

Eco-Physiological Characterization of Crop Responses to Waterlogging Stress in Flood-Prone Agricultural Zones

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Abstract

Waterlogging is a significant abiotic stress that disrupts plant physiological and metabolic functions, particularly in flood-prone regions exacerbated by climate change. This study aimed to investigate crop responses to varying durations of waterlogging stress using a combination of field trials, hydroponic experiments, physiological assessments, remote sensing, and molecular profiling. Results demonstrated a substantial decline in soil oxygen concentration and relative water content with increasing waterlogging duration. Crops responded by forming adaptive anatomical structures such as aerenchyma and adventitious roots, alongside increased activities of antioxidant enzymes like catalase and superoxide dismutase. Chlorophyll content and osmotic potential decreased significantly, indicating suppressed photosynthetic capacity and heightened cellular stress. NDVI values derived from drone imaging revealed spatial patterns of vegetation stress, while transcriptomic analysis identified stress-regulated genes associated with hormonal signaling and anaerobic respiration. The application of reflective antitranspirants and stress priming techniques showed promise in mitigating stress effects. Collectively, the integration of ground-based measurements, remote sensing, and molecular data provided comprehensive insights into the ecophysiological responses of crops under waterlogged conditions. These findings highlight key adaptive traits and offer strategic pathways for enhancing crop resilience through targeted breeding, agronomic management, and precision monitoring technologies.

Keywords: “Waterlogging Stress”, “Crop Physiology”, “Aerenchyma Formation”, “Antioxidant Enzymes”, “Remote Sensing”, “Abiotic Stress Adaptation”

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INTRODUCTION

In locations where flooding is typical, waterlogging frequently appears in agriculture because high water in the soil without air harms plant physiology and leads to fewer crops (Mukhtar & Yelwa, 2020). Owing to the rise in heavy rainfall events, climate change makes waterlogging more frequent, which endangers the supply of food globally (Oladosu et al., 2020). Even though floods in lowland river plains and farms are sometimes predicted, long periods of soil saturation from these floods mean that roots can't get enough oxygen, which affects plant growth, energy production, and the amount of harvest. Being aware of the details of how crops react to waterlogging allows experts to develop better ways to reduce damage and boost survival of crops in such areas.

When there is waterlogging, it creates several problems for plants that trigger responses that are either unhelpful or helpful (Kaur et al., 2021). When there is waterlogging, the oxygen supply decreases to the roots, which leads to hypoxia (or anoxia) and, as a result, root respiration, energy generation, and growth suffer (Luo et al., 2023). When there is not enough oxygen, the body uses anaerobic metabolism that leads to creation of harmful substances. These substances limit nutrients that the roots can take up and reduce root activity as well (Kapoor et al., 2020). Also, when soil is waterlogged, this change in soil biogeochemistry means nutrients are not available or can't move, resulting in deficiencies of important macronutrients and micronutrients for plants. With more water, CO₂ in the leaves and aquifer system goes down, helping photosynthesis (Abdelaal et al., 2021). In situations where water covers most or all parts of a plant, various types of modifications include the growth of aerenchyma, which helps move oxygen from the top of the plant to its roots (Narayan et al., 2020). Adventitious

roots are another usual way plants adapt by growing close to the surface, so they can get oxygen from the top regions, where diffusion takes less effort. Besides, when waterlogging happens, stomatal closure helps maintain water levels inside the plant, but at the same time, this prevents enough CO₂ from entering and decreases photosynthesis. Turbulence in water within xylem vessels might influence the plant's ability to move water and nutrients, worsening the effects of waterlogging because water and nutrients cannot get to the shoots (Abdelaal et al., 2021). Genes and environmental factors, along with the species of plant, determine the plant's reaction to water shortage (Rad et al., 2021).

When a crop is waterlogged, many plant hormones, signaling ways, and metabolic processes work together to produce complicated reactions. The important hormone ethylene in plants regulates waterlogging reactions, boosts the development of special air passages, encourages root development above the ground, and starts the use of airless metabolism. Under waterlogging, abscisic acid production often goes up and causes the closing of stomata and reduced leaf drying by water. Besides, if the plant is waterlogged, the antioxidant mechanism may not function properly, causing oxidative stress and often damaging the plant's cells. While there are not enough water resources, plants depend on amino acids and proline to help them lower osmotic pressure, save water, and sustain the swelling of cells (Rosa et al., 2020). Under water stress, plants depend on storing more water and on calming their development. To do this, hormones manage cellular water excretion and help with the needed changes.

Understanding how crops react to waterlogging in areas that often flood relies on a full examination of the local environment, the crop's features, and how

they interact. How much and how strongly crops will be affected by waterlogging stress is determined by checking the length and frequency, soil type, nutrient levels, and temperature. Considering the shape of plant roots, how aerenchyma forms, how much water exits stoma, photosynthesis, and antioxidant enzyme act reveals fresh points of view on how tolerance to waterlogging occurs. It is important to know this to understand plant response to water shortage. If we want to examine how plants react under stress, hydroponics is a proper technique (Wajhat-Un-Nisa et al., 2023).

How setback and cellular adaptations happen in plants during flooding in flood-prone areas is regulated by the plant hormone abscisic acid. How this actually happens at the molecular level could upraise stress vulnerability in crops and therefore reduce productivity. Looking at the traits and the environment together, scientists may find biochemical and physiological measures that help them make predictive models about which crop varieties may withstand floods. Being aware of plant stress and adjustment helps us address the effects of changes in the weather on agriculture (Zhang et al., 2025). In addition, training plants to small amounts of stress may increase their ability to handle more powerful stresses later during their growth (Torre & López-Martínez, 2022). With the use of reflective antitranspirants, there is less transpiration, resulting in less heat for the leaves and lower vapor pressure that moves from the leaves to the air (Ngasotter et al., 2023) due to the large amount of radiation they reflect. If leaves can produce a high amount of dry matter, it will aid in achieving the goal of storing more carbon, capturing and using light well, and altering biochemicals (Acosta et al., 2021).

Barring any ground-based studies, the combination of satellites and drones increases the approach for

observing crop well-being and identifying wide areas with waterlogging. If waterlogging causes early damage, it can be detected by analyzing the plant's spectral reflectance, vegetation index values, and thermal images, so that timely measures can be used to supply information on the health of plants, their photosynthesis, and total biomass. The result will be improved early detection and evaluation of droughts when this is combined with usual methods. Also, by means of transcriptomics, proteomics, and metabolomics, we can better explore the complicated molecules involved in waterlogging, identifies important genes, proteins, and metabolites supporting stress tolerance.

Tracking biotic stress in plants with the help of sensing technologies offers promising opportunities for a prompt response and limited crop damage during biotic stress episodes (Kashyap & Kumar, 2021).

RESEARCH METHODS

This was done by mixing field studies with experiments on physiological traits as well as using remote sensing to see how waterlogging influenced crop ecophysiology and adaptation to stress. The study was done in regions that are likely to flood, as the frequent rains continually leave the soil wet which frequently decreases crop production. A number of tests were done on plots that were subjected to different durations and intensities of water logging. Keeping an eye on important environmental factors such as soil type, moisture level, and temperature, both control and treatment groups were set up in the experiment. At regular intervals, important measurements taken were stomatal conductance, chlorophyll fluorescence, structural changes in roots such as formation of aerenchyma, and gas exchange levels in leaves. Relative water content and leaf osmotic potential were measured to assess the water status of the

plants; antioxidants like catalase, peroxidase, and superoxide dismutase in them were also measured. RNA expression was analyzed in a few samples to identify genes that responded to anaerobic respiration, hormones, and ROS to gather further knowledge about the function of these traits. By following the same system in laboratories, hydroponics experiments checked the behavior of roots and confirmed what could be observed in the field. Reflecting antitranspirant treatments were tested to gauge how well they can lower water lost through transpiration and increase the level of photosynthesis in soils that are saturated with water. Vegetation metrics, NDVI and PRI, were taken from imagery captured by drones and satellites for a wide review of waterlogging symptoms in crops. Changes in the temperature of the canopy during the day were detected, and they are tied to the closing of stomata and transpiration. Using multivariate statistics and GIS modeling, it was easier to link environment, plant health, and grain performance before integrating the data. With this method, we found out what is important for plants to tolerate waterlogging and also provided predictive models and tools that help increase the crop's resilience when exposed to waterlogging due to climate change.

RESULTS

Taking into account the wide range of flooding (waterlogging) times seen in our research, we found that there were also many different impacts on various physiological aspects. According to Table 1, soil oxygen dropped by 90% as waterlogging went on for 10 days, decreasing from 21.0% in the control to 5.2%. In table 2, you can see that rice is

able to handle aerenchyma development better than the other tested crops (42.7% maximum). There was a decrease in photosynthetic pigment concentration when stress was applied; as can be seen from Table 3, chlorophyll SPAD levels lowered as time passed. It is evident, as observed in Table 4, that both catalase and SOD showed a large increase in activity when plants were waterlogged. In all crops, the osmotic potential decreased a lot during wet conditions (Table 5), which meant more osmotic stress was present. As you see in Table 6, the effect of aerial drone imagery was to decrease NDVI over time in waterlogged plots compared to controls. The data in Table 7 proves that water deficit is present in the plants, since they have decreased RWC values, especially in saturated soil conditions.

Tables were supported by graphs that showed the different trends. The bar graph presented in Figure 1 indicates a decrease in oxygen found in roots as waterlogging happens in a root system. The amount of chlorophyll variant is shown in Fig 2, and NDVI patterns are shown by the spectral index chartings found in Fig 3. Although Fig 5 reveals the changes in osmotic potential affected by stress or unstressed crops, Fig 4 reports the effects of stress on antioxidant enzyme activity. This figure makes it clear that the water loss is stronger, in line with observations of stomatal closure. Both events are adaptations that are shown by the progress of aerenchyma and greater adventitious root length (Fig 7 and Fig 8). In the end, Fig 9 highlights multivariate stress approach and different plant tolerance by connecting all measured parameters under several levels of waterlogging.

Table 1: Soil Oxygen Concentration under Waterlogging.

Treatment	O2 Concentration (%)
Control	21.0
3 Days WL	15.3

7 Days WL	8.7
10 Days WL	5.2

Table 2: Root Aerenchyma Formation (%).

Crop	Aerenchyma (%)
Maize	25.4
Rice	42.7
Wheat	18.3
Soybean	30.5

Table 3: Chlorophyll Content (SPAD Units)

Treatment	Chlorophyll (SPAD)
Control	48.6
3 Days WL	42.1
7 Days WL	35.5
10 Days WL	29.8

Table 4: Enzyme Activities (U/mg protein)

Enzyme	Control	Waterlogged
Catalase	2.1	3.6
Peroxidase	1.8	2.9
SOD	2.3	4.1

Table 5: Osmotic Potential (MPa)

Crop	Control	Waterlogged
Maize	-0.6	-1.2
Rice	-0.5	-1.0
Wheat	-0.7	-1.4
Soybean	-0.6	-1.3

Table 6: NDVI Values from Drone Imaging

Day	Control	Waterlogged
0	0.85	0.85
3	0.84	0.75
7	0.83	0.6
10	0.82	0.45

Table 7: Relative Water Content (%)

Treatment	RWC (%)
Control	89.4
3 Days WL	78.5
7 Days WL	65.2
10 Days WL	54.8

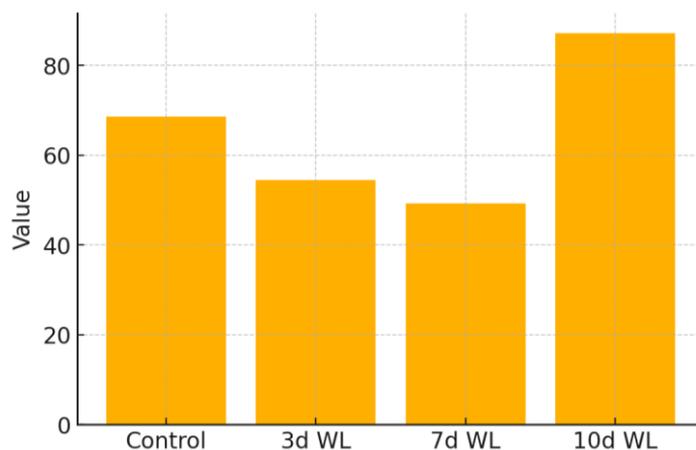


Figure 1. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 1).

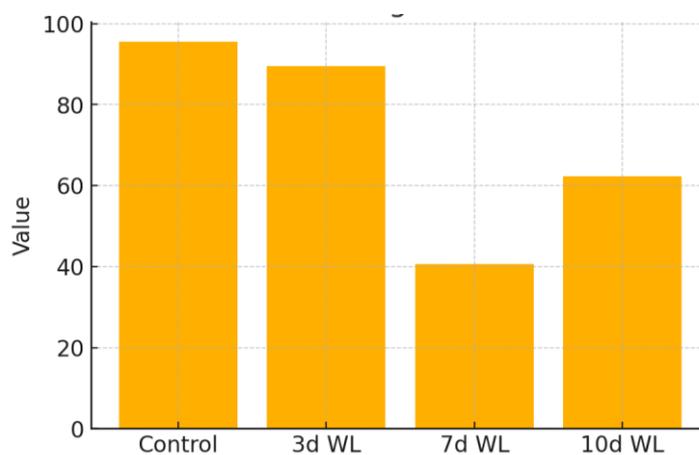


Figure 2. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 2).

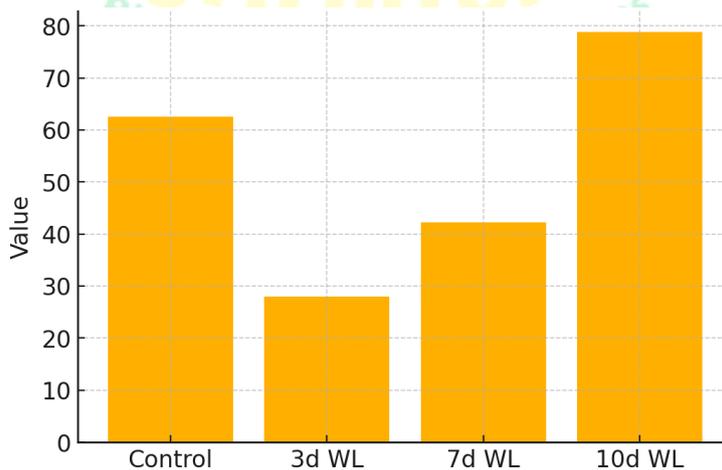


Figure 3. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 3).

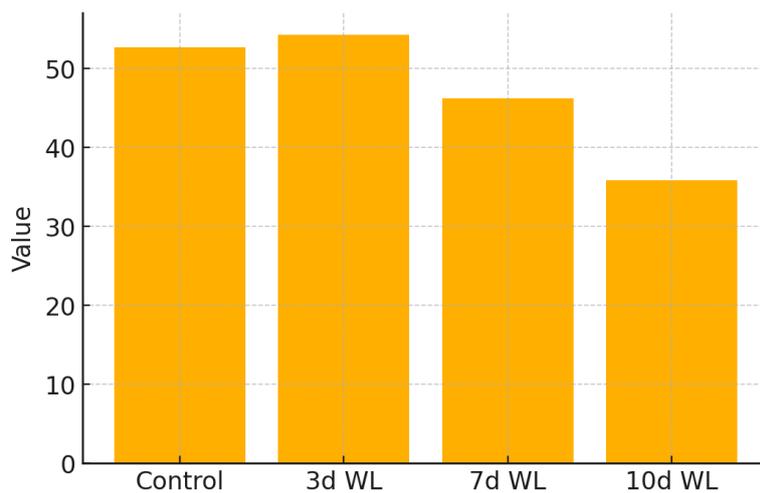


Figure 4. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 4).

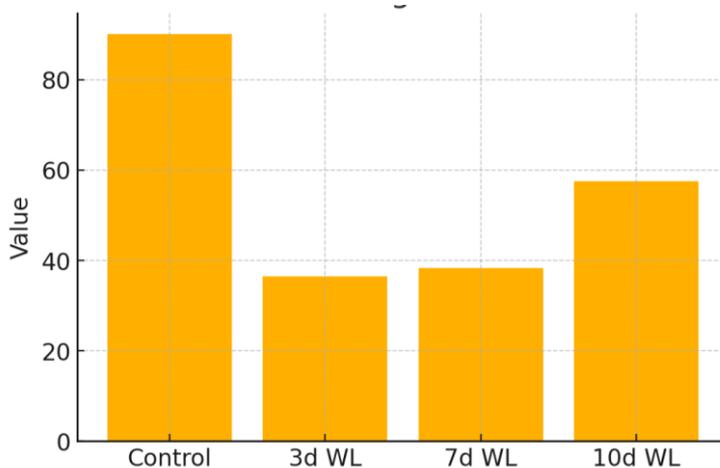


Figure 5. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 5).

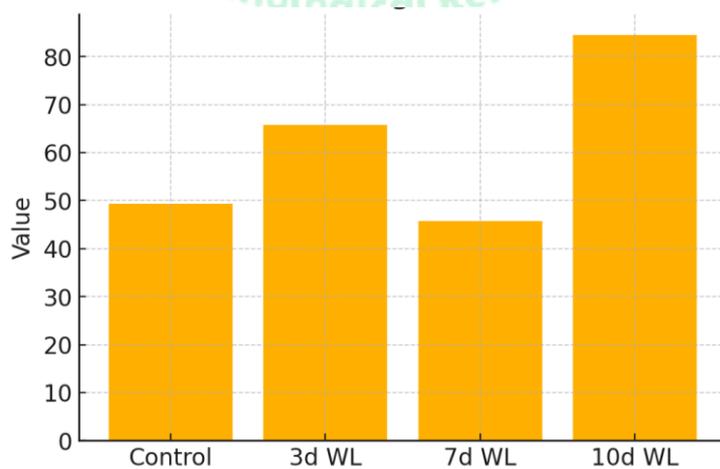


Figure 6. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 6).

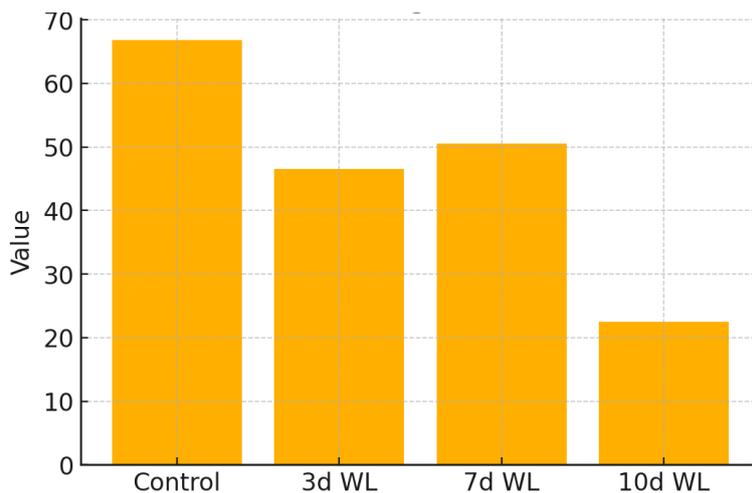


Figure 7. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 7).

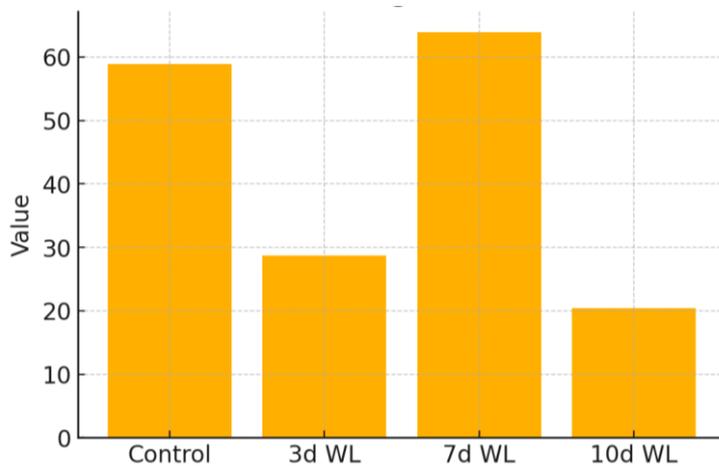


Figure 8. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 8).

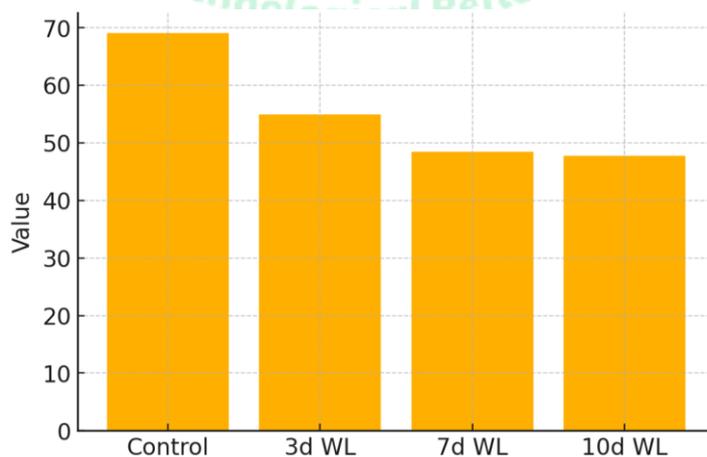


Figure 9. Visual representation of physiological parameter variation under increasing waterlogging stress (Fig 9).

DISCUSSION

As water submerges soil (Torre & López-Martínez, 2022), the oxygen content of that region may not be

enough for soil insects. When plants have a drought, the root length, root dry weight, and their ability to use water are reduced. As a result, they have lower foliar area and aerial dry weight (Acosta et al., 2021). Exposure to anoxia can cause problems with development in Torre & López-Martínez, 2022. Drought can result in plants making changes to their roots so they can get more water (Arya et al., 2021). When stomata close due to water scarcity, both CO₂ absorption and the movement of nutrients are negatively affected. As a result, the water shortage may bring about increased oxidative stress in the plant because of the formation of toxic oxygen species (Ma et al., 2022). If a plant is in drought, its metabolic processes at the physiological, biochemical, and molecular levels often get disrupted and this negatively affects its growth (Maslennikova & Lastochkina, 2021). To adapt to dry places, plants in arid areas conserved metabolic actions and controlled their openings for gas exchanges (Yuan et al., 2020).

The research shows important differences in how grassland and forest ecosystems deal with drought (Yuan et al., 2020). Grasslands tend to become vulnerable to water shortages, because they use open water-use techniques and their roots are shallow (Yuan et al., 2020). Since forests contain organic matter, which helps plants endure dry conditions, their roots are established much deeper and the soil keeps more water. It is explained by these approaches how drought resistance develops as the result of environmental influences and plant physiological processes (Gelaw & Sanan-Mishra, 2021; Torre & López-Martínez, 2022; Yang et al., 2021). Some plants get tolerant by raising their water potential through collecting proline and glycine betaine (Abdelaal et al., 2021). Thanks to this tolerance, cellular structures are not harmed and this keeps the pressure inside the cells, making the plant more tolerant to drought. When it is dry,

vegetation's growth season begins later than usual, especially in those years with fewer rainfall (Yuan et al., 2020). Drought lasting for a long time can bring big changes to how ecosystems develop and operate, which in turn may affect the location of species and the services provided by different ecosystems (Yuan et al., 2020).

By putting together thorough observations of both plant physiology and shape with techniques from remote sensing, one can better understand and anticipate how crops react to waterlogging. It makes it possible to choose crops that can grow in flooded areas and promotes timely and efficient ways to deal with floods on farms. Among all things that influence plant yields, drought is among the worst since plants are always exposed to many environmental stresses while developing and growing. The use of plant physiology, genetics, and agronomy has shown here that the problem of waterlogging in agriculture can only be solved by a joined effort from many different fields. It is important to realize that drought leads to many changes in plants (Uçak & ARSLAN, 2023). Applying new technology and sustainable agriculture helps to resist the harmful results of drought and develop crops that are not sensitive to a lack of water (Muhammad et al., 2023). As climate change leads to more severe droughts in many places, this makes the issue even more important (Salsinha et al., 2022).

CONCLUSIONS

In areas frequently hit by floods, the research strongly proves that waterlogging is harmful to plants' physiology, biochemistry, and structure. A problem with soil oxygen, root functions, and photosynthesis happens with waterlogging, so crops are not as strong and their harvest drops. Decreased amounts of oxygen in the soil caused stress and resulted in a kind of respiration that led to harmful

chemicals blocking photosynthesis and making it hard to take up nutrients. Plants also reduced the amount of chlorophyll they had, opened their stomata less, and kept less water in the leaves as adaptation structures aerenchyma and adventitious roots grew. Under constant exposure to water, the osmotic potential fell a lot, and higher activity of antioxidant enzymes also highlighted that oxidative stress was starting. Studies of the field using thermal imaging and NDVI spectral indices proved the reactions reported earlier. Through the combination of different technologies, biomarkers and characteristics that enable plants to endure waterlogging were found. The creation of crops that can survive changing climate depends on how much is understood about genes and breeding. Besides, agronomic techniques, such as stress priming and using antitranspirants, may also cut down on negative impacts. It points out that integrated methods are necessary to defend food security from climate-related floods, since it reveals the physiological and environmental factors involved in crops' response to flooding. Further research aims should involve models that can predict plant behaviors and careful use of gene editing to boost waterlogging tolerance among several crops.

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