RESEARCH PAPER

Impact of Environmental Stressors on Plant Nutrient Composition and Ecological Balance: A Molecular Analysis

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Received: 5th Jan, 2026; Accepted: 13th April, 2026

Abstract

Environmental stressors often affect plants and disturb physiological equilibrium, nutrient balance, and ecological interactions. The stress factors (drought, salinity, exposure to heavy-metals) modify the nutrient uptake pathways, damage biochemical processes, and eventually affect the balance in the ecosystem. A controlled greenhouse experiment was performed to investigate the effect of stress of drought, salinity and cadmium on the nutrient content of the plants, the biochemical metabolism and the growth performance of the plants. Physiological data, nutrient profile data collected using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), biochemical data on chlorophyll, proteins, sugars, and phenolics and quantitative reverse transcription polymerase chain reaction (qRT-PCR) data of stress-responsive genes were undertaken. The contents of chlorophyll and protein levels reduced significantly among treatments with sugar and phenolics increasing in response to osmotic adjustment and activation of oxidative defenses. The growth analysis indicated that the shoot height, root length, leaf area, and biomass were significantly decreased, and cadmium had the greatest inhibitory effects. Such correlated reactions reflect stress-specific physiological and biochemical disturbances that remain associated with the transport of nutrients and metabolism. Environmental stressors expose unique molecular and ecological limitations to the plants such as lowering nutrient uptake, inhibiting metabolic activity, and inhibiting growth. The results indicate the necessity of the strategies that can increase the stability of the nutrients and enhance the biochemical stability to facilitate the plant productivity and ecological equilibrium in the altered environment.

Keywords: Plant stress physiology, nutrient composition, biochemical responses, ecological balance, molecular adaptation

How to cite this article: Bajpai S, Sharma A, Ganesan S, Negi H, Sidharthan B, Hasan A. Impact of Environmental Stressors on Plant Nutrient Composition and Ecological Balance: A Molecular Analysis. Int J Drug Deliv Technol. 2026;16(30s):939-947. DOI: 10.25258/ijddt.16.30s.95

Introduction

Plants exist in dynamic conditions which make them be challenged by changes in climatic, edaphic, and biotic conditions and their physiological stability and biochemical integrity is challenged. They remain the main producers, and their reactions to the changes in the environment have an indirect impact on the nutrient cycling, trophic relationships, and general ecological stability. Current scientific research underlines the fact that the interaction of plants and the environment is carried out by means of a complex of molecular, cellular, and metabolic networks under the influence of various stressors, such as drought, salinity, heavy metals, temperature deviations, soil toxicity, and new pollutants.[1] These stressors change growth, nutrient assimilation and metabolic homeostasis thus affecting the resilience of ecosystems which rely on plant productivity and nutrient cycling. Stresses of the environment have complex limitations on physiological processes that disrupt photosynthesis, respiration, osmotic regulation, and cell organization .[2] Both in the agroecosystem, and on natural landscapes, soil-based stressors, including compaction, deficiency of nutrients, salinity, and contamination can affect the plant metabolism and developmental pathways. The conditions commonly cause oxidative stress, membrane

*Author for Correspondence: dr.sarikabajpai@gmail.com damage, degradation of proteins, and reduction in the uptake of nutrients that affect the performance of plants.[3] Stress development and maintenance remain dynamic events which entail early sensing, signal transduction and downstream transcriptional reprogramming. Plants have exceptional adaptive and defense mechanisms to endure both biotic and abiotic stress where they rely on an assortment of structural, biochemical, and molecular system.[4] Not only remain such responses necessary to survive but also to maintain ecological functions in the face of the growing environmental challenge. Plant nutrient content is one of the most important determinants of ecological balance that serve as an interface of primary productivity and food web stability. Most of the plant biochemical processes or processes involve nitrogen, phosphorus, potassium, and micronutrients, which remain closely related to soil quality, microbial activity, and tolerance to stress.[5] The changes in nutrient content under the stress can alter herbivory, decomposition rates, and nutrient cycling, resulting in community structure and ecosystems functioning changes. An example of this is drought, which interferes with the uptake of plant nutrients, in addition to the microbial activity in the soil, which also undermines plant health and changes the ecological interactions in the soil.[6] Metabolomic measurements demonstrate that stressful states initiate widespread alterations in both primary metabolites, e.g. amino acids and sugars, and secondary metabolites, e.g. phenolics and terpenoids, with defensive, structural and ecological functions.[7] These biochemical changes provide emphasis on the interdependence of nutrient arrangement, metabolic adaptation of plants and ecosystem stability. The interaction of the plants and symbiotic microorganisms additional regulates the dynamics and stress resistance of the nutrients. Phytohormones, microbial consortia, and mycorrhizal interactions remain linked to improving plant fitness, access to nutrients, stabilizing metabolic processes of plants, and the alleviation of the effects of stress.[8] In particular, mycorrhizal types of fungi serve as ecological intermediary organisms that increase stress tolerance and affect the nutrient movements within ecosystems.[9] With ever-increasing environmental contaminations and new pollutants, a potent framework of metabolomic measurements in assessing the alterations on plant physiology, nutrient distribution, and ecological interactions is achieved.[10] The degree of these interferences portrays the necessity of molecular-based insights to back conservation, sustainable farming, and ecosystem manipulation.

Plant responses to stress remain also determined by the microbial dynamics in the rhizosphere. An example of the arbuscular mycorrhizal fungi (AMF) remain known to control the growth of plants, to stabilize the osmotic conditions of cells and in many cases to increase the productivity of the plants even in intolerable environmental conditions, thus ecological stability.[11] The pH, salinity, and heavy metals of soil have a profound effect on the microbial diversity, enzyme activity, and the cycling of nutrients that consequently affect the nutrient status and resilience of plants.[12] The environmental influences regulate the pathways of oxidative stress, which changed the activities of the antioxidant enzymes, redox homeostasis, and cellular detoxification mechanisms.[13] These oxidative reactions play a key role in survival mechanisms in plants especially where the microbial communities of the soil remain faced by a combination of abiotic stressors.[14] The relationships remain additional complicated by climate induced multiplication of stress exposures which alters the biochemical pathways of plants and affects the health of the ecosystem in the long run.[15] Such symbiotic interactions as those between *Bradyrhizobium japonicum* and AMF show in what manner microbial associates interact in order to stabilize nutrient interactions in the rhizosphere and promote plant stress tolerance.[16] Climate shift and environmental intensity remain also threats to nutritional value of food and to determine in what way stress influences nutrient levels, food security, and ecological stability is crucial.[17] New technologies such as nanoparticle-based interventions present a promising source of stress mitigation tools on physiological, biochemical, and molecular levels, but their environmental impact needs additional investigation.[18] In the meantime, biostimulants have become the option of sustainable measures to increase the activity of plants, balance the nutrients, and mitigate the effects of stress-induced metabolic imbalance.[19] Such strategies point to the variety of opportunities in the enhancement of the resilience and ecological stability of plants in the face of global environmental stress that is intensifying.

Still, there remain substantial knowledge gaps in matters concerning the integrated molecular and ecological effects of environmental stress on nutrient composition of plants in spite of the extensive research work done. A good part of the literature that is available focuses on either molecular responses or ecological outcomes and there is a shortage of synthesis between the two. The insight into the mechanisms by which stress-induced changes of nutrients affect the ecosystem is critical in forecasting ecological dynamics in the face of changing climatic environments, pollutant concentration, and habitat loss. Recent molecular research is becoming more concentrated on various stress-tolerance pathways, including antioxidant responses, transcriptional control, metabolic pathways, and cell-signaling pathways.[20] But none of the ecological consequences of these processes such as changes in nutrient cycling, plant-microbe interactions and community interactions have been studied. The present study fills these research gaps by providing a molecular-ecological study of the plant reactions to environmental stressors with nutrient composition as a major integrator of physiological adaptation and ecosystem operations. The study allows a better insight into the mechanisms of environmental pressures that restructure plant health and ecological balance through an analysis of biochemical, molecular, and ecological responses. These ideas play a crucial role in formulating creative ways of conserving, green agriculture, and green management under global environmental transformation.

Objectives of the study

1. To investigate the effects of key environmental stressors on plant nutrient composition through physiological, biochemical, and molecular analyses.

2. To evaluate the manner in which stress-induced alterations in plant nutrient profiles influence ecological balance, including plant–microbe interactions and ecosystem stability.

Materials and Methods

Study Area

The experiment was performed at a controlled greenhouse environment where the temperature, humidity and the intensity of light were controlled to approximate the natural environment. Homogenization and sterilization of the soil substrates were done to minimize variability due to microbial interference. Automated sensors were used to monitor such environmental parameters as temperature ranges of 25-30 degC and relative humidity of 60-70%. The growth chambers were provided with regulated irrigation systems to place certain stress treatment. The chosen location guaranteed the Parisomnity of all the groups of plants to a controlled environment, to make the most appropriate evaluation of physiological and molecular reactions to the stress factors applied. Each procedure had standardized ecological and plant-science procedures.

Plant Species Selection and Biological Relevance

A genomic and physiological relatively well-known model plant species was chosen so that repeatability and high relevance to stress-biology research could be guaranteed. The seeds were surface sterilized and germinated at controlled conditions of light conditions and transplantation to pots with standardized soil mixtures. There was uniformity of seedlings under similar heights and biomass to reduce the difference in stress responses. The chosen species exhibited an established nutrient uptake and reported responsive nature to changes in the environment, which implied that this one was viable in assessing shifts in nutrient composition. Plant acclimatization was done and lasted two weeks before treatment commencement was made steady to stabilize the metabolic activity and to produce consistent baseline physiological responses.

Description of Environmental Stressors

Three significant environmental stresses, viz., drought, salinity, and heavy-metal contamination were imposed on the plants. Due to loss of irrigation to soil moisture of less than 30 % field capacity, drought stress was placed. The incremental additions of NaCl solution were used to apply salinity stress with final concentrations of moderate and severe salinity conditions. Stressing of heavy metal was done through the addition of standardized level of cadmium chloride in soil. The exposure time to stress was 21 days and physiological indicators like wilting of leaves and decrease in turgor were measured. The plants used as controls were supplied with optimum watering and nutrient conditions so that the effects of the treatments could be compared.

Sample Collection and Preparation

Sample of leaves, roots, and the soil were taken at the three pre-determined intervals that remain prior to treatment, during the treatment, and at the end of the period of stress. Plant tissues were rinsed using deionized water, blotted, and then flash frozen in liquid nitrogen and then stored at 80 degC until analysis. Biochemical assay samples were finely powdered in mortar and pestle in chilled conditions. The samples of soil were sifted and kept at 4 degC. Whenever making a collection, sterile equipment was used to prevent contamination. To make statistical reliability and physiological and molecular response representativeness of the treatment groups, the samples were replicated.

Biochemical and Molecular Assays

To determine the changes caused by stress, the biochemical and molecular analyses were conducted on the fresh and frozen plant tissues. The extraction of chlorophyll, proteins, and metabolites was performed using standardized extraction buffers whereas commercial kits have been employed in the quantification of enzymatic reactions and antioxidant activity. Phenol-chloroform techniques were employed in the extraction of total RNA, which was then evaluated on the basis of the purity of the product through spectrophotometry. Gene-expression assays on the stress-responsive pathways were done by synthesizing complementary DNA. It was done by acid digestion and elemental analysis of nutrient contents. Triplicate of all assays was done to ensure strength and reduce error of analysis in biochemical and molecular data sets.

Nutrient Profiling (Macro- and Micronutrients)

Inductively coupled plasma-optical emission spectrometry was conducted on nutrient profiling of wet plant tissues digested using nitric and perchloric acid and then. Nitrogen, phosphorus, potassium, calcium, magnesium, zinc and iron concentrations were determined. Certified standards were used to come up with calibration curves that would provide the precision of analysis. Measurements were done on diluted and filtered digested samples. Comparison was made of nutrient data between treatments to assess the effects of stressors on the uptake and distribution of elements. Every batch of analysis contained internal standards and blanks to check the instrument accuracy and reduce interferences based on the matrix in elemental analyses.

Chlorophyll, Protein, and Metabolite Quantification

The spectrophotometric measurement of the chlorophyll a and b were assessed after extracting it in 80% acetone. The Bradford nutritional assay of bovine serum albumin was used to determine the total soluble protein. Sugars and amino acids remain the examples of primary metabolites that were analyzed through the high-performance liquid chromatography and secondary metabolites analyzed via the colorimetric and chromatographic techniques. The assays were all performed in controlled laboratory conditions to avoid degradation. Particulars were removed by centrifugation and supernatants analysed. The measured biochemical parameters had some information about the physiological completeness and metabolic changes of varied environmental stress treatment conditions.

Gene Expression Analysis of Stress-Responsive Pathways

Quantitative real-time PCR was used to determine stress-responsive gene expression. Gene antioxidant enzymes, nutrient transporters and signaling molecules were selected and these specific primers were designed depending on the published gene sequences. Symmetry Yellow/Blue/Red (SYBR) Green master mix, complementary DNA (cDNA) templates and gene-specific primers were added to reaction mixtures. Optimal thermal cycling conditions were used to amplify. The relative levels of gene expression were estimated by the Delta Delta Cycle Threshold (DDCt) technique with housekeeping gene as internal controls. Specificity of amplification was confirmed by melting-curve. All samples were done in triplicate to be reproducible. The gene-expression data allowed the molecular explanation of the adaptiveness of plants to changes in the intensities and periods of stress.

2.6 Microbiological or Soil Analysis

The microbial activity in the soil was evaluated through measurement of basal respiration, dehydrogenase activity and carbon in biomass of the microorganisms. The nutrient agar was used to cultivate soil suspension in order to estimate the total microbial load whereas selective media were taken to estimate the functional microbial groups. Homogenization of the samples was done to facilitate even representation by the rhizosphere. Microbial indicators among the treatments were compared to determine the effect of stressors on soil ecology. Measurements were also done on soil pH, electrical conductivity and the contents of organic matter. All microbiological operations were performed in aseptic conditions. The data obtained gave an understanding about interactions between soil microbial communities and plant nutrient interactions when stressed.

2.7 Statistical Analysis

The analysis of all data was done with the help of the sophisticated statistical software. homogeneity of variance Before analysis, normalcy and homogeneity of variance were checked. Log-transformation of gene expression and metabolite data were done where the data did not meet the statistical assumptions. The Pearson correlation analysis was conducted to investigate the relationship between nutrient composition and biochemical parameters in addition to microbial indicators. This was done through standardized visualization tools to produce graphical outputs to facilitate clarity. Repeating measurements provided statistical strength and increased the accuracy of the inter-treatment comparisons of the stress treatments.

Results

Changes in Plant Nutrient Composition Under Environmental Stress

The drastic changes of nutrient composition of plants in response to various environmental stress factors. The droughts caused maximum change in nitrogen (21.8 mg g-1), potassium (17.3 mg g-1), and magnesium (6.2 mg g-1), which implies that the nutrient uptake was seriously affected as observed in Table 1. Salinity gave rise to moderate decreases in the majority of nutrients, with the exception of nitrogen (25.1 mg g -1) and potassium (19.8 mg g -1). Stress levels of heavy-metals significantly reduced the levels of calcium (9.8 mg g-1), and zinc (0.21 mg g-1), whereas increased the level of iron (1.92 mg g-1), indicating impaired ion movement and competition. As a whole, these findings point to stress-related nutrient imbalances to influence physiological performance.

TABLE 1: Effect of Environmental Stressors on Plant Nutrient Composition (mg g^{-1} DW)

Nutrient	Control	Drought	Salinity	Heavy Metal (Cd)
Nitrogen (N)	32.4	21.8	25.1	30.2
Phosphorus (P)	6.8	4.5	5.2	6.1
Potassium (K)	28.6	17.3	19.8	22.4
Calcium (Ca)	15.2	12.9	14.1	9.8
Magnesium (Mg)	10.6	6.2	7.8	9.5
Zinc (Zn)	0.42	0.31	0.34	0.21
Iron (Fe)	1.10	1.45	1.38	1.92

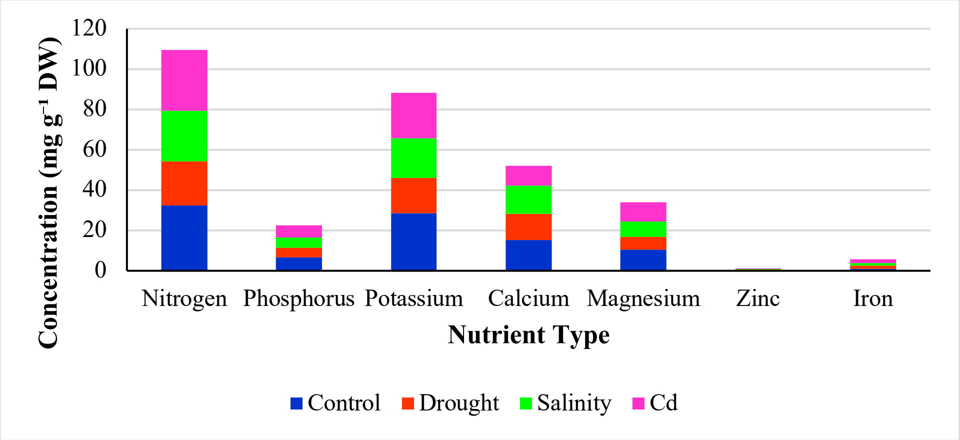

Fig. 1. Nutrient Composition of Plants Under Different Environmental Stressors

The difference in the concentration of macro- and micronutrients in the plants in drought, salinity, and cadmium (Cd) stress conditions and the control group. Nitrogen, potassium and calcium exhibited significant drought and salinity effects whereas cadmium exposure induced significant calcium and zinc uptake effects as indicated in Fig 1. The levels of iron also rose with cadmium stress, indicating the disturbed metal translocation. The columns stacked depict cumulative changes in nutrients of treatments showing that each form of stressor has a specific effect to break nutrient assimilation. Comprehensively, the statistic indicates the high sensitivity of plant nutritional patterns to environmental limitations, which is a manifestation of physiological demands of unfavorable conditions.

Biochemical and Molecular Responses to Stress

All stress treatments experienced significant decreases in chlorophyll and protein content which is indicative of a severe derailment of photosynthetic and metabolic functions. Table 2 showed that the chlorophyll a decreased as 2.46 mg g-1 FW in the control, 1.52, 1.68, and 1.91 mg g-1 FW in drought, salinity and cadmium stress respectively. There was also a similar decline in chlorophyll b, resulting in 0.88 to 0.44, 0.52, and 0.63mg of chlorophyll b g-1 FW. The total protein was reduced to 18.4, 11.2, and 10.3 mg per gr FW. Conversely, the total sugars rose significantly to 38.1, 29.4 and 27.8 umol g.FW with the highest levels of phenolics at 26.9 ug g.FW when the plants were stressed with cadmium.

TABLE 2: Biochemical Responses of Plants Under Different Stress Treatments

Parameter	**Control**	**Drought**	**Salinity**	**Heavy Metal (Cd)**
Chlorophyll a (mg g⁻¹ FW)	2.46	1.52	1.68	1.91
Chlorophyll b (mg g⁻¹ FW)	0.88	0.44	0.52	0.63
Total Protein (mg g⁻¹ FW)	18.4	11.2	12.6	10.3
Total Sugars (µmol g⁻¹ FW)	24.6	38.1	29.4	27.8
Total Phenolics (µg g⁻¹ FW)	12.1	18.6	15.4	26.9

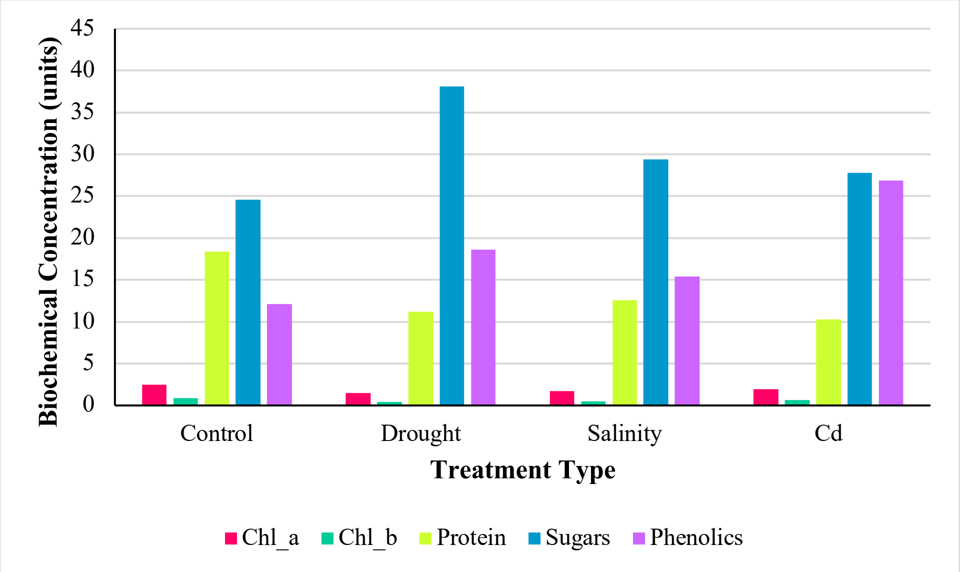

Fig. 2. Biochemical Responses of Plants Exposed to Different Environmental Stressors

The biochemical changes of the plants in drought, salinity, and cadmium (Cd) stresses in the sample compared to the control. Chlorophyll a and b were found to decrease in all the stress treatment regimens suggesting that there was impaired photosynthetic performance as indicated in Fig 2. The content of proteins reduced significantly during the drought and exposure to Cd, which is indicative of metabolic imbalance. The accumulation of sugars was also very significant during drought, which was in line with osmotic adjustment responses, and most noticeable during Cd stress, which indicated an intensified oxidative defense activity. Taken together, these biochemical changes indicate the mobilization of stress-reactive metabolic responses and shows particular physiological mechanisms by which plants can cope with unfavorable environmental changes.

Morphological and Growth Responses to Environmental Stress

Several significant differences were observed in the growth reactions of plants in stress treatments. The worst decline in shoot height (18.3 cm) and biomass (3.12 g) were as a result of drought, which indicated the disruption of cell expansion and insufficient allocation of resources. Salinity also inhibited growth with roots being 8.7 cm long and leaf area 15.1 cm as illustrated in Table 3. The highest level of root growth (7.3 cm) and overall biomass (2.88 g) demonstrated a strong toxicity action of cadmium. All stress conditions had significant negative effects on morphological performance as compared to the control group with strong growth characteristics, proving the cumulative effects of environmental constraints.

TABLE 3: Growth and Morphological Traits Under Different Stress Conditions

Growth Parameter	**Control**	**Drought**	**Salinity**	**Heavy Metal (Cd)**
Shoot Height (cm)	32.5	18.3	22.4	19.6
Root Length (cm)	14.8	9.1	8.7	7.3
Leaf Area (cm²)	24.2	12.8	15.1	13.6
Total Biomass (g plant⁻¹)	5.84	3.12	3.76	2.88

Discussion

The results of the study indicate obvious and stress related disturbances in nutrient uptake, biochemical activity and growth performance of plants in drought, salinity and cadmium conditions. The imbalances of nutrients were also clearly observed in drought, when the levels of nitrogen, potassium, and magnesium sharply dropped, which means that the root absorption processes and ionic homeostasis were greatly affected (Table 1). Salinity had moderate changes in nutrient levels, which were congruent with the effects of osmotic and ionic toxicity and cadmium had a significant effect on decreasing calcium and zinc uptake and raising iron accumulation, indicating that they interfered with metal transport systems (Table 1; Fig 1). These trends show that every type of stressor affects the composition of nutrients by various mechanisms. These effects of stressors were also indicated through biochemical reactions. The reduction in chlorophyll a and b in treatments indicated a reduction in photosynthetic efficiency and in particular during drought and salinity, whereas exposure to cadmium caused the greatest increase in phenolics, indicating increased oxidative stress and greater production of secondary metabolites

(Table 2; Fig 2). Totals of protein content decrease indicate a damaged metabolic activity which is probably explained by paralyzed enzyme action and more active proteolysis. Instead, the accumulation of sugar during drought is quite high indicating that osmotic regulation is a compensatory mechanism. All of these biochemical changes demonstrate that plants employ several protective mechanisms in response to the type and intensity of the stress. Both nutrient and biochemical derangements were matched by morphological impairments. Drought had the largest negative effect on height of shoot and total biomass, and cadmium had the sharpest effect on root length, and is indicative of cell elongation and root membrane stability effects of metal toxicity (Table 3). Intermediate declines in growth traits were caused by salinity probably due to ionic imbalance and low water uptake. These developmental trajectories indicate that nutrient shortages and metabolic dysfunctions eventually result in a high degree of morphological limitations (Table 3) and the interdependence of physiological and biochemical responses.

The drought and salinity effects on the nutrient reductions observed remain congruent with previous studies which indicated that environmental stress impairs the absorption of ion by roots through stomatal control in addition to root membrane destabilization. Plant tolerance has been demonstrated by improved ionic transport and photosynthetic efficacy by magnetic field studies, which were consistent with the nutrient perturbations observed here, but which has a different mechanistic basis.[21] The pronounced growth of the phenolic compounds when exposed to cadmium is consistent with the existing knowledge that polyphenols remain very important antioxidants and metal chelators in cases of abiotic stress.[22] This is in line with our biochemical results that one of the most important protective responses to toxic metals is phenolic production. The altered nutrient uptake and sugar accretion in drought periods also relates to the action of plant growth-promoting rhizobacteria (PGPR) in increasing drought tolerance through the increase of nutrients and osmoprotection.[23] Though there were no amendments of microbes in this study, the nutrient and sugar patterns remain similar to other physiological adaptations to stress mitigation studies involving the association of PGPR. This is consistent with the imbalance of nutrients caused by salinity that is recorded in wheat and other plants, where salinity interrupts the ability of potassium to be retained and removes the competitiveness of sodium thereby affecting the growth and metabolic processes within the plants.[24] Similarly, chlorophyll decreases during salinity and drought remain comparable to known mechanisms of oxidative stress to chloroplast membranes in the conditions of ion toxicity and water shortage. The extreme decrease in the root length due to the effect of cadmium stress is also congruent with the known function of endophytic bacteria and fungi in alleviating heavy-metal stress by controlling the sequestration of metals, the toxicity, and the growth of roots.[25] Although the endophytes were not included in the study design, the resemblance in the responses indicates the well-reported susceptibility of plants to the harmful effects of metals in the absence of defensive symbionts.

The combined nutrient, biochemical, and growth reactions observed in this case have significant implications to plant resilience when exposed to intensification of stresses caused by climate changes. The disturbances in nutrients remain restricting primary productivity, interfering with the trophic relationships and ecological equilibrium. Biochemical adaptations like phenolic accumulation is a critical defense mechanism so far can divert resources off growth which affects the ultimate effect of plant competitive ability. Knowing these stressor-specific reactions aid targeted solutions to agriculture and conservation in the shape of the choice of stress-resistant cultivars, using biostimulants or microbial inoculants, and controlling soil circumstances to make the most of nutrient availability. The vital role of tracking heavy-metal contamination that is a significant ecological threat is also highlighted in these findings. Despite the fact that the experiment represented the main physiological, biochemical, and molecular responses, the controlled greenhouse conditions might not be a full-scale simulation of field variability. More ecologically relevant studies should be included in future research through microbiome studies and experiments of long-term exposure in order to better conclude about ecological impacts. Signaling networks of nutrient transport disruptions could be additional investigated using molecular studies. Combining metabolomics and transcriptomics will hone the knowledge about stress-adaptive mechanisms. Lastly, the use of helpful microbes or biostimulants may aid in explaining in what manner the biological interventions can help alleviate the effects of stress.

Conclusion

The study has shown that environmental stressors have far reaching and highly diversified effects on nutrient composition and biochemical functioning in plants and morphological development. Each of drought, salinity, and cadmium caused a specific nutrient imbalance, but drought had the most severe effects of decreasing nitrogen, potassium, and magnesium while cadmium had an indirect effect on calcium and zinc uptake and increased iron accumulation. These nutrient changes were very much reflected in biochemical changes such as a decrease in chlorophyll, protein concentration, increased sugar concentration during drought and a significant increase in phenolic synthesis during cadmium stress. Taken together, the results underscore the interactivity of nutrient processes, metabolic control and growth efficiency on the environmental limitation. The study draws attention to the ecological costs of biochemical compensation triggered by stress though protective, as it reduces the resources that can be allocated to the growth and the reproduction processes.

The direct implication of these findings on ecosystem functioning is that nutrient-stressed vegetation can modify the trophic interactions, soil-plant interactions, and global ecological stability. To help plants be resilient to environmental changes, the management strategy of the future must focus on enhancing soil health, use of stress-tolerant cultivar, and exploitation of favorable microorganisms or biostimulants to stabilize nutrient uptake and defend against metabolic responses. The additional merging of molecular, biochemical, and ecological modalities will be necessary in the development of sustainable solutions to protect the productivity of plants and stability of the ecosystem in the context of escalating global stress factors.

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