ≤ 0.05)	**81017**		
Interaction (Genotype*Treatment)			
Sem ±	26195		
CD (P ≤ 0.05)	**76103**		

Gross Return (2024)			
	W. L	**Control**	**Mean**
Acc 1666	630200	670067	650133
Acc.1630	472267	519800	496033
W-355	418600	602600	510600
Bhima Dark Red	616400	602600	609500
Bhima Red	363400	552000	457700
Bhima Raj	570400	651667	611033
Bhima Shubra	561200	524400	542800
Bhima Super	400200	464600	432400
Mean	504083	573467	
Interaction (Treatment*Genotype)			
SE (m) ±	25708		
CD at 5%	**77124**		
Interaction (Genotype*Treatment)			
Sem ±	25387		
CD (P ≤ 0.05)	76161		

Net Return (2023)			
	W. L	**Control**	**Mean**
Acc 1666	263928	459928	361928
Acc.1630	197040	365566	281303
W-355	90734	243016	166875
Bhima Dark Red	351840	575550	463695
Bhima Red	72340	319700	196020
Bhima Raj	89540	323713	206626
Bhima Shubra	-5060	193089	94014
Bhima Super	62306	114972	88639
Mean	140333	324442	
Interaction (Treatment*Genotype)			
Sem ±	27967		
CD (P ≤ 0.05)	**81017**		
Interaction (Genotype*Treatment)			
Sem ±	26195		
CD (P ≤ 0.05)	**76103**		

Net Return (2024)			
	W. L	**Control**	**Mean**
Acc 1666	462934	516289	489611
Acc.1630	305001	366022	335511
W-355	251334	448822	350078
Bhima Dark Red	449134	448822	448978
Bhima Red	196134	398222	297178
Bhima Raj	403134	497889	450511
Bhima Shubra	393934	370622	382278
Bhima Super	232934	310822	271878
Mean	336817	419689	
Interaction (Treatment*Genotype)			
Sem ±	25708		
CD (P ≤ 0.05)	**77124**		
Interaction (Genotype*Treatment)			
Sem ±	25387		
CD (P ≤ 0.05)	**76161**		

W.L = Waterlogging; DAT = Days After Transplanting; SEm± = Standard Error of Mean; CD at 5% = Critical Difference at 5% significance; All monetary values in ₹ ha^{-1}.

(a) Effect of waterlogging treatment on economics of onion genotypes during 2023 and 2024.

The cost of cultivation (COC) did not vary among genotypes (a uniform ₹160522 ha^{-1}, being the treatment-pooled mean) but differed between main plots, with waterlogging incurring a higher COC (₹167266) than the control (₹153778) owing to the additional cost of imposing and managing waterlogged conditions. Gross return and net return exhibited significant differences due to treatment, genotype, and their interaction in both years, whereas the benefit–cost (B:C) ratio, being a derived ratio, followed the same trend descriptively. The control treatment consistently recorded higher gross return (₹478220 in 2023, ₹573467 in 2024), net return (₹324442 and ₹419689), and B:C ratio (3.11 and 3.73) compared to waterlogging stress, which recorded lower gross return (₹307599 and ₹504083), net return (₹140333 and ₹336817), and B:C ratio (1.84 and 3.01). Among the genotypes, the best economic performer differed between years: in 2023, Bhima Dark Red exhibited the highest gross return (₹624217), net return (₹463695), and B:C ratio (3.92), while in 2024, Acc 1666 recorded the highest gross return (₹650133), net return (₹489611), and B:C ratio (4.06), demonstrating superior profitability under both stress and non-stress conditions (Table 24). Conversely, Bhima Super consistently recorded the lowest values across both years gross return (₹249161 and ₹432400), net return (₹88639 and ₹271878), and B:C ratio (1.56 and 2.71) indicating the poorest economic returns and greatest susceptibility to waterlogging stress. The sharp decline in profitability under waterlogged conditions is a direct consequence of yield loss, since oxygen deprivation in the root zone restricts aerobic respiration, nutrient uptake, and bulb development, thereby lowering marketable bulb yield and gross return, while the higher cost of managing waterlogged fields further compresses net return and B:C ratio. Notably, genotypes like Acc 1666 and Bhima Dark Red sustained remunerative returns under stress, suggesting yield-stabilizing adaptations such as enhanced root aeration and more robust stress tolerance. In contrast, genotypes like Bhima Super, Bhima Shubra, and Bhima Red suffered steep economic losses, likely owing to less effective stress-response mechanisms.

(b) Interaction effect between waterlogging treatment and genotypes on economics during 2023–2024.

The interaction between genotype and treatment was significant for both gross return and net return (Table 25). At the gross return level in 2023, Bhima Dark Red under control recorded the highest gross return (₹729328), while Bhima Shubra under waterlogging stress exhibited the lowest (₹162206). In 2024, Acc 1666 under control attained the maximum gross return (₹670067), statistically at par with Bhima Raj (₹651667), Acc 1666 under waterlogging (₹630200), Bhima Dark Red under waterlogging (₹616400), and Bhima Dark Red and W-355 under control (₹602600 each), whereas Bhima Red under waterlogging registered the lowest (₹363400). For net return in 2023, Bhima Dark Red under control produced the highest net return (₹575550), while Bhima Shubra under waterlogging recorded the lowest in fact a negative net return (₹−5060), indicating the crop failed to recover its cost of cultivation. In 2024, Acc 1666 under control recorded the maximum net return (₹516289), statistically at par with Bhima Raj under control (₹497889), Acc 1666 under waterlogging (₹462934), Bhima Dark Red under waterlogging (₹449134), and W-355 and Bhima Dark Red under control (₹448822 each), whereas Bhima Red under waterlogging showed the minimum (₹196134).

Under control conditions, all genotypes realized markedly higher returns owing to unrestricted vegetative growth, bulb development, and consequent yield, which translated directly into greater gross and net returns. However, the significant reduction in returns under waterlogging showed the cumulative economic penalty of prolonged anaerobic stress, culminating in the most susceptible combination (Bhima Shubra × waterlogging) recording a negative net return in 2023 the clearest economic expression of hypoxic injury restricting root respiration, nutrient uptake, and yield. The superior interaction performance of Acc 1666 and Bhima Dark Red, which remained profitable even under waterlogging, reflects their genetic potential for yield stability under stress, possibly through efficient oxygen transport and osmotic adjustment. Conversely, the poor economic performance of Bhima Super, Bhima Shubra, and Bhima Red under waterlogging highlights their vulnerability to hypoxic conditions and underscores the critical need for genotype specific selection to protection farm profitability in waterlogging-prone areas.

CHAPTER V

SUMMARY AND CONCLUSION

Summary

The present investigation entitled "Screening onion genotypes for growth, yield, and economics of production under waterlogged conditions and its impact on physico-chemical properties of soil" was conducted at ICAR–Directorate of Onion and Garlic Research, Rajgurunagar, Pune (Maharashtra) during late *kharif* 2023 and 2024. The study evaluated the physiological, biochemical, and yield responses of eight onion genotypes to waterlogging stress imposed at 45–55 DAT. Key morpho-physiological traits such as plant height, number of leaves, leaf area, and neck thickness were monitored at different growth stages. Biochemical parameters including pyruvic acid content, proline accumulation, antioxidant activity, protein content, and total soluble solids were also assessed. Furthermore, the impact of waterlogging on soil nutrient status, microbial enzyme activity, and economics of production was evaluated. The salient findings of the study are summarized below.

- **Plant Growth and Morphology:** Waterlogging stress significantly reduced plant height, number of leaves, leaf area, and neck thickness from 55 DAT onwards through harvest. Control plants consistently outperformed waterlogged plants across both seasons. Genotypes such as Acc. 1666, Bhima Dark Red, and Acc. 1630 exhibited superior tolerance by maintaining greater growth parameters under stress. In contrast, susceptible genotypes like Bhima Shubra and Bhima Super showed the most severe growth reductions under waterlogging.

- **Physiological Response:** Waterlogging reduced total leaf chlorophyll content at 55 and 75 DAT, confirming hypoxia-driven pigment degradation and diminished photosynthetic capacity. Acc. 1666 consistently retained the highest chlorophyll content, while Bhima Shubra recorded the lowest, indicating strong genotypic contrasts under stress. Membrane Stability Index (MSI) likewise declined under waterlogging from 55 DAT onward. However, Acc. 1666 and Bhima Dark Red maintained the highest MSI values, evidencing superior membrane integrity and lower electrolyte leakage. Conversely, Bhima Super and Bhima Shubra were the most affected genotypes. Higher chlorophyll and MSI in Acc. 1666 explain its sustained photosynthesis and growth under flooding. These two traits emerge as complementary and rapid physiological indicators for screening waterlogging tolerance in onion.

- **Biochemical Responses:** Waterlogging led to marked reductions in important biochemical traits, including pyruvic acid, proline content, antioxidant capacity, protein percentage, and total soluble solids. Among all genotypes, Acc. 1666 exhibited the highest biochemical resilience, indicating enhanced metabolic stability and superior stress adaptation. Conversely, genotypes such as Bhima Shubra and Bhima Super showed weaker antioxidant defense and lower biochemical quality under waterlogging stress.

- **Plant Nutrient Bulb (Sulphur):** Across both seasons, waterlogging significantly altered bulb sulphur content at mid-season (55 DAT). Tolerant genotypes, especially Acc. 1666, maintained higher sulphur levels under stress. Susceptible genotypes such as Bhima Red and Bhima Super showed marked declines in sulphur content. By harvest, treatment differences narrowed considerably, indicating partial recovery of sulphur metabolism as soils drained and aerobic conditions were restored.

- **Yield and Productivity:** Onion bulb yield was significantly reduced by waterlogging stress in both 2023 and 2024. Control plants consistently achieved higher yields than waterlogged plants. Bhima Dark Red and Acc. 1666 exhibited the highest yields under both control and waterlogged conditions, underscoring their potential as waterlogging-tolerant cultivars. Lower yields in genotypes such as Bhima Shubra and Bhima Super were associated with reduced growth, impaired metabolism, and poor stress adaptation.

- **Soil Health and Microbial Impact:** Prolonged waterlogging significantly diminished soil enzymatic activities (dehydrogenase, acid and alkaline phosphatase, and urease) and soil microbial biomass carbon at 55 DAT. These reductions reflect suppressed aerobic microbial metabolism under anaerobic conditions. The disruption in soil biological function further constrained nutrient cycling and availability, compounding the stress effects on plant growth and productivity. Soil available macronutrients (N, P, K, S, Ca, Mg) and micronutrients (Fe, Cu, Mn, B) also declined significantly under waterlogging.

- **Genotype × Treatment Interaction:** Significant interaction effects were observed across most parameters, highlighting substantial genetic variability in response to waterlogging. Genotypes varied distinctly in their ability to maintain growth, biochemical functions, and yield under hypoxia. These results emphasize the importance of genetic selection for tolerance traits in breeding programmes aimed at waterlogging-prone environments.

- **Economics:** Waterlogging stress markedly reduced the economics of onion production in both seasons. The cost of cultivation was higher under waterlogging (₹167266 ha^{-1}) than control (₹153778 ha^{-1}) owing to the added cost of managing waterlogged fields, and control plots consistently recorded higher gross returns (₹478220 and ₹573467 ha^{-1}), net returns (₹324442 and ₹419689 ha^{-1}), and B:C ratios (3.11 and 3.73) than waterlogged plots (gross ₹307599 and ₹504083; net ₹140333 and ₹336817; B:C 1.84 and 3.01) across 2023 and 2024. The best economic performer varied by year — Bhima Dark Red led in 2023 (gross ₹624217, net ₹463695, B:C 3.92) and Acc 1666 in 2024 (gross ₹650133, net ₹489611, B:C 4.06) — both remaining profitable even under stress owing to their yield-stabilizing tolerance. In contrast, susceptible genotypes such as Bhima Super and Bhima Shubra returned the lowest values, with the Bhima Shubra × waterlogging combination recording a negative net return (₹−5060 ha^{-1}) in 2023, failing to recover its cost of cultivation

Conclusion

Waterlogging stress imposed a profound negative impact on onion growth, physiology, biochemical composition, yield, and economic returns. The primary cause of this damage was oxygen deficiency in the root zone, which led to impaired root respiration, disrupted nutrient uptake, decreased photosynthetic efficiency, and metabolic disturbances. Soil health was also adversely affected, as waterlogging suppressed microbial and enzymatic activities essential for nutrient cycling. The reduction in soil available nutrients further constrained plant nutrition and growth sustainability, creating a compounding effect of above-ground and below-ground stress on onion productivity.

Among the eight genotypes tested, Acc. 1666 consistently demonstrated superior tolerance to waterlogging stress across both cropping seasons. It maintained higher growth parameters, biochemical resilience, yield, and significantly better economic performance with higher gross and net returns and B:C ratios. Its physiological robustness is likely attributable to efficient root aeration, osmotic adjustment, and a strong antioxidant defense system. The accumulation of stress metabolites such as proline and enhanced antioxidant activity in this genotype indicated adaptive mechanisms that mitigate oxidative damage and maintain cell viability. Bhima Dark Red also showed promising tolerance traits, particularly in growth maintenance, biochemical quality, and economic returns, making it a viable genotype for cultivation in waterlogging-prone areas.

Susceptible genotypes, including Bhima Shubra and Bhima Super, exhibited significant growth retardation, reduced biochemical integrity, lowest yields, and poor economic returns under waterlogging. These genotypes lacked adequate adaptive responses, making them vulnerable to hypoxic stress and metabolic disruption. Furthermore, the significant decline in soil microbial biomass carbon and enzyme activities under waterlogging highlighted the detrimental impact of prolonged anaerobic conditions on soil biological health. This disruption in soil functions further exacerbated the nutrient stress experienced by susceptible genotypes, contributing to their poor performance.

The significant genotype × treatment interactions confirmed the existence of exploitable genetic variability in waterlogging tolerance within the tested onion germplasm. Selecting genotypes such as Acc. 1666 and Bhima Dark Red, which exhibit multifaceted stress resilience encompassing physiological, biochemical, yield, and economic stability, is crucial for developing climate-resilient onion cultivars suited to flood-prone areas. Future research should focus on elucidating the molecular and genetic bases of these tolerance mechanisms and incorporating them into widely adapted onion varieties. Additionally, integrated crop and soil management strategies targeting waterlogging mitigation should be developed to enhance productivity, profitability, and sustainability in affected agroecosystems.

Suggestions for Future Work

- Conduct molecular and genetic studies to identify key genes and pathways responsible for waterlogging tolerance in onion genotypes.
- Investigate root anatomical traits and physiological mechanisms that support oxygen transport and nutrient uptake under waterlogging stress.
- Employ QTL mapping and genomic selection approaches to breed onion varieties with improved waterlogging tolerance.
- Study soil microbial community composition and enzyme activities to understand their role in supporting plant resilience during waterlogging.
- Evaluate agronomic practices such as raised bed cultivation, improved drainage systems, and organic amendments to reduce the impact of waterlogging on onion production.
- Validate the performance of tolerant genotypes through multi-location and multi-year field trials to ensure consistent and stable performance across diverse environments.
- Integrate screening for both waterlogging tolerance and disease resistance to develop robust and resilient onion cultivars for monsoon-season cultivation.
- Assess the economic viability and farmer adoption potential of tolerant genotypes and management strategies through participatory socio-economic studies.

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Appendix I: Calendar of operations and weekly metrological data of 2023 and 2024 cropping season.

Calendar of operations 2023

Sr. No.	**Date**	**Calendar of Operations**	**Material Used**	**Quantity Used / Sample Collected/Time required**
1	30/07/2023	Ploughing, Disking, Rotavator, Collection of Stubbles	Tractor Machinery	1 Tractor, 1 Disc Harrow
2	1/8/2023	Bed Preparation, Bed Shaping	Mould board plough, Raised bed maker	1 Mould board plough,
3	1/8/2023	Soil Sample Collection	Auger (Blade type)	Control plot – 3 samples, Waterlogging – 3 samples, (Flatbed)
4	2/8/2023	Fertilizer Application	FYM, 10:26:26, Bensulf	FYM – 5 t/ha, NPK – 100:50:50 kg/ha, Sulfur – 30 kg/ha
5	4/8/2023	Transplanting	—	—
6	5/8/2023	Irrigation	Flood irrigation	
7	9/8/2023	Irrigation and 1st Top Dressing (Flatbed)	Urea (Broadcast)	35.2 g/split/plot (FB)
8	10/8/2023	Spraying	Mancozeb + Carbosulfan	2 g/lit + 2 ml/lit
10	16/08/2023	2nd Top Dressing (Flatbed)	Urea (Broadcast)	35.2 g/split/plot (FB)
12	23/08/2023	3rd Top Dressing (Flatbed), Weeding, Spraying	Urea, Profenofos + Propiconazole	35.2 g/split, 2 ml/lit + 2 ml/lit
13	24/08/2023	Weeding (Flatbed)	—	—
14	25/08/2023	Drenching (Flatbed)	Cabrio Top	2 g/lit
15	28/08/2023	4th Top Dressing (Flatbed)	Urea	570 g/split

18	4/9/2023	5th Top Dressing (Flatbed), Spray (tricycle 20L Fipronil), Flatbed 2nd Top Dressing, Weeding	Fipronil, Urea	As per treatment
19	7/9/2023	Irrigation	flood	
20	11/9/2023	Irrigation	flood	
21	16/09/2023	Irrigation	flood	
22	23/09/2023–02/10/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
23	24/09/2023	Irrigation	control plot	
24	24/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
25	25/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
26	26/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
27	27/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
28	28/09/2023	Irrigation	control plot	
29	28/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
30	29/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
31	30/09/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
32	1/10/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
33	2/10/2023	Waterlogging Treatment	flood/sprinkler	4-5 cm depth /sprinkler for 5-6 hr.
34	2/10/2023	Irrigation	control plot	

35	4/10/2023	spraying	Cabrio Top and carbosulphan	
36	8/10/2023	Weeding (Flatbed)		
37	24/10/2023	Irrigation	flood	
38	9/11/2023	Harvesting	—	—
39	10/11/2023	Grading	Manually	

Appendix I: Continued…

Calendar of operation 2024

Sr. No.	Date	Calendar of Operations	Material Used	Quantity Used / Sample Collected / Time Required
1	31/07/2024	Ploughing, Disking, Rotavator, Collection of Stubbles	Tractor Machinery	1 Tractor, 1 Disc Harrow
2	2/8/2024	Bed Preparation, Bed Shaping	Mould board plough, Raised bed maker	1 Mould board plough
3	2/8/2024	Soil Sample Collection	Auger (Blade type)	Control plot – 3 samples, Waterlogging – 3 samples, (Flatbed)
4	3/8/2024	Fertilizer Application	FYM, 10:26:26, Bensulf	FYM – 5 t/ha, NPK – 100:50:50 kg/ha, Sulfur – 30 kg/ha
5	5/8/2024	Transplanting	—	—
6	6/8/2024	Irrigation	Flood irrigation	
7	10/8/2024	Irrigation and 1st Top Dressing (Flatbed)	Urea (Broadcast)	35.2 g/split/plot (FB)
8	11/8/2024	Spraying	Mancozeb + Carbosulfan	2 g/lit + 2 ml/lit
9	17/08/2024	2nd Top Dressing (Flatbed)	Urea (Broadcast)	35.2 g/split/plot (FB)
10	24/08/2024	3rd Top Dressing (Flatbed), Weeding, Spraying	Urea, Profenofos + Propiconazole	35.2 g/split, 2 ml/lit + 2 ml/lit
11	25/08/2024	Weeding (Flatbed)	—	—
12	26/08/2024	Drenching (Flatbed)	Cabrio Top	2 g/lit
13	29/08/2024	4th Top Dressing (Flatbed)	Urea	570 g/split
14	31/08/2024	Irrigation	Drip	—

15	4/9/2024	Irrigation	Drip	1 hr
16	5/9/2024	5th Top Dressing (Flatbed), Spray (tricycle 20L Fipronil), Flatbed 2nd Top Dressing, Weeding	Fipronil, Urea	As per treatment
17	8/9/2024	Irrigation	Flood	
18	12/9/2024	Irrigation	Flood	
19	17/09/2024	Irrigation	Flood	
20	24/09/2024–03/10/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
21	25/09/2024	Irrigation	Control plot	
22	25/09/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
23	26/09/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
24	27/09/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
25	28/09/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
26	29/09/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
27	30/09/2024	Irrigation	Control plot	
28	30/09/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
29	1/10/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
30	2/10/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
31	3/10/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr

32	4/10/2024	Waterlogging Treatment	Flood/Sprinkler	4–5 cm depth / sprinkler for 5–6 hr
33	4/10/2024	Irrigation	Control plot	
34	5/10/2024	Spraying	Cabrio Top and Carbosulfan	
35	9/10/2024	Weeding (Flatbed)		
36	25/10/2024	Irrigation	Flood	
37	10/11/2024	Harvesting	—	—
38	11/11/2024	Grading	Manually	

Appendix II: Weekly meteorological data of 2023-2024.

Weekly Meteorological data 2023

Week No	Temp. Max	Temp. Min	Relative Humidity 8.45 A M	Relative Humidity 2.45 P M	VELOCITY (km/hr.)	SUNSHINE (Hr.)	RAIN (mm)	Evaporation(mm)
25	24.4	19.6	85.4	84.3	6.2	2.2	4.4	2.9
26	29.4	22.6	87.4	85.3	7.2	2.6	4.9	2.1
27	29.3	22.9	84.4	78.7	8.6	1.4	0.0	2.8
28	27.8	22.5	87.9	85.6	7.0	0.8	3.3	1.3
29	25.7	18.9	92.9	88.0	7.1	0.4	8.9	0.4
30	26.4	22.4	86.4	82.0	12.3	1.8	0.9	0.9
31	27.3	22.2	87.3	79.0	7.2	3.6	1.8	1.3
32	28.3	21.8	87.9	72.3	6.6	6.3	0.4	2.5
33	28.6	21.9	85.1	79.1	6.7	5.4	1.2	1.9
34	30.1	20.7	85.3	73.7	5.3	7.2	0.0	2.2
35	29.6	22.1	87.7	75.9	8.4	6.4	4.3	2.5
36	29.6	20.9	82.6	76.4	7.9	5.5	0.0	3.0
37	28.4	21.8	92.3	72.0	4.1	3.1	8.4	1.5
38	28.8	21.1	92.3	76.1	2.4	2.8	22.1	0.8
39	31.6	20.5	86.9	58.9	2.2	6.8	0.8	1.6
40	34.1	21.3	74.9	57.4	1.9	6.0	0.0	3.3
41	33.4	21.6	75.3	63.0	2.0	7.1	1.1	3.0
42	32.9	17.4	75.1	55.9	2.2	9.1	0.0	4.0
43	32.3	16.6	67.0	60.4	2.5	8.3	0.0	3.8
44	31.7	18.3	71.3	56.6	2.9	5.3	0.0	3.0
45	31.5	16.3	37.1	30.7	2.0	7.7	0.0	3.9
46	30.7	17.1	78.0	62.0	2.3	7.1	1.9	3.4
47	29.5	17.1	82.3	65.5	2.8	6.1	0.0	3.9

Appendix II: Continued.

Weekly Meteorological Data 2024

Week No	Temp. Max	Temp. Min	Relative Humidity 8.45 A M	Relative Humidity 2.45 P M	VELOCITY (km/hr.)	SUNSHINE (Hr.)	RAIN (mm)	Evaporation(mm)
25	55.7	40.0	146.0	134.0	12.7	13.5	-	8.2
26	54.4	41.4	152.8	126.3	9.7	3.4	18.8	6.8
27	52.2	41.1	151.5	133.8	15.0	2.1	10.5	4.2
28	50.9	39.2	157.3	129.5	11.3	3.8	10.5	2.5
29	49.1	39.6	159.3	146.5	14.7	0.7	10.0	2.0
30	45.6	39.0	165.5	157.3	14.0	0.1	32.0	0.6
31	46.0	39.9	164.3	154.0	43.2	0.4	27.5	0.6
32	27.3	22.6	86.7	77.4	6.0	2.7	1.7	1.2
33	31.6	22.8	87.9	68.7	2.9	5.7	4.6	3.2
34	30.2	22.3	93.3	84.4	5.0	2.3	15.1	1.2
35	27.3	21.8	89.6	84.1	6.2	3.7	5.2	1.1
36	28.3	22.5	85.1	73.7	4.9	3.0	0.5	1.9
37	29.4	20.6	87.3	71.6	5.4	5.5	0.0	2.8
38	31.9	20.5	83.3	64.3	4.8	6.6	0.0	2.6
39	29.9	22.5	90.1	75.1	4.3	4.3	8.5	1.6
40	33.2	20.9	81.7	62.6	3.4	7.0	3.2	2.2
41	32.3	22.2	86.6	68.9	5.0	5.9	0.0	2.8
42	31.7	22.5	90.3	75.6	2.9	6.5	7.9	2.1
43	32.6	20.6	84.7	57.9	2.5	8.6	0.0	3.7
44	33.3	19.4	84.3	58.9	2.3	8.6	0.0	4.2
45	32.2	16.2	74.0	62.7	2.3	8.8	0.0	4.3
46	31.1	15.6	73.9	65.1	2.6	9.2	0.0	4.0
47	30.5	14.2	77.0	64.6	2.3	8.3	0.0	4.1
48	29.2	11.7	72.0	61.1	2.8	7.6	0.0	4.3

Appendix III: Price details utilized for estimating the cost of cultivation (Rs. ha^{-1}) of *kharif* onion.

Sr.no	Particulars	Quantity	Rate	Total Cost	Total Cost
	Field Operations			**2023**	**2024**
1	Ploughing	1	4200	4200	4200
2	Harrowing/Disking	1	4000	4000	4000
3	Land Levelling/bed preparation	1	2000	2000	2000
4	Flatbed Layout and bed shaping	1	1500	1500	1500
Cost of seed					
5	Seed / (8 genotypes)	8	2500	20000	20000
6	Seed sowing Labour and charges	6	350	2100	2100
7	Nursery uprooting and transplanting (labour charges)	10	350	3500	3500
Irrigation charges					
7	Flood Irrigation charges/ha			0	0
8	Labour For irrigation	10	350	3500	3500
9	Total irrigations	5	1147	5733	5733
Manures and Fertilizers					
10	Farm yield manure	15000	5	75000	75000
11	Urea	75	5	398	397.5
12	Phosphorus	40	13	520	520
13	Murat of potash	40	36	1440	1440
14	Sulphur	30	45	1350	1350
15	Labour used for manures and fertilizers operation	10	350	3500	3500
Plant protection					
16	Plant protection labour (3)	2	573	1146	1146
17	Mancozeb	1	520	624	624
18	Carbosulfan	1	619	1238	1238
19	Profenofos	1	666	500	499.5
20	Cabrio Top	18	198	3465	3465
21	Sticker	125	3	375	375
22	Chlorpyriphos 20% EC	1	530	530	530
23	Fipronil	0.5	1720	860	860
24	Weeding (4)	32	300	9600	9600
Harvesting					
	Harvesting, cutting and grading			0	0
25	Labour required and charges	12	350	4200	4200
26	Miscellaneous costs (Transportation cost)	1	2500	2500	2500
	Total cost			**153778**	**153778**

Note:

The present investigation comprised eight onion (*Allium cepa* L.) genotypes, each sown at the recommended seed rate of 8 kg ha^{-1}. Accordingly, the total seed actually required for the experiment was 64 kg (8 genotypes × 8 kg ha^{-1}), amounting to Rs 1,60,000 (64 kg × Rs 2500 kg^{-1}) at the prevailing market price of Rs 2500 kg^{-1}. However, since the cost of cultivation has been worked out on a per-hectare (unit-area) basis, the seed cost in the above table has been computed using a single standardized seed rate of 8 kg ha^{-1} (8 kg × Rs 2500 = Rs 20,000 ha^{-1}) and has not been multiplied by the number of genotypes.

Appendix III: Continued.

Price details utilized for estimating the cost of cultivation treatment wise (Rs. ha^{-1}) of *kharif* onion.

Treatment	S.NO	Inputs	Price	Days/Hours	Total Cost	
					2023	**2024**
Waterlogging Treatment	1	Cost of common Inputs	153778		153778	153778
	2	Flood irrigation	1146	8	9168	9168
	3	Sprinkler Irrigation	72	60	4320	4320
Total					**167266**	**167266**
Treatment	**S.NO**	**Inputs**	**Price**	**Days/Hours**	**Total Cost**	
					2023	**2024**
Control Treatment	1	Cost of common Inputs	153778		153778	153778
Total					**153778**	**153778**