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REVIEW ARTICLE

Environmentally friendly agronomic strategies for managing abiotic stresses in crops

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Abstract

Most of the agricultural land undergoes abiotic stress, which can significantly reduce crop production both qualitatively and quantitatively. Numerous abiotic stressors, including temperature stress (heat and cold), salinity, drought, heavy metal contamination, nutrient deficiency or toxicity have negative impact on crops and limit their productivity and quality. Understanding the mechanisms of major abiotic stressors and their negative impacts on crop yield helps to improve crop resilience and productivity through agronomic management. Biochar, kaolin, super absorbents, seaweed extracts, yeast extracts and nanoparticles are the promising environment friendly agronomic approaches that can mitigate the negative effects of abiotic stresses on crops and improve their productivity. This review mainly focuses on different abiotic stressors, their impacts on crop productivity and environment friendly management strategies.

Keywords: abiotic stressors; crop production; sustainable agriculture; yield loss

Introduction

The world will need to feed 9.7 billion by 2050 and, within this period also face several challenges, including increased demand for food and resources, strain on ecosystems and potential for social and political instability. These challenges are exacerbated by climate change, resource depletion and poverty, which are already impacting global food security. The changing weather pattern will cause a severe interruption to agricultural systems as per the forecast of IPCC (1). In the last two decades, about 37 % irrigated lands were covered by salinity whereas global warming has induced the rapid evapotranspiration that causes drought. Therefore, hunger and malnutrition become an issue for stress prone areas. By 2030, to achieve the “Climate Action” and “Zero Hunger” goal of SDGs, it’s unavoidable to reconstruct the conventional agricultural systems. Stress induces abrupt physiological and metabolic changes in plants. Stress in plant can be classified as internal that causes from mutations or abnormal cell divisions and external that derives from biotic and abiotic origins. The key abiotic stressors are drought, salinity, temperature stress (heat and cold), heavy metal contamination, nutrient deficiency or toxicity (2).

Around the world, abiotic stresses affect about 90 % of arable land, leading to yield losses of up to 70 % (2). Extreme high temperature alters the structural changes that accelerate the evapotranspiration and impose the water stress as well as drought. Drought reduces the photosynthesis rate by altering the stomatal closure and reducing leaf area and increases the rate of osmolytes and Reactive oxygen species (ROS) (3). Salinity results in accumulation of sodium (Na^+) and chloride (Cl^-) ions that imposes the oxidative and ionic stress on plant and hinders the water use potential as well as causes cell damage. Heavy metals like Cr, Cd, Ni, Zn, As and Hg causes soil pollution as well as may accumulate in plant cell to cause damage. Crop productivity and growth is hindered by these stresses as a consequence of osmotic stress, nutritional imbalance and oxidative stress (4). These climate driven abiotic stresses have emerged as a major threat to global food security. The impact of it on crop production causes $170 billion or more annual loss. Drought stress results in minimum $80 billion cost on crop production annually. Soil flooding causes $22 billion (price rate of 2021) annual loss in agriculture (5). According to FAO, global annual loss of $30 billion was estimated in crop production due to salinity. Increased atmospheric ozone concentration are responsible for around $40 billion crop yield loss globally (5).

Understanding about the abiotic stressors, the major limiting factors affecting crop production both qualitatively and quantitatively and their management options are very crucial in agriculture (6). Therefore, in this review, we focus on various aspects of ten important abiotic stressors that affect crop plants: drought, submergence, salinity, heat, cold, heavy metals, wind, pollutions, nutrient deficiency/lode and CO_2. To develop a clear and holistic understanding of abiotic stressors, their impact on crops and the strategies used to manage them, this review adopted a structured but narrative-driven approach. The methodology comprised four interconnected steps: i) locating relevant literature; ii) selecting studies using explicit criteria; iii) gathering detailed agronomic data and iv) organizing insights through thematic synthesis. This approach enabled us to capture both the quantitative evidence presented in the literature and the contextual nuances related to mitigation practices.

Major abiotic stresses in crops

Plant experiences stress resulting from both biotic and abiotic factors. Abiotic stresses are drought, submergence, salinity, heat, cold, heavy metals, wind, pollutions, nutrient deficiency or toxicity and CO_2 (Fig. 1). Among the stresses, some are internal, caused by mutations or abnormal cell divisions, while others are external. Major abiotic stresses that affect crops are discussed below:

Drought

Drought is termed as severe threat to growth and yield of crop in the coming decades as the rainfall pattern has changed leading to raise the atmospheric CO_2 and temperature (7). Besides, high light intensity and dry wind increase the evaporation of water from soil which can also trigger the drought stress. Drought occurs not only due to lack of water in soil, the inability of root to uptake water due to low temperature and salinity in soil can also be a reason for water stress (8). Drought reduces leaf water potential, turgor pressure, stomatal closure that affects photosynthesis, nutrient metabolism, respiration and carbohydrates metabolism as well as plant growth and development (9).

Submergence

Submergence can be defined with two terms like 'surface waterlogging', when the surface of soils is flooded due to poor draining and 'root-zone waterlogging', when the entire root zone is drowned with water (10). In response to submergence, plant faces two physiological challenges as hypoxia or moisture injury when oxygen level decreases below the optimum level at both short and long-term flooding and anoxia or flooding injury when there is complete lack of oxygen at long term flooding condition (11). Both conditions limit the aerobic respiration that leads to aeration stress and energy efficiency. As a result, toxicants are accumulated and threatened the plants productivity and survivality (12). Moreover, flooding affects the soil pH by buffering the carbonate under the partial pressure of CO_2 and redox potential (Eh) leading to an amendment of proton and cation balances (13). Besides, plants induce ethylene accumulation under submergence that enhances the gene expression and triggers the breakdown of chlorophyll by activating chlorophyllase enzyme.

Salinity

With yearly addition of 0.3–1.5 million ha, one billion ha land around the 100 countries of the world lost more than 20 % of its production due to salinity (14). Salinity can arise in soil either by sea water as well as atmospheric deposition are defined as natural causes or by poor drainage facilities, using briny water for irrigation as well as improper management of water that are defined as secondary or anthropogenic process (14). Salinity imposes stress on the plants through osmotic and ionic imbalance. Water uptake capacity of the root decreases as the soil water increases, with higher Na^+ and Cl^- than the plant and leads to the osmotic stress. Osmotic stress gives rise to hyper ionic stress, whereas the increasing accumulation of Na^+ and Cl^- ions in plant tissues inhibits the uptake of other nutrients like K^+ ions that regulate the cell turgor, activity of enzymes and membrane potentiality. As a secondary product of salinity, ROS causes oxidative damages of protein, lipids and DNA (15).

Heat stress

When 50 % of the plants die due to a certain temperature, the situation can be defined as heat stress. The killing temperature varies with plant type, like the highest 60 °C-120 °C temperature was reported in higher plants during the daytime (16). Actively growing plant tissue can rarely withstand the temperature above 45 °C, whereas dry seeds and pollen grains can survive up to 120 °C and 70 °C temperature, respectively (17). Plants usually try to stabilize their tissue water with sufficient soil moisture content rather than have a limited supply (18). But high temperature exposure reduces the leaf tissue water along with root mass that coincides with the water scarcity in many crops like sugarcane,

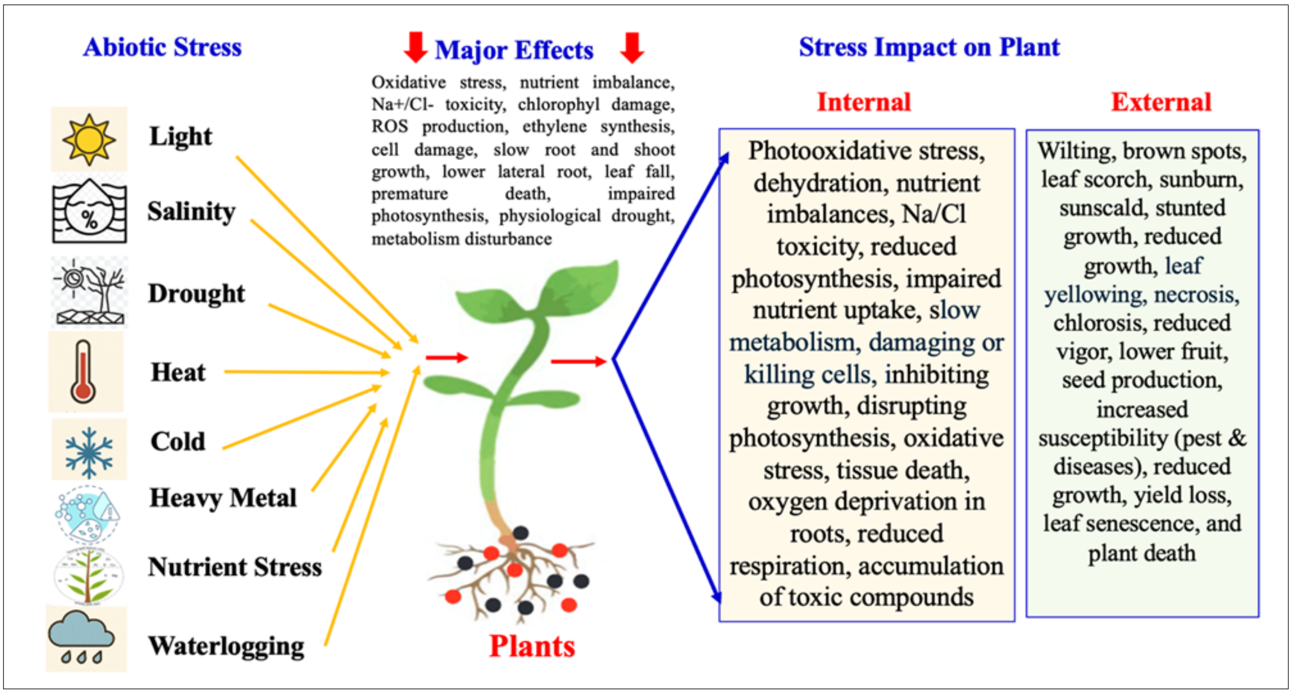

Fig. 1. Abiotic stressors and their consequences on plant performances (growth, development and productivity).

tomato etc. (19). Thylakoids face the structural changes under high temperature that reduce the rate of photosynthesis (20). Rapid evapotranspiration rate has influenced the production of glucose that affects the osmotic adjustment of the plant under heat stress (21). Extreme heat may also increase the lipid fluidity, ROS production that results in reduced seed germination, plant growth, leaf rolling, pollen viability, parthenocarpy, fruit discoloration and ultimately the fruit yield of plant (22).

Cold stress

Plant faces two types of cold injuries, i.e. chilling (0 °C –20 °C) and freezing (< 0 °C). At sub-zero temperature, ice crystals are formed at the extracellular space of the plant that increases the electrolytic leakage at the membrane lipid phase and reduces the water potential of the apoplastic solution. As a result, dehydration may induce as plant cells get punctured that results water as well as cytosol outflow from the cell (23). ROS are also accumulated at high level that damages cellular structures and macromolecules under cold stress (24). Malondialdehyde (MDA) is an important indicator of cold stress. The MDA content was increased rapidly at the rate of 0.20 μmol g^{-1} from fifth day, whereas it was raised slowly in first three to four days at 1 °C that predicted seedling injury may happen between 3-5 days at this temperature.

Heavy metals

The elements that have relatively high density exceeding 5 g cm^{-3} as well as atomic weight greater than 20 atomic number and exhibit pliability, conduction ability, stability of cation and specificity of ligand can be termed as heavy metals. Plants can absorb only easily soluble metals present in the soil. These metals can be classified into two groups depending on their necessity for plant. For enzyme and protein structures, Co, Cu, Fe, Mn, Mo, Ni, V and Zn are required in minute quantities, whereas Pb, Cd, Hg and As regarded as "risk" as they have destructive effects on crops. Though some metals have a beneficiary effect, it can be detrimental if they exceed their acceptable levels in the soil. The root is the entrance of metal and move towards the aerial parts of the plants with the influence of transpiration via xylem. Crop shooting tissues hold a very minimal percentage of heavy metals (25, 26). Heavy metals affect the plant by disturbing the protein structure and inhibiting the function of cellular molecules.

Wind

Wind is a complex but neglected stress that causes mechanical pressure as well as exchange of leaf gas and heat (27). Responses of plants towards wind may vary along the terminal or basal stem. Wind reduces the leaf boundary layer as well as plant temperature (28). Wind mediated plant produces short and thick petioles with more rounded leaf blades that result water stress as well as dehydration of the plant (28). Due to heavy wind, leaves become rolled up that reduces the effective leaf area. Heavy and continuous unidirectional wind may cause bending of plants and inhibit the stem elongation (29).

Pollutions

Pollution of air, land or water causes from industrial, commercial as well as transportation system becomes a global issue now. Many factories emit huge CO_2 and other CFCs which cause air pollution. It affects the plant photosynthesis rate by hindering photosynthesis. Heavy use of pesticides and improper waste disposal cause soil as well as water pollution that affects plant nutrition uptake.

Nutrient deficiency and toxicity

Sixteen elements i.e. carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, zinc, copper, boron, molybdenum and chlorine are known as essential for metabolism in plants (30). Deviation from the needed balanced proportions for plants causes nutritional imbalance and stress (Fig. 1). Therefore, the plant faces stunted growth, low yield and finally death. Toxicity of nutrients may show similar consequences like deficiency (31).

CO_2

CO_2 regulates the stomatal opening of leaves through which CO_2 is diffused for photosynthesis. On the other hand, it is also used as a trail of water diffusing out. Previous studies reported 5 % fall in stomatal density and 22 % reduction in stomatal conductance due to high photosynthetic rate with elevated CO_2 that affects the plant water use and assimilation rate that limits the photosynthesis rate (32). High concentration of CO_2 also affects the respiratory ATP synthesis that directly hampers the uptake of O_2. Another study reported plant diabetes with an increasing CO_2 rate that stimulates the production of methylglyoxal that is responsible for diabetes mellitus in wheat leaves (33). Rising CO_2 levels could heighten plant vulnerability to frost, potentially diminishing productivity benefits and influencing agriculture, forestry and ecosystem dynamics (34).

Crop quality deterioration due to abiotic stresses

Drought

Drought stress can be characterized by reduced cell growth that results from low turgor pressure (35). Cell enlargement can also be hampered due to hindrance of water flow to the elongated cell from xylem that ultimately reduces the plant height and leaf area under water stress (36). Besides the cytological impact, drought has a great impact on the crop as well as grain quality like starch, mineral elements, protein or lipid content. About 65 % of grain is composed of starch that can be drastically affected due to water stress during grain filling. Among the four key enzymes, inactivation of adenosine diphosphate-glucose pyrophosphorylase can cease the starch accumulation of barley (37) and corn (38). AGPase can also inhibit the cell-wall synthesis that causes reduced starch content in potato (39). The ROS produced under drought stress is injurious to lipid production (40). In a consequence, fluidity and intrinsic-membrane protein activities may also be hampered. Moreover, a reduced transpiration rate also hampers the nutrient uptake of the crop by increasing N and reducing the P uptake (41). In cotton, altering N and K uptake was previously reported (42). Low mobility of PO_4^{3-} towards the plant tissue reduced the P and PO_4^{3-} contents. Water stress also affects the nutrient use efficiency. K^+ applied sunflower showed drastic decline in stomatal opening rate under drought stress (43).

Submergence

Floods cause two-thirds of all damages and losses to crops from 2006 to 2016 over the world (44). Plants are lacking O_2, CO_2 and sunlight under flooded soil which lowers the carbohydrate rate as well as growth and development of plants by interfering the photosynthesis and aerobic respiration (45). Hypoxia induces the production of ROS such as superoxide radicals, hydroxyl radicals and hydrogen peroxide that disrupt lipids, pigments, proteins and nucleic acids metabolism of plants (11). A severe lipid peroxidation and membrane injury was observed in mung, maize and pigeon pea due to increasing superoxide radicals (46). Likewise, reoxygenation of organs and tissues can injure plants at post-submergence by inducing oxidative stress. For example, leaf dehydration is the consequence of re-exposure to atmospheric oxygen after 7–10 days of submergence in rice (47). The low pH under submergence may cause aluminium or manganese phytotoxicity, calcium deficiency and reduced mineralization. The high soil redox potential affects the availability and concentration of different plant nutrients (13). Previous studies revealed that submergence reduces K and N uptake by 89.5 % and 88.7 %, respectively as well as the rice cooking and testing qualities (48).

Salinity

Plant responses to salinity either within a minute to days that causes closing of stomata as well as inhibition of shoot cell expansion or over days and weeks that impair metabolic processes and cell death (49). In Broccoli this biphasic response was observed whereas the growth reduction was much higher in first week of salinity stress (50). Photosynthesis rate is reduced due to stomatal closure caused by abscisic acid synthesis and unavailability of CO_2 under salt stress. Salinity hampers the photosynthesis of Spinach by reducing stomatal and mesophyll conductivity to CO_2 as well as chlorophyll content that hampers the light absorbance in sunflower also (51). Salt stress reduced the leaf area expansion and lowered the light interception that leads to 80 % loss of growth in radish (52). Moreover, high concentration of Na^+ and Cl^- results in nutrient deficiency by ionic competition between $Na^+/Ca^{2+}/K^+$, Ca^{2+}/Mg^{2+} and Cl^-/NO^{3-} in plant tissues. Na^+ accumulation stops the activity of many enzymes which may regulate by the availability of K in soil (26). Blossom-end rot that is caused by Ca^{2+} deficiency, reported in saline water irrigated tomato, pepper fruits and eggplants (53). Salinity causes sterility of spikelet in rice (54) and lint quality in cotton (55).

Heat stress

Temperature above the threshold level causes heat stress that reduces crop quality by altering the starch, sugar, gene expressing protein and fatty acid content in cereals and other grain crops (Table 1). In rice, 35 °C night temperature at the pre-flowering stage reduces the panicle number up to 75 % (Table 1). Heat stress during grain filling creates an imbalance in the starch synthesis degradation by increasing the rate of starch degrading enzymes such as alpha amylase which leads to the production of chaffy grain in rice (66) observed a negative effect of heat stress on grain protein of *Pusa* 1121 rice. Previous researchers reported decreased rate in chalkiness and head rice due to heat along with high relative humidity (67). Heat stress increases the rate of protein synthesis in bread wheat that subsequently increases the gliadin proportion and reduces the glutenin (68). Dough quality declined due to decreasing the glutenin-to-gliadin ratio and presence of large glutenin polymers at high temperature exposure (69).

Cold

With the changing climate, cold periods have increased, that reduces the production and quality of many temperate and arid zone crops (Table 2). Plant integrates a variety of responses towards cold stress that interferes with plant's metabolism, cell wall structure, photosynthesis and ROS homeostasis (75). As a result, crops exposed to chlorosis, flavescence, wilting and leaf shrinkage under cold stress (76). Different crops have different levels of tolerance towards the low temperature. For example, only 10 % of ice in the tissues can be tolerated by beans (*Phaseolus vulgaris*), whereas the rate is 50 % for sugar beet (77). Rice, maize, cotton and soybean, the economically leading crops, are very sensitive to chilling temperatures at the reproductive phase that may cause death of these plants (78).

Table 1. Effects of heat stress on quality deterioration in different crops

Crop	Effects	Reference
Rice	-As the temperature exceeds 25 °C –28 °C, tiller number and biomass decline	(56)
	-Under HS (40 °C day /35 °C night) at the pre-flowering stage, panicle number was reduced to 75 %	(57)
	- Heat stress hinders assimilate production by reducing photosynthetic rate	(58)
Wheat	-Above 35.8 °C temperature, starch content declined by reducing the rate of sucrose converting to starch -Starch content lost by 58 % at 37/28 °C related to 24/17 °C day/night temperature	(59)
Barley	Exposure to 35 °C for 5 days caused alteration of endosperm structure and degraded storage product during seed filling stage	(60)
Soybean	-35 °C reduces the oil content by 2.6 % compared to 29 °C -Denaturation of b-conglycinin and damaged globulin and phaseolin alters the seed composition -Above 40 °C day temperature, N and P content declined -β-glucosidase can't transcript at 40/30 °C day/night temperature that express a gene responsible for seed size	(61, 62)
Lentil	Degradation of albumins and globulins in seed	(63)
Rapeseed	Composition of fatty acid was affected by temperature rising from 10 to 26.5 °C	(64)
Sunflower	Affects the fatty acid biosynthesis that alters the oil composition	(65)

Table 2. Effects of cold stress on quality deterioration in different crops

Crop	Effects	Reference
Rice	-25 % yield drop due to cold stress at booting stage -Decreased chlorophyll content as cold stress alters the arrangement of grana as well as lamellar structure and number of chloroplast	(70)
Corn	-Inhibition of pod set if the temperature drops below 15 °C during the flowering stage -Growth reduction, low level of gibberellins and heterosis in hybrids at 10 °C -12 °C temperature	(71)
Rye	Decreased about 60 % of N xylem flow by lowering the temperature from 20 °C to 7 °C affecting the nitrates absorption and N accumulation in the roots	(72)
Soybean	Become susceptible to damping off at 4 °C	(73)
Mustard	About 30 % of N xylem flow decreased at 7 °C temperature	(72)
Tobacco	-Change in microstructures of leaves that lead to necrotic spots, reducing chloroplast pigment content and the maturity of tobacco leaves - Decreased root activity that inhibits the nitrogen uptake and impairs carbon and nitrogen metabolism of flue-cured tobacco	(74)

Heavy metals

Soil-plant environmental system has been greatly affected by increasing use of fertilizers as well as industrialization that excreted toxic heavy metal exudes to the open water source and soil get contaminated with Cd like metals that may reside unchangeable there over thousand years (79). Crops require a very little amount of certain heavy metals for growth and development and excessive amount causes toxicity (Table 3). Phytotoxicity of heavy metals forms ROS that disrupts the redox equilibrium, cell structure and inhibits cytoplasmic enzyme activity and leads to the reduction of crop production (26). Moreover, toxicity in soil reduces the photosynthesis rate, mineral nutrient uptake and enzyme activity that ultimately results in the inhibition of growth as well as death of the plant (92). Enzyme activities useful for plant metabolism may also be hampered due to heavy metal interference with activities of soil microorganisms. These toxic effects (both direct and indirect) lead to a decline in plant growth which sometimes results in the death of plant.

Wind

When wind carries sand, ice or micro particles, it causes macroscopic damages by rupturing the epidermis leading to cracks in the cuticle that reduces the capability of plant to control water loss (93). Such type of damages was recorded in strawberry (94). Broad-spectrum herbicides like 2,4-D, dicamba, or other hormone-type herbicides that are used in cotton and other cereal and grain crops, can travel up to a mile with minimal wind speed like 5 mph. These cause serious damage to the vegetables. Moreover, wind can alter the root growth as well as root: shoot ratio (95).

Pollution

Other than the animals and human, pollution also causes damages to plants. Air gets polluted by carbon, sulphur and nitrogen oxides as well CFC. Increased solar UV radiation resulting from ozone depletion has caused a reduction in biomass production (between 11 % and 22 % less) and a decrease in total leaf area (ranging from 24 % to 31 % less) in two plant species, *Colobanthus quitensis* and *Deschampsia antarctica*, along the Antarctic Peninsula (96). Polluted soil with toxic chemical hinders the nutrient uptake of plant and causes cell damage. Another devastating pollutant is acid rain which is a type of precipitation characterized by a low pH level, resulting from the reaction of sulphur dioxide and nitrogen oxides with atmospheric water. This acidic rainfall can alter the composition of soil, disrupting the nutrient supply essential for both plants and soil microorganisms. It can penetrate plant tissues through their outer layers, impacting vital processes such as photosynthesis and the metabolism of nitrogen and sulphur, often leading to stunted growth (97).

Nutrient deficiency and toxicity

Nutrient deficiency as well as toxicity cause drastic loss in crop quality (Table 4). For example, starch and sugar content get reduced due to inhibition of photosynthetic electron transport in Fe-deficient maize plants (106). Superoxide radicals are produced under Mg^{2+} deficiency in bean leaves (109). Boron deficiency downregulates genes involved in cell wall organization, reducing pectin and cellulose levels in the roots, which hinders root growth. It also affects phytohormone levels and signalling pathways, decreasing jasmonic acid, abscisic acid and other compounds, while increasing ethylene precursors (110).

CO_2

Although increased CO_2 availability is expected to enhance photosynthesis, plants require other macro and micronutrients that become less available under elevated CO_2 conditions. Thus, crop faces a loss in quality with declined nutrition. Studies reported a loss of 9.5 % protein in vegetables that is distributed by 10.5 % of fruit, 12.6 % of stem and 20.5 % of root vegetables (111). The reduction of 4 % wheat protein concentration in greenhouse was also found (112). Previous studies revealed that 5 %-14 % protein concentrations were decreased in wheat, rice and barley grains as well as in potato tubers with high CO_2 in the atmosphere (113). Plants micronutrient concentrations were also reported to

Table 3. Effects of heavy metal stress on quality deterioration in different crops

Heavy metal	Crop	Effects	Reference
As	Rice	-In rice grain, the acceptable level was 1.0 mg As kg^{-1} but the irrigated water got contaminated with 0-8 mg As L^{-1}	(80)
		-Reduced dry matter production	(81)
	Canola	-Chlorosis, wilting and stunted growth at the 13.3 µM As rate	
Cd	Wheat	Decrease in plant nutrient content	(82)
Co	Tomato	-50 mg Co kg^{-1} induced the increased rate in nutrient content whereas 100 mg Co kg^{-1} to 250 mg Co kg^{-1}, reductions in plant nutrient content were recorded	(83)
	Mung bean	-50 mg Co kg^{-1} soil concentration reported with increased plant growth, nutrient content, biochemical content and antioxidant enzyme activities while reductions were recorded at 100 mg Co kg^{-1} to 250 mg Co kg^{-1}	(84)
Cr	Onion	-Cr concentrations more than 150 mg L^{-1} caused the reduction of morpho-physiological quality of plant	(85)
	Spearmint	-No significant lose at the rate up to 13.5 µM while chlorophyll a and total carotenoids reduced gradually with the rate of 15.75 µM	(86)
Mn	Pea	-Reduction in chlorophylls a and b content when Mn supply got increased from 250 µM to 3000 µM	(87)
	Tomato	-Reduction of chlorophyll content and slower plant growth was reported in both 8.6 and 9.6 µM concentration of Mn	(88)
Ni	Wheat	-The Ni^{2+} treatment with 40 mmol m^{-3} rate can increase leakage of K^+	(25)
Pb	Maize	-Total proteins increased in shoots at 1.0 mM while decreased at 25 - 500 mM -At 1.0 mM concentration, the reduction in protein content in shoot was 9.13 %	(89)
Zn	Cluster bean	-25 mg L^{-1} Zn concentration in soil may improve the growth and physiology -50 mg Zn L^{-1} had adverse effect on the plant's physiology and reduced the growth	(90)
	Pea	~1000 µM Zn content reduced plant growth, chlorophyll content and induced structural alterations in chloroplast that resulted the reduction of granal thylakoids	(91)

Table 4. Effect of nutrient deficiencies on quality deterioration in different crops

Nutrient	Available form	Effect on plant	Reference
N	N_2, NO_3^-, NO_2^- and NH_4^+	Excess NO^{3-} reduces the root: shoot ratio by inhibiting root growth	(98)
		Nitrogen deficiency causes stunted growth, chlorosis at older leaves first, chloroplast disintegration leading to loss of chlorophyll, low fruit setting and finally death of the plant	(99)
		Nitrate in assistance with several genes, is believed to be involved in transportation of cytokinins from root to leaves	(99)
P	$H_2PO_4^-$, HPO_4^{2-}	Decrease in shoot–root dry weight ratio whereas shoot gets more affected	(100)
		Affects the formation of reproductive organs	(101)
		Phosphoenolpyruvate carboxylase in tobacco catalyzes the primary fixation of atmospheric carbon	(102)
		Induction of iron and zinc deficiency	(99)
K	K^+	Plant tends to lodge and drought due to K^+ deficiency	(103)
		Excess K^+ supply causes nitrogen deficiency and may interfere with the uptake of divalent cations like Ca^{2+} and Mg^{2+}	
S	SO_4^{2-}	Tomato faced reduction in chlorophyll and protein due to low level of sulfur	(104)
Ca	Ca^{2+}	Premature shattering of fruits and buds due to insufficient Ca	
		Mg^{2+} absorption gets interfered due to excess Ca in soil	
Mg	Mg^{2+}	Insufficient Mg supply reduces the carotenoid content from 0.21mg/gm fresh wt. (control) to 0.11 mg/gm fresh wt. in rape leaves	(105)
Fe	Fe^{3+}, Fe^{2+}	Insufficient Fe may lower the rate of starch, sugar and proteins	(106)
		Water-logged soils may induce the Fe toxicity that causes bronzing of plant	
B	$B(OH)_3$ $B(OH)_4^-$	Boron deficiency induces the activity of RNase that causes the reduction of RNA content in tomato	(107)
		In field bean, phosphate uptake gets hindered due to boron deficiency	(108)
		Flowering is affected by boron toxicity	

be lost under elevated CO_2. Nitrogen assimilation is also inhibited in some crops like wheat and cucumber by reducing nitrate uptake under elevated CO_2 (114). Amino acid concentration was also affected in potato (115) and sweet pepper (116) which reveals an uncertain metabolic process. High CO_2 levels, by causing dilution and limiting transpiration, have been found to reduce the content of minerals like Mg, Fe and Zn by 9.2 %, 16.0 % and 9.4 %, respectively (111). Grain crops experienced a reduction in mineral content due to elevated CO_2, with Fe levels declining more drastically in wheat (5.1 %) and rice (5.2 %) compared to other crops (117). Moreover, with increased CO_2 rate, a decreased rate in Na, Ca, Mg and S by 5.5 %, 14.5 %, 7.2 % and 12.3 % respectively was found in wheat (118).

Crop yield loss due to abiotic stresses

Drought stress

Yield losses in the field under drought typically range from 30 % to 90 % (119). Mild drought conditions have shown to decrease rice yields by 30 % to 64 %, while severe drought can lead to losses of 65 % or more compared to normal conditions (120). About 50 %-60 % yield reduction can occur in wheat due to drought stress (121). Different experimental results showed that in wheat (Durum), maize, soybean, cotton, tobacco, potato (cv. Spunta) and rye (hybrid), about 25 %, 81 %, 44 %, 50 %, 71 %, 53 % and 27 % yield losses occur, respectively, depending on various factors such as the growth stage during which drought occurs, its duration, severity, regions and specific crop varieties involved (122). The above results are presented in Fig. 2 considering average yield loss and optimum crop yield.

Waterlogging and sub-mergence

Data from a global meta-analysis showed that waterlogging reduces global crop yields by around 32.9 % (average). Key factors include crop type, growth stage and waterlogging duration. During the reproductive stage, it causes greater yield reductions (41.9 %) than the vegetative stage (34.7 %) (123). Moreover, prolonged

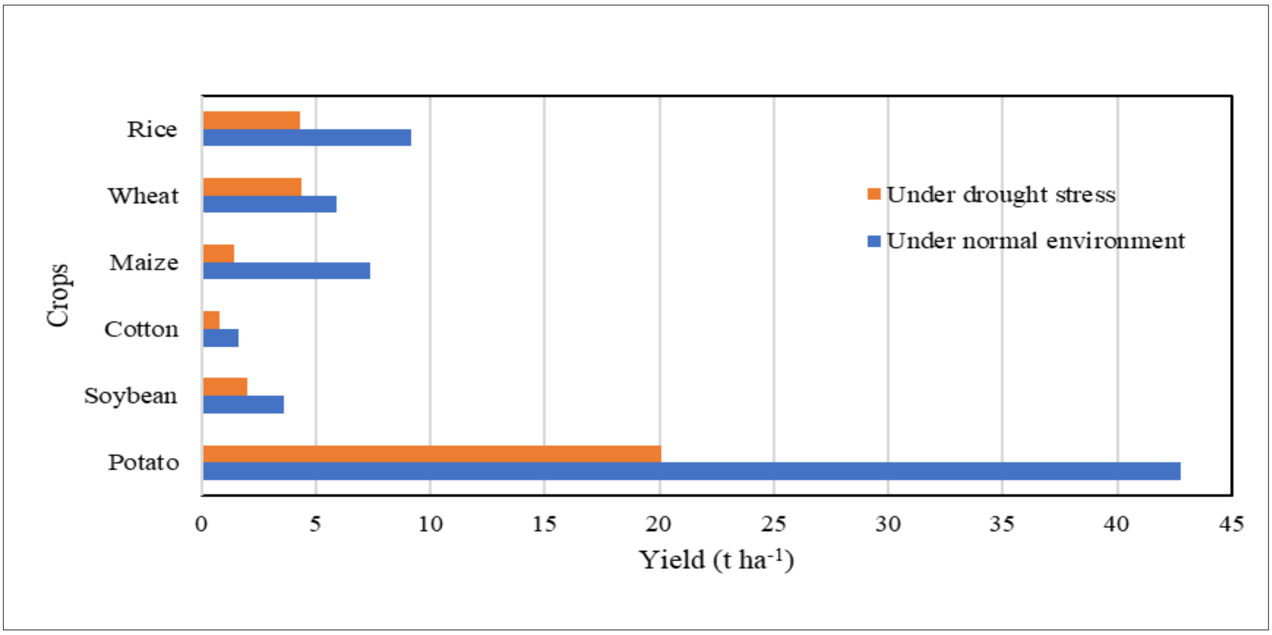

Fig. 2. Crop yield reduction by drought stress (prepared from 120, 122, 124).

waterlogging led to reductions in crop yield, with the most significant declines (53.19 % and 55.96 %) occurring when the duration ranged from 15 to 28 days under both field and potted conditions (123). Wheat experiences a reduction of 25.53 % while cotton suffers 59.95 % decrease (123). Rice experiences up to 31.68 % yield loss at jointing and booting stage depending on the degree of waterlogging (124). Soybean yield loss in reproductive stage ranges from 20 %-39 % (125). Two days of flooding during intensive growth and flowering stage of potato dropped total yield by 64 % and 59 %, respectively, while eight days of flooding cause almost complete yield loss (126). Maize yield was reduced by 16 % on average in extreme wet condition (127). The above results are presented in Fig. 3 considering average yield loss and optimum crop yield.

Salinity stress

Extent of losses due to salinity stress depends on crop type specifically cultivars, salinity levels and timing of exposure. Rice, soybean and beans are considered as highly sensitive crops while wheat, maize, potato etc. are moderately sensitive crops based on their response to salinity stress. Studies suggest that average yield losses of crops like rice, wheat, maize, cotton, chickpea, groundnut, barley, sorghum and brassica are 40 %, 30 %, 55 %, 15 %, 20 %, 38 %, 35 %, 33 % and 50 % respectively (128). Soybean yields can decrease by as much as 40 % depending on the level of salinity (129). The above results are presented in Fig. 4 considering average yield loss and optimum crop yield.

Heat stress

One-degree centigrade rise in global average temperature would lead to an average decline in yields by 6.0 % for wheat, 3.2 % for rice, 7.4 % for maize and 3.1 % for soybeans (130). Studies shows that high temperature reduces grain yield by 46.63 % in wheat (131). During booting and flowering stage of rice, 36 °C-40 °C temperatures led to significant sterility and results in 13.8 %-28.5 % yield loss (132). In maize, 50 % yield loss may occur due to high temperature in flowering stage and lag phase which is comparatively higher than yield loss (26 %) due to high temperature in effective grain filling stage (133). Experiment with three cultivars of soybean Z1307, ZH39 and ZH76 showed that increase in nighttime temperature from 18 °C to 28 °C results in 12 %-34 %, 33 %-18.2 % and 25 %-45.4 % yield reductions, respectively (134). During boll period of cotton, 2 °C to 3 °C increase in daily temperature (31 °C -35 °C) results in 30 %-40 % yield loss (135). Research on potato cultivars reveals that 15 days of heat stress (35/25 °C Day/night) in late June under adequate soil moisture reduced total yield by 12 % (136). The above results are presented Fig. 5 considering average yield loss and optimum crop yield.

Cold or low temperature stress

Wheat yield is more vulnerable to low temperatures during the booting stage than during the jointing stage. Under low temperature conditions during the booting stage, grain yield per plant decreased by 13.9 %-85.2 % in spring wheat and 3.2 %–85.9 % in semi-winter wheat (137). Studies showed that low air temperatures as the primary cause of yield losses with water stress playing a secondary role cause maize yield loss of approximately 57 % (138). Low temperature stress causes yield reductions in rice reaching up to 38.6 % (139). For soybeans, cold stress at flowering reduces seed yield by an average of 24 % (140). Severe cold events in cotton can cause yield reduction up to 40 % (141). Exposure of potato to low temperatures significantly impairs growth and causes 40 %-60 % tuber yield losses (142). The above results are presented in Fig. 6 considering average yield loss and optimum crop yield.

Heavy metals

An experimental result showed that economic yield and biomass of vegetable crops reduced by 9 %-67 % and 9 %-32 % in copper, zinc, lead and cadmium contaminated soil (143). Recent studies have investigated the link between heavy metal toxicity and the downward trend in rice yield. This correlation was also addressed earlier (144). Lower crop yield and compromised grain quality in cereal plants extensively reported earlier (145).

Mitigation strategies

Soil management

Implementing strategies such as incorporating organic matter, cultivating cover crops and minimizing tillage can significantly enhance soil fertility and conserve moisture (Table 5). Practices such as conservation tillage reduce soil disturbance, which helps to limit moisture loss, minimize compaction and improve soil structure. This practice improves water infiltration, increases water -holding capacity and enhances organic matter content (156).

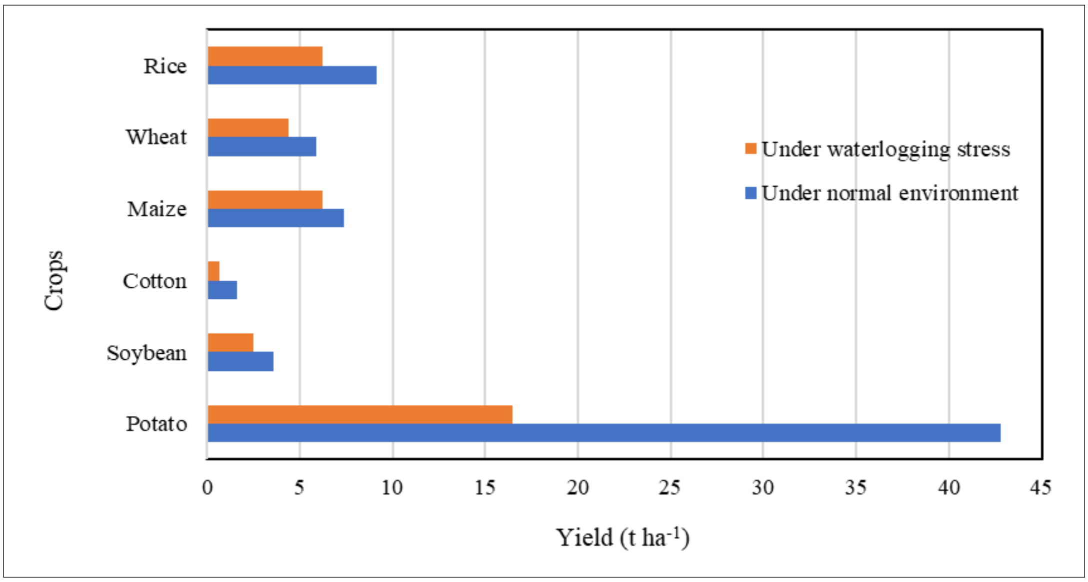

Fig. 3. Crop yield reduction by waterlogging (prepared from 122-127).

Table 5. Soil management for mitigating abiotic stresses

Factor	Management	Effect/Outcome	Reference(s)
Tillage	Conservation tillage	-alleviates drought stress and enhances WUE when compared to conventional tillage	(146)
		-It increases WUE by 19.1 %–28.4 % in wheat and 10.1 %–23.8 % in maize	(147)
	No-till practices	-conserves 20 %–30 % more water	(148)
		-contributes to enhancing erosion control and improving the efficiency of water and fertilizer application	(149)
Intercropping	Maize + potato, wheat + faba, maize + mungbean	-conserves soil water, reduces runoff and evaporation and improves WUE compared to sole cropping	(146)
		-suppresses weeds	(146)
Mulching	Use of organic mulches	-boosts crop yields, especially under drought conditions; A study showed increased yield of sesame with mulching	(150)
	Use of straw mulches	-reduces evaporation, helps to maintain soil moisture and minimizes salt build-up at the root zone	(151)
		-also enhances soil moisture retention and boosts water and nitrogen use efficiency, improving overall plant performance in wheat	(152)
Soil amendments	Application of compost, gypsum, sulfuric acid	-improves soil structure, reduces salinity by replacing sodium with calcium (gypsum) and enhances soil health	(153)
Crop rotation	Inclusion of legumes in rotation	-reduces heavy metal uptake by cereals, enhances soil health and minimizes metal contamination	(154)
Soil pH management	Application of lime to acidic soils	-raises pH, reduces solubility of metals like cadmium and lead	(155)

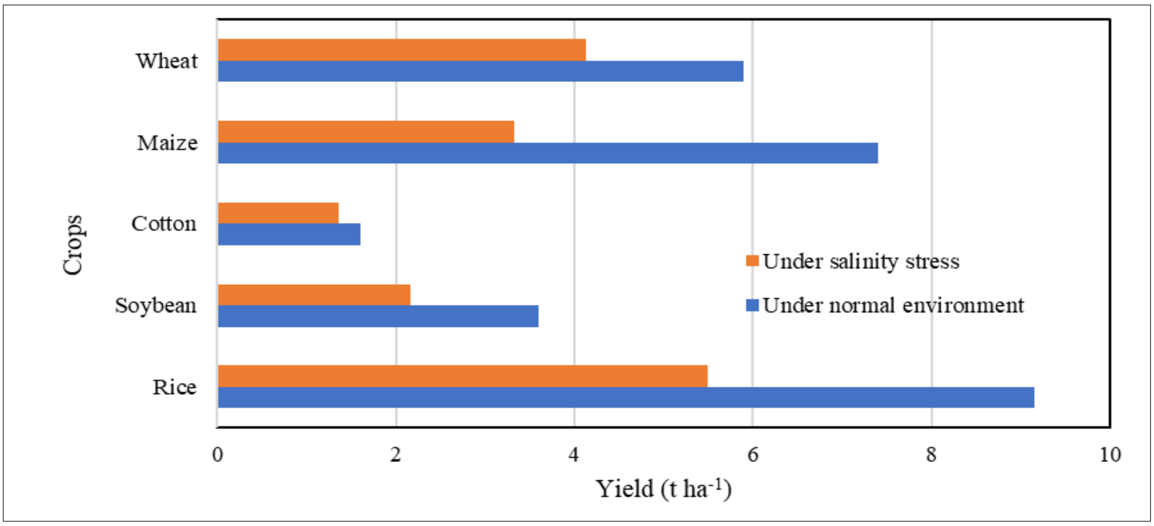

Fig. 4. Yield reduction by salinity stress (prepared from 122, 124, 127, 128).

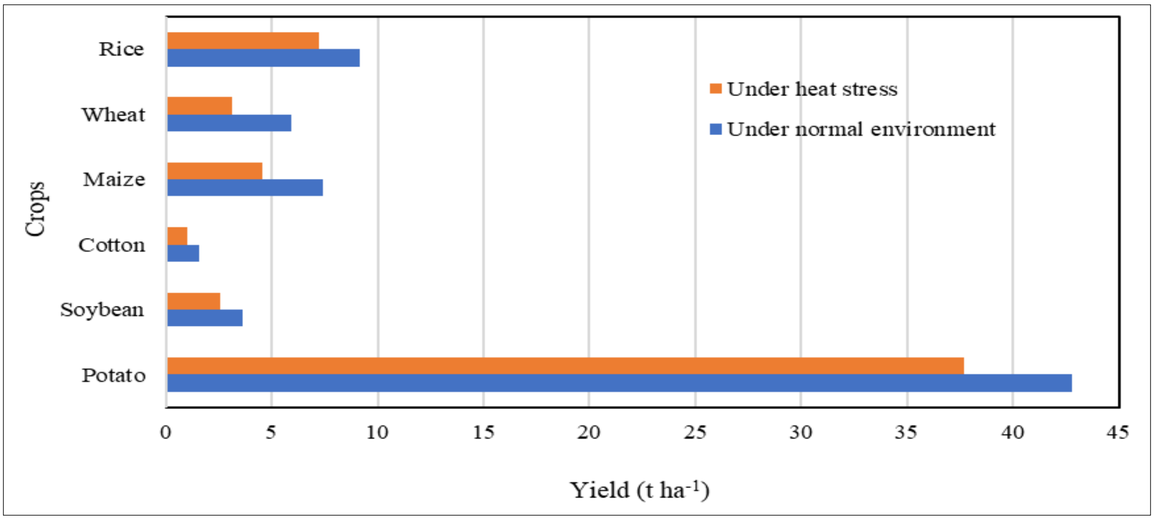

Fig. 5. Crop yield reduction by heat stress (prepared from 122, 124, 131-136).

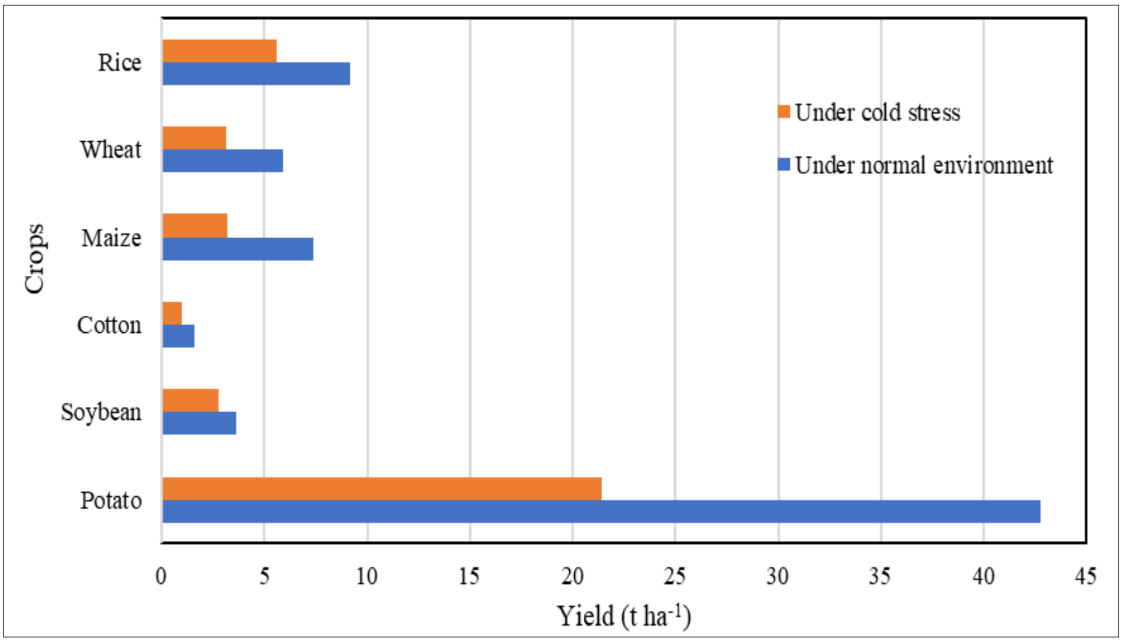

Fig. 6. Crop yield reduction by cold stress (prepared from 122, 124, 137-142).

Moreover, mulching whether with organic or inorganic materials effectively reduces evaporation (151), enhancing water-use efficiency (WUE) by 10 %-20 % (157).

Crop management

Crops and varieties should be chosen based on available water resources (146). Choosing the right time for planting or sowing can help avoid heat stress during critical growth phases such as anthesis and grain filling, thereby improving crop yields (Table 6). The cultivar 'Golden Promise' is a salt-tolerant barley variety developed in Scotland through induced mutation (168). Additionally, 'AZ Germ Salt 1' is a salt-tolerant alfalfa cultivar developed in the USA through backcrossing selection (168).

Water management

Supplemental irrigation significantly improved *Rabi* sorghum productivity. As shown in Table 7, applying two life-saving irrigations at critical growth stages increased grain yield by 88 % and fodder yield by 65 %, indicating a strong positive response to improved moisture availability. In regions with limited water availability, micro-irrigation methods such as drip and sprinkler irrigation should be promoted to minimize yield loss (170). Additionally, practices like deficit irrigation and skip furrow irrigation help reduce water loss (146). Collecting rainwater during the monsoon season for use during dry spells is another effective drought mitigation strategy (151). Furthermore, irrigation scheduling aligned with critical growth stages, combined with efficient application methods and soil moisture monitoring, enhances crop productivity by alleviating the effects of heat stress (162).

Nutrient management

Applying the right nutrients can alleviate drought stress and enhance plant growth. Proper nutrient management increases water uptake, particularly from deeper soil layers, which improves WUE and reduces the impact of drought (174). The use of essential nutrients, such as controlled-release fertilizers, can also help crops thrive under waterlogged conditions (Table 8). Careful application of fertilizers especially low-salinity and chloride-free types, can prevent the worsening of soil salinity (177). Maintaining optimal nutrient levels is crucial for protecting crops against elevated temperatures. In particular, the management of micronutrients plays a vital role in mitigating heat stress in plants (178).

Other ways of mitigating abiotic stress

Employing plant growth regulators such as auxins and cytokinin can enhance plant resilience under waterlogged conditions (183). Seed priming with various agents also improves crop performance under abiotic stresses, including heat, drought and low temperatures (184). However, low heritability and the complex network of minor and major quantitative trait loci (QTLs) pose limitations to direct selection for improving crop performance under heat stress (HS) conditions (185). A strategic approach involves the genetic tailoring of key physiological traits such as canopy structure, delayed senescence, photosynthetic efficiency, reduced respiration and reproductive performance to incorporate QTLs for HS tolerance, mirroring methods used for drought tolerance (78). In addition, microorganisms, particularly plant growth-promoting rhizobacteria (PGPR), can enhance plant tolerance to salinity by improving root development and nutrient uptake (Table 9). Modern breeding and biotechnology leverage tools like microarray-based phenotyping to uncover thermotolerance diversity and identify heat-resilient genotypes, while phytoremediation research uses genetic and molecular engineering to develop plants (e.g. wheat) with reduced heavy metal uptake through enhanced expression of metal-binding proteins (196, 197).

Emerging technologies for the management of abiotic stress

There are many emerging technologies that can be very effective against abiotic stresses, such as the use of biochar, kaolin, super absorbents, seaweed extracts, yeast extracts, nanoparticles etc (Table 10). The application of biochar has proven effective in mitigating various abiotic stresses, including drought, heavy metals, heat, salinity, waterlogging and cold, while simultaneously improving crop yield and soil properties (198, 199). Kaolin helps reduce the effects of abiotic stresses such as heat and drought by lowering canopy temperature, minimizing water stress and reflecting solar radiation from leaf surfaces (Table 10). A list of emerging technologies that can potentially be used in different

Table 6. Crop management for mitigating abiotic stresses

Factor	Management	Effect/Outcome	Reference(s)
Drought-tolerant Crop and Variety Selection	Selecting low-water-demand crops (e.g. pearl millet, sorghum, chickpeas, barley, mustard, cotton, sunflower, castor)	-Diversifying high-water-demand crops with low-water crops can improve profitability and water-use efficiency (WUE)	(158)
	Swarnaprabha and Kattamodan (rice) varieties	-Shows better drought tolerance, with less leaf rolling and better water retention	(159)
	Longzhong alfalfa variety	-Shows superior performance due to its higher water retention and antioxidant activity	(160)
Crop Diversity	Diversifying crops with varying root depths and water-use efficiencies; e.g. sweet potato, soybean, millet and peanut rotations	-Improves average equivalent yields (up to 32 %) and water productivity (24 %–68 %) compared to winter wheat-summer maize	(161)
		-Enhances soil water storage in the top 180 cm by 3 %-9 % when planted prior to wheat	(161)
Sowing Strategies	Adjusting sowing dates to align with rainfall and temperature	-Reduces stress at critical stages; strengthens root systems; improves drought resilience. Barley and maize perform better with early sowing	(146)
	Optimizing sowing time to avoid heat stress during critical growth phases like anthesis and grain filling.	-Early sowing enhances wheat yield; late sowing reduces protein, oil content and vigour in seeds of soybean	(162)
Waterlogging-Tolerant Varieties	Selecting tolerant genotypes like FR13A, FR43B (India) and Kurkaruppan, Goda Heenati, Avalu (Sri Lanka)	-Enhances flood tolerance and crop survival	(163)
Salt-Tolerant Crops	Cultivating tolerant varieties like sugar beet, cotton, barley, KRL1-4, CSR-1, CSR-2, CSR-3	-Increases productivity in saline conditions. Regional performance varies. (e.g. KRL1-4 performs better in Northern India but poorly in Pakistan due to heavier soil and waterlogging)	(163)
Pruning to avoid cold stress	Cutting alfalfa 4–6 weeks before the first frost	-Improves winter survival via increased root carbohydrate reserves.	(164)
Heavy Metal Tolerance	Using wheat and barley varieties with resistance to heavy metals	-Allows cultivation in contaminated soils	(165)
	Cd-tolerant *Brassica juncea* cultivar	-Shows increased antioxidant activity and reduced oxidative stress	(151)
Phytostabilization	Using species like *Alnus* spp., *Amaranthus hybridus, Brassica* spp., Betulaceae and Poaceae families	-Reduces heavy metal uptake	(166)
Rhizofiltration	Employing aquatic (hyacinth, duckweed) and terrestrial (Indian mustard) plants with dense root systems	-Cleanses contaminated water, marsh water through effective root filtration	(167)

Table 7. Water management practices for mitigating abiotic stress in crops

Strategy	Management/Use	Effect/Outcome	Reference(s)
Supplemental irrigation	Two life-saving irrigations at critical growth stages in *Rabi* sorghum	-Increased grain yield by 88 % and fodder yield by 65 %.	(169)
Micro irrigation	Adoption of drip irrigation in water-limited regions	-Reduces yield loss and improves water-use efficiency by 28 %–58 % compared to broad bed furrow and 45 %–68 % compared to flood irrigation in cotton	(170)
	Drip irrigation in chickpeas	-Significant water savings due to higher application efficiency	(171)
	Sprinkler irrigation in wheat	-Increases yield by 16 % and water productivity by 31 % compared to border irrigation	(146)
Rainwater harvesting	Raised and sunken bed systems	-Saves irrigation water for vegetable farming during drought	(151)
Drainage	Subsurface tile drainage and Bio-drainage (using water-absorbing trees)	-removes excess water mitigates salinity	(172)
	Managing high winter soil moisture and mixed cropping with alfalfa and grasses	-Reduces root and crown heaving caused by freeze–thaw cycles	(164)
Water management during heat stress	IW/CPE ratio of 0.75 in conditions of limited water supply is recommended and 1.2 ratio in conditions of unlimited supply	-Optimizes yield in wheat when applied during tiller to flowering stages	(173)

Table 8. Nutrient management practices for mitigating abiotic stress in crops

Strategy	Management/Use	Effect/Outcome	Reference(s)
Nutrient management under drought stress	Potassium (K) application	-Leads to higher yields under drought conditions, e.g. maize, pearl millet	(175)
	Nitrogen (N) application	-Enhances drought resistance by promoting root growth.	(160)
Nutrient management under submergence	Application of controlled-release fertilizers; Use of potassium (K) and boron (B)	-Helps crops survive waterlogging conditions; Mitigates negative impacts of waterlogged conditions	
Nutrient management under salinity	Use of organic matter and fertigation with sulfuric acid	-Enhances nutrient uptake and reduces salt stress	(177)
	Application of silicon (Si) and potassium (K)	-improves crop tolerance to salinity	(162)
Nutrient management under heat stress	Nitrogen (N) application in rice under heat stress	-Prevents lipid peroxidation by supporting carbon metabolism and light energy use	(178)
	Zinc (Zn) use under heat stress in wheat	-Maintains membrane integrity and protects against heat damage	(179)
	Calcium (Ca) supplementation in potatoes	-Counteracts heat stress by supporting physiological functions	(180)
Nutrient management under cold stress	Adequate potassium (K) in alfalfa under cold stress	-Enhances photosynthesis, reduces respiration, maintains turgor and minimizes ROS	(181)
	Application of potassium (K) and phosphorus (P) after final fall cutting in	-Stores root carbohydrates for cold stress-related processes	(182)

Table 9. Other strategies for mitigating abiotic stress in crops

Factor	Management	Effect/Outcome	Reference(s)
Biological approaches	Seed inoculation with rhizobacteria	-Enhances heat stress tolerance in wheat	(186)
	Treatment with *Bacillus* and *Azospirillum* spp.	-Reduces ROS production and improves heat stress tolerance	(187)
	Use of rhizosphere bacteria	-Helps plants cope with metal stress and enhances metal absorption	(188)
	Use of phytosiderophores	-Enhances nutrient uptake in Zn or Fe deficient plants	(188)
Chemical and hormone applications	Exogenous application of glycine betaine (GB) and proline (20 mM each)	-Improves heat stress tolerance in sugarcane by enhancing membrane stability and antioxidant activity	(189)
	Proline application	-Protects carbon metabolism enzymes and antioxidant system, aiding heat stress tolerance in chickpea	(190)
	Salicylic acid (SA) application (a key osmo-protectant)	-educes electrolyte leakage and enhances antioxidant activity, improving heat stress tolerance in grapevine	(191)
Plant growth regulators	Exogenous 24-epibrassinolide (24-EBL) application	-Improves antioxidant activity and heat stress tolerance in mustard	(192)
	Foliar application of 0.15 % ammonium molybdate	-Helps alleviate the effects of low-temperature stress	(151)
	Foliar application of gibberellin acid	-Helps mitigate cadmium's adverse effects on crops	(188)
Seed priming and treatment	Seed priming in rice and wheat	-Promotes early flowering (8–10 days) and maturity (9–10 days), reducing heat stress and maximizing yields	(193)
	Priming tomato seeds	-Improves osmotic adjustment, stomatal conductance and overall growth under heat stress	(19)
	Barley seed treatment with glycine-betaine	-Reduces membrane damage, improves photosynthesis and increases biomass under heat stress	(194)
	Priming with *Calpurnia aurea* leaf extract	-Mitigates free radicals and improves photosynthetic pigment levels under heat stress	(195)
Breeding and biotechnology	Use of microarray technology	-A valuable tool to analyze gene expression under heat stress, e.g. 262 % increase in transcript response in *Arabidopsis*	(196)
	Screening of wheat varieties	-Some genetically screened varieties exhibit lower cadmium absorption while maintaining high yield	(197)

crop fields to mitigate abiotic stresses are summarised in Table 11.

Conclusion

Abiotic stresses pose significant constraints to crop productivity and the evidence synthesized in the review highlights several actionable agronomic, technological and policy-oriented pathways to strengthen crop resilience. Agronomic interventions such as optimized fertilizer regimes, particularly the combined use of nitrogen and potassium, have been consistently shown to enhance yield stability under stress conditions. Similarly precision irrigation strategies, including deficit irrigation and improved water -use techniques, help mitigate drought-induced yield loss while improving resource efficiency. Integrating advanced seed priming methods, growth regulators and nutrient based treatments further strengthens plants' physiological tolerance to adverse environmental conditions.

Emerging technologies such as crop-suitability modelling, remote sensing tools and decision-support systems hold significant promises for forecasting climate risks, monitoring crop responses and guiding farmers toward more informed management decisions. The adoption of climate smart practices and early warning systems can play a transformative role in sustaining productivity under variable climates. In addition, developing crop and region-specific agronomic packages for stress prone areas, integrating remote sensing with on-farm data to refine real-time stress diagnostics, breeding and molecular studies focused on stress tolerant genotypes and long-term, multi-

Table 10. Key mechanisms, benefits, limitations and sustainability of crop stress-mitigating emerging technologies

Amendment	Mechanism	Advantages	Disadvantages / Limitations	Sustainability Implications	References
Biochar	It immobilizes heavy metals through sorption, complexation and precipitation, lowering their bioavailability. In the rhizosphere, biochar reduces bulk density, increases organic matter and shifts microbes (higher Proteobacteria/Acidobacteria ratio), strengthening root morphology and nitrogen metabolism. Under heat, this leads to higher nitrogen-assimilation and photosystem proteins and reduced heat-shock proteins. During drought and salinity, biochar boosts soil water and nutrient retention, maintains ionic balance by restricting Na^+ and enhancing K^+ and reduces ROS, MDA and H_2O_2, stabilizing membranes and lowering osmotic stress. Additionally, organic molecules from biochar leachates enter plants and interact with stress-related proteins; one molecule can mimic succinic acid and potentially activate cold-response pathways. Together, these layered mechanisms improve overall plant resilience.	- Enhances root/shoot growth (+23 % root, + 11 % shoot under salinity). - Improves nitrogen uptake and metabolism. - Reduces oxidative damage (MDA, H_2O_2) and stress markers. - Upregulates stress-responsive genes (OsDREB1A/B, OsMYB2, OsWRKY76, OsiSAP8, OsCOIN). - Improves soil properties and nutrient availability. - Increases heat and cold stress tolerance.	- Effectiveness varies with feedstock, pyrolysis, type and dose. - Potential toxic compounds or pH shifts. - Mostly pot-based studies; field scalability uncertain. - Low/high leachate concentrations may reduce effectiveness or cause soil/economic issues. - Mechanisms of many organic molecules unclear.	- Supports soil health and fertility. - Enhances crop resilience under stress. - Contributes to carbon sequestration. - Reduces chemical input needs. - Can act as functional additive for targeted stress tolerance.	(198- 203)
Kaolin (in Persian Walnut)	- Foliar kaolin forms a reflective particle film that increases leaf albedo, reducing heat load and leaf temperature. Reduces vapor pressure difference (VPD) by lowering leaf-to-air temperature gradient. It helps to maintain water status (RWC) under drought by reducing thermal stress.	Improves gas exchange (under some conditions) and photosyn-thetic performance. - Increases chlorophyll concentration. - Boosts leaf K content, improving ionic balance. - Enhances kernel / nut quality (e.g. better kernel color) under water stress. - Reduces sunburn and leaf damage under high temperature / light stress.	Shading effect: kaolin film can reduce the amount of PAR (photosyn-thetically active radiation), slightly lowering photosynthesis (A_{max}). - Effectiveness may depend on genotype: different walnut cultivars respond differently (sunburn, RWC). - Requires foliar application, which might be labour-intensive and weather-sensitive. - High kaolin concentration or repeated sprays may have economic / logistical constraints.	Cheap and relatively low-tech method to protect trees from heat and drought stress. - Can improve nut yield quality under water-limited conditions, potentially increasing farmer returns under stress. - By reducing leaf temperature and stress, may help walnut cultivation remain more resilient under climate change (warmer, drier summers). - Because kaolin is inert and mineral-based, environmental risk is relatively low compared to chemical mitigants.	(204)
Super Absorbents	SAPs are hydrophilic, cross-linked polymers that absorb large amounts of water via osmotic gradients and swelling of polymer chains. In soil, SAP acts as a water reservoir-stores excess water and releases it slowly under drying conditions. Also improves soil physical properties: increases porosity and water retention, decreases bulk density and moderates evaporation/ percolation.	- Enhances soil water-holding capacity and increases plant-available water. - Improves plant growth and yield under drought or limited irrigation. - Helps reduce irrigation frequency and improves water-use efficiency. - May reduce compaction and enhance soil structure.	- High cost may limit large-scale adoption. - Performance varies with polymer type, soil texture, rate and environmental conditions. - Long-term field durability and actual performance remain insufficiently studied. - Synthetic SAPs may persist in soil and potentially behave like microplastics.	- Offers potential for water-saving agriculture in arid/ semi-arid regions. - Can enhance crop resilience under drought and improve productivity. - Sustainability depends on biodegradable SAPs, lifecycle impacts and soil health. - Environmental risks exist if non-degradable SAPs accumulate over time.	(205, 206)

Seaweed extracts	Seaweed extracts (SWE) supply a mix of bioactive compounds-hormones, antioxidants, amino acids, minerals and polysaccharides-that enhance plant stress responses. When used as seed priming or foliar treatments, these compounds improve metabolic activity, activate antioxidant enzymes and boost ROS scavenging, protecting cells from oxidative damage. SWE also modulates water relations, enhancing stomatal conductance and leaf water content under drought, while increasing osmolytes like proline and soluble sugars to maintain osmotic balance. In heat-stressed seedlings, SWE reduces hydrogen peroxide and malondialdehyde accumulation, stabilizing membranes and supporting growth. Some extracts additionally regulate stress-responsive genes, contributing to systemic resilience and improved physiological performance under abiotic stresses.	Improves germination and seedling establishment under heat, drought and salinity stress. - Enhances biomass accumulation and growth parameters under water-limited or heat-stressed conditions. - Boosts antioxidant capacity, reducing oxidative damage (lower H_2O_2, MDA). - Modulates stress-related genes for systemic drought/heat tolerance. - Reduces canopy temperature and membrane injury, supporting physiological resilience.	Effects are species- and extract-specific; not all seaweeds or formulations give the same response. - Concentration-dependent; excessive or insufficient doses may be ineffective. - Most studies are pot/controlled-environment based; field-level efficacy may differ. - Batch-to-batch variation of commercial extracts may reduce reproducibility. - Cost and logistics may limit adoption in large-scale or resource-limited farming systems.	Natural bio-stimulant strategy that enhances crop resilience to abiotic stresses (heat, drought, salinity). - Improves water-use efficiency and seedling establishment under stress, reducing dependency on synthetic protectants. - Supports sustainable agriculture when properly sourced; environmental impact depends on seaweed harvesting and extract standardization. - Reduces crop losses, contributing to climate-resilient food production.	(207-211)
Yeast extracts	Yeast extract (YE) supplies amino acids, vitamins and growth regulators that are readily absorbed by leaves, enhancing metabolic activity and supporting plant growth under stress. Under salinity, YE helps maintain growth even when osmotic adjustments like proline or sugar accumulation are limited, indicating its role mainly via nutrient and regulatory support. When combined with glycine betaine (GB) under cold stress, YE activates antioxidant enzymes such as peroxidase and catalase, protecting cells from oxidative damage and stabilizing membranes, thereby improving overall stress tolerance.	- Enhances growth parameters (root length, shoot growth, leaf number, biomass) under salinity stress. - Improves seedling and vegetative growth under cold stress. - Increases antioxidant capacity, reducing oxidative damage. - Can improve crop yield and quality under mild to moderate stress.	- Effects are dose-dependent; optimal concentrations are needed for best results. - Foliar spray applications may be labor-intensive for large-scale production. - Under high salinity, osmoprotectant accumulation (proline, sugars) may remain low, indicating a limitation in strong osmotic adjustment. - Results may vary among species and cultivars; long-term effects not fully assessed.	- YE is a biobased, eco-friendly strategy that can reduce the need for chemical protectants. - When combined with glycinebetaine or SA, it offers multi-pathway stress mitigation (nutrient supply + osmotic/oxidative protection). - Supports sustainable crop production under salinity and cold stress conditions.	(212, 213)
Nanoparticles	Nanoparticles modulate antioxidant defences by activating enzymes like SOD, CAT and POD, which scavenge reactive oxygen species produced under drought, salinity, heat, or heavy-metal stress. Certain NPs, such as silicon-based or engineered nanocarriers, improve osmolyte accumulation (e.g., proline), maintain chlorophyll and carbohydrate levels, stabilize membranes and enhance water retention. Advanced NPs can also deliver stress-protective molecules or nutrients in a controlled, targeted manner, improving photosynthesis, water-use efficiency and overall plant resilience under abiotic stress.	- Boost plant tolerance to multiple abiotic stresses (drought, salinity, heat, heavy metals). - Improve growth, biomass, photosynthetic capacity and biochemical traits. - Enable efficient and targeted nutrient or bioactive molecule delivery. - Reduce oxidative damage via enhanced antioxidant defense.	- Potential toxicity and accumulation in plants, soil, or food chain. - Behavior varies depending on NP type, size, coating and application method. - High production and application costs; field-scale delivery is challenging. - Regulatory, safety and long-term ecological impacts not fully understood.	- Potential to reduce conventional agrochemical use via targeted and efficient delivery. - Can enhance crop resilience under climate stress. - Sustainability depends on safe, biodegradable, or biocompatible NP design and responsible application. - Requires careful monitoring to prevent environmental or food-chain contamination.	(214-216)

Table 11. Emerging technologies for the management of abiotic stress in crops

Technology	Management/Use	Effect/Outcome	Reference (s)
Biochar	Application in saline soils	-Improves WUE, nutrient uptake, enzymatic activity; reduces heavy metal presence via high cation exchange capacity.	(198, 199)
	1 % in barley under drought	-Improves root and shoot growth.	(198)
	5 % in wheat under heavy metal stress	-Increases growth and dry weight.	(199)
	40 g kg $^{-1}$ in rice under heat stress	-Enhances nitrogen uptake and root traits.	(200)
	5 % in maize under salinity	-Boosts proline content.	(201)
	2 % in wheat under salinity	-Improves root and shoot length.	(202)
	10 % in rice under cold stress	-Improves cold tolerance.	(203)
Kaolin	5 %–7.5 % in walnuts under drought	-Enhances chlorophyll content, gas exchange, kernel quality and lowers leaf temperature.	(204)
Super absorbents	Soil amendment with superabsorbent polymers (SAP) in soybeans under drought	-Enhances growth, biomass, leaf area and yield.	(205)
Seaweed extracts	In eucalyptus under multiple stresses	-Improves biomass by 9.17 % (salinity), 8.39 % (drought), 18.02 % (combined).	(206)
	3–5 mL L^{-1} in *Brassica juncea*	-Enhances growth, yield and temperature stress tolerance.	(207)
	Extracts from *Ulva fasciata, Cystoseira compressa, Laurencia obtusa* in cowpea and maize	-Aid salinity stress tolerance.	(208)
	Ascophyllum nodosum in soybean	-Supports growth during drought.	(209)
	Fucus spiralis, Ulva lactuca, Laminaria ochroleuca in fababean	-Enhance growth under drought.	(210)
	Ascophyllum nodosum in spinach	-Benefits heat tolerance.	(211)
	Inoculation in lettuce under high salinity (100–150 mM NaCl)	Improves growth, reduces proline, sugar and chlorophyll levels; helps salinity tolerance and nutrient improvement.	(212)
	Foliar extract in tomatoes under cold stress	Improves vegetative growth, yield, sugar, vitamin C and carotenoids.	(213)
	AMF (1 %) + yeast extract (2 %) in wheat under salinity	Boosts growth and yield.	(217)
Nanoparticles	Silicon (Si-NPs) and zinc oxide (ZnO-NPs)	Alleviate drought, salinity, chilling and heavy metal stress.	(214)
	Biogenic NPs in wheat	Increase antioxidant enzymes and reduce ROS under cold stress.	(215)
	TiO_2 NPs in soybeans	Reduce Cd toxicity and improve photosynthesis.	(216)

location field trials to validate technological and management recommendations under diverse conditions should also give high priority. Moreover, uncovering the coordinated regulation of plant responses to various stresses will need multidisciplinary actions in the future, as this is crucial for crop breeding and production.

Policy support is essential for scaling these innovations. Investments in extension services, climate information delivery, subsidies or incentives for stress mitigating technologies and strengthened seed systems can accelerate adoption at the farm level. Ensuring that farmers in vulnerable regions have access to stress tolerant varieties, timely weather advisories and training in modern agronomic practices will be crucial for climate resilient agriculture.

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Authors' contributions

FME, AKMAI and AKMMI developed the concept of this manuscript. FME, NNP and URAT carried out the literature review and wrote the initial draft. FA, AKMAI and AKMMI contributed initial feedback and revision. AKMAI and AKMMI finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Intergovernmental Panel on Climate Change (IPCC). Climate change 2014 synthesis report. Geneva: IPCC; 2014.
2. Mantri N, Patade V, Penna S, Ford R, Pang E. Abiotic stress responses in plants: present and future. In: Ahmad P, Prasad M, editors. Abiotic stress responses in plants. New York: Springer; 2012. p. 1-19.
3. Ibrahim W, Zhu YM, Chen Y, Qiu CW, Zhu S, Wu F. Genotypic differences in leaf secondary metabolism, plant hormones and yield under alone and combined stress of drought and salinity in cotton genotypes. Physiol Plant. 2019;165(2):343-55. https://doi.org/10.1111/ppl.12862
4. Shahid MA, Sarkhosh A, Khan N, Balal RM, Ali S, Rossi L, et al. Insights into the physiological and biochemical impacts of salt

stress on plant growth and development. Agronomy. 2020;10 (7):938. https://doi.org/10.3390/agronomy10070938

5. Razzaq A, Wani SH, Saleem F, Yu M, Zhou M, Shabala S. Rewilding crops for climate resilience: economic analysis and de novo domestication strategies. J Exp Bot. 2021;72(18):6123-39. https://doi.org/10.1093/jxb/erab276

6. Kopecká R, Kameniarová M, Černý M, Brzobohatý B, Novák J. Abiotic stress in crop production. Int J Mol Sci. 2023;24(7):6603. https://doi.org/10.3390/ijms24076603

7. Arbona V, Manzi M, de Ollas C, Gómez-Cadenas A. Metabolomics as a tool to investigate abiotic stress tolerance in plants. Int J Mol Sci. 2013;14:4885-911. https://doi.org/10.3390/ijms14034885

8. Salehi-Lisar SY, Bakhshayeshan-Agdam H. Drought stress in plants: causes, consequences and tolerance. In: Hossain M, Wani S, Bhattacharjee S, Burritt D, Tran LS, editors. Drought stress tolerance in plants. Cham: Springer; 2016. p. 1-16. https://doi.org/10.1007/978-3-319-28899-4_1

9. Li C, Jiang D, Wollenweber B, Li Y, Dai T, Cao W. Waterlogging pretreatment during vegetative growth improves tolerance to waterlogging after anthesis in wheat. Plant Sci. 2011;180:672-8. https://doi.org/10.1016/j.plantsci.2011.01.009

10. Visser EJW, Voesenek LACJ, Vartapetian BB, Jackson MB. Flooding and plant growth. Ann Bot. 2003;91(2):107-9. https://doi.org/10.1093/aob/mcg014

11. Sairam RK, Kumutha D, Ezhilmathi K, Deshmukh PS, Srivastava GC. Physiology and biochemistry of waterlogging tolerance in plants. Biol Plant. 2008;52(3):401-12. https://doi.org/10.1007/s10535-008-0084-6

12. Waters I, Kuiper PJC, Watkin E, Greenway H. Effects of anoxia on wheat seedlings I. Interaction between anoxia and other environmental factors. J Exp Bot. 1991;42(244):1427-35.

13. Pezeshki SR. Wetland plant responses to soil flooding. Environ Exp Bot. 2001;46:299-312. https://doi.org/10.1016/S0098-8472(01)00107-1

14. Food and Agriculture Organization (FAO). Status of the world's soil resources (SWSR): main report. Rome: FAO; 2015.

15. Gupta B, Huang B. Mechanism of salinity tolerance in plants: physiological, biochemical and molecular characterization. Int J Genomics. 2014;2014:701596. https://doi.org/10.1155/2014/701596

16. Turner NC, Kramer PJ, editors. Adaptation of plants to water and high temperature stress. New York: John Wiley & Sons; 1980.

17. Firmansyah, Argosubekti N. A review of heat stress signalling in plants. IOP Conf Ser Earth Environ Sci. 2020;484:012041. https://doi.org/10.1088/1755-1315/484/1/012041

18. Machado S, Paulsen GM. Combined effects of drought and high temperature on water relations of wheat and sorghum. Plant Soil. 2001;233:179-87. https://doi.org/10.1023/A:1010346601643

19. Morales D, Rodríguez P, Dell'Amico J, Nicolás E, Torrecillas A, Sánchez-Blanco MJ. High-temperature preconditioning and thermal shock imposition affects water relations, gas exchange and root hydraulic conductivity in tomato. Biol Plant. 2003;47:203-8. https://doi.org/10.1023/B:BIOP.0000022252.70836.fc

20. Wahid A, Gelani S, Ashraf M, Foolad MR. Heat tolerance in plants: an overview. Environ Exp Bot. 2007;61:199-223. https://doi.org/10.1016/j.envexpbot.2007.05.011

21. Gates DM. Transpiration and leaf temperature. Annu Rev Plant Physiol. 1968;19:211-38. https://doi.org/10.1146/annurev.pp.19.060168.001235

22. Paupière MJ, Van Heusden AW, Bovy AG. The metabolic basis of pollen thermotolerance: perspectives for breeding. Metabolites. 2014;4(4):889-920. https://doi.org/10.3390/metabo4040889

23. Sun X, Zhu Z, Zhang L, Fang L, Zhang J, Wang Q, et al. Overexpression of ethylene response factors VaERF080 and VaERF087 from *Vitis amurensis* enhances cold tolerance in *Arabidopsis*. Sci Hortic. 2019;243:320-6. https://doi.org/10.1016/j.scienta.2018.08.055

24. Krasensky J, Jonak C. Drought, salt and temperature stress-induced metabolic rearrangements and regulatory networks. J Exp Bot. 2012;63(4):1593-608. https://doi.org/10.1093/jxb/err460

25. Pandolfini T, Gabbrielli R, Comparini C. Nickel toxicity and peroxidase activity in seedlings of *Triticum aestivum* L. Plant Cell Environ. 1992;15(6):719-25. https://doi.org/10.1111/j.1365-3040.1992.tb01014.x

26. Sarkar S, Khatun M, Era FM, Islam AK, Anwar M, Danish S, et al. Abiotic stresses: alteration of composition and grain quality in food legumes. Agronomy. 2021;11(11):2238. https://doi.org/10.3390/agronomy11112238

27. Ennos AR. Wind as an ecological factor. Trends Ecol Evol. 1997;12 (3):108-11. https://doi.org/10.1016/S0169-5347(96)10066-5

28. Anten NP, Alcalá-Herrera R, Schieving F, Onoda Y. Wind and mechanical stimuli differentially affect leaf traits in *Plantago major*. New Phytol. 2010;188(2):554-64. https://doi.org/10.1111/j.1469-8137.2010.03379.x

29. Jaffe MJ, Forbes S. Thigmomorphogenesis: the effect of mechanical perturbation on plants. Plant Mol Biol. 1993;12(3):313-24. https://doi.org/10.1007/BF00027213

30. Arnon DJ. Trace elements in plant physiology. In: Wallace T, editor. Chronica Botanica. Waltham (MA); 1954.

31. Xu G, Magen H, Tarchitzky J, Kafkafi U. Advances in chloride nutrition of plants. Adv Agron. 1999;68:97-110. https://doi.org/10.1016/S0065-2113(08)60844-5

32. Ainsworth EA, Rogers A. The response of photosynthesis and stomatal conductance to rising CO_2: mechanisms and environmental interactions. Plant Cell Environ. 2007;30(3):258-70. https://doi.org/10.1111/j.1365-3040.2007.01641.x

33. Takagi D, Inoue H, Odawara M, Shimakawa G, Miyake C. The Calvin cycle inevitably produces sugar-derived reactive carbonyl methylglyoxal during photosynthesis. Plant Cell Physiol. 2014;55 (2):333-40. https://doi.org/10.1093/pcp/pcu007

34. Lutze J, Roden J, Holly C, Wolfe J, Egerton J, Ball M. Elevated atmospheric CO_2 promotes frost damage in evergreen tree seedlings. Plant Cell Environ. 2002;21(6):631-5. https://doi.org/10.1046/j.1365-3040.1998.00296.x

35. Taiz L, Zeiger E. Plant physiology. 4th ed. Sunderland (MA): Sinauer Associates; 2006.

36. Hussain M, Malik MA, Farooq M, Ashraf MY, Cheema MA. Improving drought tolerance by exogenous application of glycinebetaine and salicylic acid in sunflower. J Agron Crop Sci. 2008;194(3):193-9. https://doi.org/10.1111/j.1439-037X.2008.00305.x

37. Thitisaksakul M, Jiménez RC, Arias MC, Beckles DM. Effects of environmental factors on cereal starch biosynthesis and composition. J Cereal Sci. 2012;56(1):67-80. https://doi.org/10.1016/j.jcs.2012.04.002

38. Ali Q, Anwar F, Ashraf M, Saari N, Perveen R. Ameliorating effects of exogenously applied proline on seed composition, oil quality and antioxidant activity of maize under drought stress. Int J Mol Sci. 2013;14(1):818-35. https://doi.org/10.3390/ijms14010818

39. Ballmer T, Hebeisen T, Wüthrich R, Gut F. Potential for drip irrigation in potato production under changing climatic conditions. Agrarforschung Schweiz. 2012;3(5):244-51.

40. Ahmad P, Jamsheed S, Hameed A, Rasool S, Sharma I, Azooz MM, Hasanuzzaman M. Drought stress-induced oxidative damage and antioxidants in plants. In: Ahmad P, editor. Oxidative damage to plants: antioxidant networks and signaling. Waltham (MA): Academic Press; 2014. p. 345-67. https://doi.org/10.1016/B978-0-12-799963-0.00011-3

41. Garg BK. Nutrient uptake and management under drought: nutrient

-moisture interaction. Curr Agric. 2003;27:1-8.

42. McWilliams D. Drought strategies for cotton. Cooperative Extension Service Circular 582. New Mexico State University; 2003.

43. Lindhauer MG. Influence of K nutrition and drought on water relations and growth of sunflower (*Helianthus annuus* L.). Z Pflanzenernahr Bodenk. 1985;148(6):654-69. https://doi.org/10.1002/jpln.19851480608

44. Food and Agriculture Organization (FAO). The impact of disasters and crises on agriculture and food security. Rome: FAO; 2017. p.168.

45. Voesenek LACJ, Jackson MB, Toebes AHW, Vriezen WH, Colmer TD. Desubmergence-induced ethylene production in *Rumex palustris*: regulation and ecophysiological significance. Plant J. 2003;33(2):341-52. https://doi.org/10.1046/j.1365-313x.2003.01632.x

46. Shabala S, editor. Plant stress physiology. Wallingford: CABI; 2017.

47. Fukao T, Yeung E, Bailey-Serres J. The submergence tolerance regulator SUB1A mediates crosstalk between submergence and drought tolerance in rice. Plant Cell. 2011;23(1):412-27. https://doi.org/10.1105/tpc.110.080325

48. Chen Y, Song J, Yan C, Hong X. Effects of submergence stress at the vegetative growth stage on hybrid rice growth and grain yield in China. Chil J Agric Res. 2021;81(2):191-201. https://doi.org/10.4067/S0718-58392021000200191

49. Roy SJ, Negrão S, Tester M. Salt resistant crop plants. Curr Opin Biotechnol. 2014;26:115-24. https://doi.org/10.1016/j.copbio.2013.12.004

50. López-Berenguer C, García-Viguera C, Carvajal M. Are root hydraulic conductivity responses to salinity controlled by aquaporins in broccoli plants? Plant Soil. 2006;279(1):13-23. https://doi.org/10.1007/s11104-005-7010-x

51. Alvino A, D'Andria R, Delfine S, Lavini A, Zanetti P. Effect of water and salinity stress on radiation absorption and efficiency in sunflower. Ital J Agron. 2000;4(2):53-60.

52. Marcelis LFM, Van Hooijdonk J. Effect of salinity on growth, water use and nutrient use in radish (*Raphanus sativus* L.). Plant Soil. 1999;215:57-64. https://doi.org/10.1023/A:1004742713538

53. Machado RMA, Serralheiro RP. Soil salinity: effect on vegetable crop growth and management practices to prevent and mitigate soil salinization. Horticulturae. 2017;3(2):30. https://doi.org/10.3390/horticulturae3020030

54. Hussain S, Bai Z, Huang J, Cao X, Zhu L, Zhu C, et al. 1-Methylcyclopropene modulates physiological, biochemical and antioxidant responses of rice to different salt stress levels. Front Plant Sci. 2019;10:124. https://doi.org/10.3389/fpls.2019.00124

55. Muhammad S, Ditta A, Iqbal MS, Hussain SB, Khan MI, Ramzan M, et al. Effect of salinity stress on cotton growth and role of marker-assisted breeding and agronomic practices for salinity tolerance. Scholars Rep. 2018;4(1):1-13.

56. Xu Y, Zhang L, Ou S, Wang R, Wang Y, Chu C, Yao S. Natural variations of SLG1 confer high-temperature tolerance in indica rice. Nat Commun. 2020;11(1):5441. https://doi.org/10.1038/s41467-020-19320-9

57. Soda N, Gupta BK, Anwar K, Sharan A, Singla-Pareek SL, Pareek A. Rice intermediate filament OsIF stabilizes photosynthetic machinery and yield under salinity and heat stress. Sci Rep. 2018;8(1):4072. https://doi.org/10.1038/s41598-018-22131-0

58. Zhang G, Lian C, Yun L, Zhang S, Tang Z, Zheng H, et al. Effects of high temperature stress on microscopic and ultrastructural characteristics of mesophyll cells in flag leaves of rice. Rice Sci. 2009;16(1):65-71. https://doi.org/10.1016/S1672-6308(08)60058-X

59. Hurkman WJ, McCue KF, Altenbach SB, Korn A, Tanaka CK, Kothari KM, et al. Effect of temperature on expression of genes encoding enzymes for starch biosynthesis in developing wheat endosperm. Plant Sci. 2003;164(5):873-81. https://doi.org/10.1016/S0168-9452(03)00076-1

60. Wallwork MAB, Jenner CF, Logue SJ, Sedgley M. Effect of high temperature during grain filling on the structure of developing and malted barley grains. Ann Bot. 1998;82:587-99. https://doi.org/10.1006/anbo.1998.0721

61. Thomas JM, Boote KJ, Allen LH, Gallo-Meagher M, Davis JM. Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance. Crop Sci. 2003;43(4):1548-57. https://doi.org/10.2135/cropsci2003.1548

62. Sehgal A, Sita K, Siddique KHM, Kumar R, Bhogireddy S, Varshney RK, et al. Drought and heat stress effects on seed filling in food crops. Front Plant Sci. 2018;9:1705. https://doi.org/10.3389/fpls.2018.01705

63. Sita K, Sehgal A, Bhandari K, Kumar J, Kumar S, Singh S, et al. Impact of heat stress during seed filling on seed quality and yield in lentil (*Lens culinaris* Medikus). J Sci Food Agric. 2018;98(13):5134-41. https://doi.org/10.1002/jsfa.9054

64. Canvin DT. Effect of temperature on oil content and fatty acid composition of oils from several oilseed crops. Can J Bot. 1965;43:63-9. https://doi.org/10.1139/b65-008

65. Harris HC, McWilliam JR, Mason WK. Influence of temperature on oil content and composition of sunflower seed. Aust J Agric Res. 1978;29(6):1203-12. https://doi.org/10.1071/AR9781203

66. Chaturvedi AK, Bahuguna RN, Pal M, Shah D, Maurya S, Jagadish KS. Elevated CO_2 and heat stress interactions affect grain yield, quality and mineral nutrient composition in rice. Field Crops Res. 2017;206:149-57. https://doi.org/10.1016/J.FCR.2017.02.018

67. Yan H, Wang C, Liu K, Tian X. Heat stress reduces grain weight and quality in rice and effects are aggravated by low relative humidity. PeerJ. 2021;9:e11218. https://doi.org/10.7717/peerj.11218

68. Labuschagne MT, Elago O, Koen E. Influence of temperature extremes on quality and starch characteristics in bread, biscuit and durum wheat. J Cereal Sci. 2009;49:184-9. https://doi.org/10.1016/j.jcs.2008.09.001

69. Balla K, Rakszegi M, Li Z, Bekes F, Bencze S, Veisz O. Quality of winter wheat in relation to heat and drought shock after anthesis. Czech J Food Sci. 2011;29(2):117-28. https://doi.org/10.17221/227/2010-CJFS

70. Sun J, Zheng T, Yu J, Wu T, Wang X, Chen G, et al. TSV protects rice chloroplasts from cold stress by interacting with plastidic thioredoxin Z. New Phytol. 2017;215(1):240-55. https://doi.org/10.1111/nph.14482

71. Rood SB, Major DJ, Jones MD, Pharis RP. Low temperature eliminates heterosis for growth and gibberellin content in maize. Crop Sci. 1985;25(6):1063-8. https://doi.org/10.2135/cropsci1985.0011183X002500060040x

72. Laine P, Bigot J, Ourry A, Boucaud J. Effects of low temperature on nitrate uptake and nitrogen transport in *Secale cereale* L. and *Brassica napus* L. New Phytol. 1994;127(4):675-83. https://doi.org/10.1111/j.1469-8137.1994.tb02970.x

73. Serrano M, Robertson AE. Effect of cold stress on damping-off of soybean caused by *Pythium sylvaticum*. Plant Dis. 2018;102(11):2194-200. https://doi.org/10.1094/PDIS-12-17-1963-RE

74. Hu CM, Hou XL, Wang M. Effects of low temperature on photosynthetic and fluorescence parameters of non-heading Chinese cabbage. Acta Bot Boreali-Occident Sin. 2008;28:2478-84.

75. Kazemi-Shahandashti SS, Maali-Amiri R. Global insights into protein responses to cold stress in plants. J Plant Physiol. 2018;226:123-35. https://doi.org/10.1016/j.jplph.2018.03.022

76. Li Y, Ren K, Hu M, He X, Gu K, Hu B, et al. Cold stress during harvest affects tobacco leaf quality and curing characteristics. BMC Plant Biol. 2021;21(1):131. https://doi.org/10.1186/s12870-021-02895-w

77. Cary JW. Frost damage in seedlings. Crops Soils. 1975;27(1):16-8.

78. Farooq M, Aziz T, Wahid A, Lee DJ, Siddique KHM. Chilling tolerance in maize: agronomic and physiological approaches. Crop Pasture

Sci. 2009;60(6):501-16. https://doi.org/10.1071/CP08427

79. Kumar M. Crop plants and abiotic stresses. J Biomol Res Ther. 2013;3(1). https://doi.org/10.4172/2167-7956.1000e125

80. Abedin MJ, Cotter-Howells J, Meharg AA. Arsenic uptake and accumulation in rice irrigated with contaminated water. Plant Soil. 2002;240(2):311-19. https://doi.org/10.1023/A:1015792723288

81. Cox MS, Bell PF, Kovar JL. Differential tolerance of canola to arsenic when grown hydroponically or in soil. J Plant Nutr. 1996;19(12):1599-610. https://doi.org/10.1080/01904169609365224

82. Yourtchi MS, Bayat HR. Cadmium toxicity effects on growth and nutrient content of durum wheat. Int J Agric Crop Sci. 2013;6(15):1099-103.

83. Jayakumar K, Rajesh M, Baskaran L, Vijayarengan P. Changes in nutritional metabolism of tomato exposed to cobalt chloride. Int J Food Nutr Saf. 2013;4(2):62-9.

84. Jayakumar K, Jaleel CA, Azooz MM. Phytochemical changes in green gram under cobalt stress. Glob J Mol Sci. 2008;3(2):46-9.

85. Nematshahi N, Lahouti M, Ganjeali A. Chromium accumulation and growth response of onion (*Allium cepa*). Eur J Exp Biol. 2012;2(4):969-74.

86. Asrar Z, Khavari-Nejad RA, Heidari H. Excess manganese effects on pigments of *Mentha spicata*. Arch Agron Soil Sci. 2005;51(1):101-7. https://doi.org/10.1080/03650340400026602

87. Doncheva S, Georgieva K, Vassileva V, Stoyanova Z, Popov N, Ignatov G. Effects of succinate on manganese toxicity in pea plants. J Plant Nutr. 2005;28(1):47-62. https://doi.org/10.1081/PLN-200042161

88. Shenker M, Plessner OE, Tel-Or E. Manganese nutrition effects on tomato growth and antioxidant activity. J Plant Physiol. 2004;161(2):197-202. https://doi.org/10.1078/0176-1617-00931

89. Hussain A, Abbas N, Arshad F, Akram M, Khan ZI, Ahmad K, et al. Effects of lead on growth attributes of maize. Agric Sci. 2013;4(5):262-5. https://doi.org/10.4236/as.2013.45037

90. Manivasagaperumal R, Balamurugan S, Thiyagarajan G, Sekar J. Effect of zinc on germination and seedling growth of cluster bean. Curr Bot. 2011;2(5):11-15.

91. Doncheva S, Stoynova Z, Velikova V. Influence of succinate on zinc toxicity in pea plants. J Plant Nutr. 2001;24(6):789-804. https://doi.org/10.1081/PLN-100103774

92. Kabata-Pendias A. Trace elements in soils and plants. 3rd ed. Boca Raton (FL): CRC Press; 2001. https://doi.org/10.1201/9781420039900

93. Armbrust DV. Physiological responses to wind and sandblast damage in grain sorghum. Agron J. 1982;74(1):133-5. https://doi.org/10.2134/agronj1982.00021962007400010034x

94. MacKerron DKL. Wind damage to the surface of strawberry leaves. Ann Bot. 1976;40(2):351-4. https://doi.org/10.1093/oxfordjournals.aob.a085137

95. Feng J, Huang P, Wan X. Interactive effects of wind and light on growth and architecture of poplar saplings. Ecol Res. 2019;34:94-105. https://doi.org/10.1111/1440-1703.1013

96. Xiong FS, Day TA. Effects of solar UV-B radiation on photosynthesis and biomass of Antarctic vascular plants. Plant Physiol. 2001;125(2):738-51. https://doi.org/10.1104/pp.125.2.738

97. Lal N. Effects of acid rain on plant growth and development. E-J Sci Technol. 2016;11(5):85-101.

98. Zhang H, Jennings A, Barlow PW, Forde BG. Dual pathways for regulation of root branching by nitrate. Proc Natl Acad Sci USA. 1999;96(11):6529-34. https://doi.org/10.1073/pnas.96.11.6529

99. Reddy KJ. Nutrient stress. In: Physiology and molecular biology of stress tolerance in plants. Dordrecht: Springer; 2006. p.187-217. https://doi.org/10.1007/1-4020-4225-6_7

100. Fredeen AL, Rao IM, Terry N. Influence of phosphorus nutrition on growth and carbon partitioning in soybean. Plant Physiol. 1989;89(1):225-30. https://doi.org/10.1104/pp.89.1.225

101. Barry DAJ, Miller MH. Phosphorus nutritional requirement of maize seedlings for maximum yield. Agron J. 1989;81:95–9. https://doi.org/10.2134/agronj1989.00021962008100010017x

102. Toyota K, Koizumi N, Sato F. Transcriptional activation of phosphoenolpyruvate carboxylase by phosphorus deficiency in tobacco. J Exp Bot. 2003;54:961–9. https://doi.org/10.1093/jxb/erg095

103. Lindhauer MG. Influence of K nutrition and drought on water relations and growth of sunflower (*Helianthus annuus* L.). Z Pflanzenernahr Bodenk. 1985;148:654–69. https://doi.org/10.1002/jpln.19851480608

104. Willenbrink J. On the relationships between protein turnover and sulfur supply of chloroplasts. J Plant Physiol. 1967;56:427–38.

105. Baszynski T, Warcholowa M, Krupa Z, Tukendorf A, Krol M, Wolinska D. Effect of magnesium deficiency on photochemical activities of rape and buckwheat chloroplasts. J Plant Physiol. 1980;99:295–303. https://doi.org/10.1016/S0044-328X(80)80143-7

106. Sharma S, Sanwal GG. Effect of iron deficiency on the photosynthetic system of maize. J Plant Physiol. 1992;140:527–30. https://doi.org/10.1016/S0176-1617(11)80782-0

107. Dave IC, Kannan S. Boron deficiency and its associated enhancement of RNase activity in bean plants. J Plant Physiol. 1980;97:261–3. https://doi.org/10.1016/S0044-328X(80)80078-X

108. Robertson GA, Loughman BC. Reversible effects of boron on the absorption and incorporation of phosphate in *Vicia faba* L. New Phytol. 1974;73:291–8. https://doi.org/10.1111/j.1469-8137.1974.tb04762.x

109. Cakmak I, Marschner H. Magnesium deficiency and high light intensity enhance antioxidant enzyme activities in bean leaves. Plant Physiol. 1992;98:1222–7. https://doi.org/10.1104/pp.98.4.1222

110. Li J, Fan H, Song Q, Jing L, Yu H, Li R, et al. Physiological and molecular bases of the boron deficiency response in tomato. Hortic Res. 2023;10:uhad229. https://doi.org/10.1093/hr/uhad229

111. Dong J, Gruda N, Lam SK, Li X, Duan Z. Effects of elevated CO_2 on nutritional quality of vegetables. Front Plant Sci. 2018;9:924. https://doi.org/10.3389/fpls.2018.00924

112. Broberg M, Högy P, Pleijel H. CO_2-induced changes in wheat grain composition. Agronomy. 2017;7:32. https://doi.org/10.3390/agronomy7020032

113. Taub DR, Wang XZ. Why are nitrogen concentrations lower under elevated CO_2? J Integr Plant Biol. 2008;50:1365–74. https://doi.org/10.1111/j.1744-7909.2008.00754.x

114. Bloom AJ, Burger M, Asensio JSR, Cousins AB. Carbon dioxide enrichment inhibits nitrate assimilation in wheat and *Arabidopsis*. Science. 2010;328:899–903. https://doi.org/10.1126/science.1186440

115. Högy P, Fangmeier A. Atmospheric CO_2 enrichment affects potato tuber quality. Eur J Agron. 2009;30:85–94. https://doi.org/10.1016/j.eja.2008.07.006

116. Piñero MC, Pérez-Jiménez M, López-Marín J, del Amor FM. Fruit quality of sweet pepper under saline irrigation and foliar calcium application. J Sci Food Agric. 2018;98:1071–8. https://doi.org/10.1002/jsfa.8557

117. Myers SS, Zanobetti A, Kloog I, Huybers P, Leakey ADB, Bloom AJ, et al. Increasing CO_2 threatens human nutrition. Nature. 2014;510:139–42. https://doi.org/10.1038/nature13179

118. Högy P, Fangmeier A. Effects of elevated atmospheric CO_2 on wheat grain quality. J Cereal Sci. 2008;48:580–91. https://doi.org/10.1016/j.jcs.2008.01.006

119. Hussain S, Hussain S, Qadir T, Khaliq A, Ashraf U, Parveen A, et al. Drought stress in plants: implications and mitigation strategies.

Plant Sci Today. 2019;6:389–402. https://doi.org/10.14719/pst.2019.6.4.578

120. Kumar A, Bernier J, Verulkar S, Lafitte HR, Atlin GN. Breeding for drought tolerance in rice. Field Crops Res. 2008;107:221–31. https://doi.org/10.1016/j.fcr.2008.02.007

121. Ahmad A, Aslam Z, Javed T, Hussain S, Raza A, Shabbir R, et al. Screening wheat genotypes for drought tolerance. Agronomy. 2022;12:287. https://doi.org/10.3390/agronomy12020287

122. Dietz KJ, Zörb C, Geilfus CM. Drought and crop yield. Plant Biol. 2021;23:881–93. https://doi.org/10.1111/plb.13304

123. Tian L, Zhang Y, Chen P, Zhang F, Li J, Yan F, et al. Effects of waterlogging regime on crop yield: a meta-analysis. Front Plant Sci. 2021;12:634898. https://doi.org/10.3389/fpls.2021.634898

124. Zhen B, Zhou X, Lu H, Li H. Effects of waterlogging on rice growth at jointing–booting stage. Water. 2024;16:1981. https://doi.org/10.3390/w16141981

125. Rhine MD, Stevens G, Shannon G, Wrather A, Sleper D. Yield and nutritional responses of soybean to waterlogging. Irrig Sci. 2010;28:135–42. https://doi.org/10.3390/w16141981

126. Jović Z, Broćić Z, Velimirović A, Dolijanović Ž, Komnenić A. Influence of flooding on potato productivity. Acta Hortic. 2021;1320:133–8. https://doi.org/10.17660/ActaHortic.2021.1320.17

127. Li Y, Guan K, Schnitkey GD, DeLucia E, Peng B. Excessive rainfall and maize yield loss in the USA. Glob Chang Biol. 2019;25:2325–37. https://doi.org/10.1111/gcb.14628

128. Atta K, Mondal S, Gorai S, Singh AP, Kumari A, Ghosh T, et al. Salinity stress impacts and tolerance mechanisms in crops. Front Plant Sci. 2023;14:1241736. https://doi.org/10.3389/fpls.2023.1241736

129. Khan MA, Asaf S, Khan AL, Ullah I, Ali S, Kang SM, et al. Endophytic bacteria alleviate salt stress in soybean. Ann Microbiol. 2019;69:797–808. https://doi.org/10.1007/s13213-019-01470-x

130. Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, et al. Temperature increase reduces global crop yields. Proc Natl Acad Sci U S A. 2017;114:9326–31. https://doi.org/10.1073/pnas.1701762114

131. Modarresi M, Mohammadi V, Zali A, Mardi M. Response of wheat yield to high temperature. Cereal Res Commun. 2010;38:23–31. https://doi.org/10.1556/CRC.38.2010.1.3

132. Aghamolki MTK, Yusop MK, Oad FC, Zakikhani H, Jaafar HZ, Musa MH. Heat stress effects on rice yield. J Food Agric Environ. 2014;12:741–6.

133. Li T, Zhang X, Liu Q, Liu J, Chen Y, Sui P. Yield penalty of maize under heat stress. J Integr Agric. 2022;21:2465–76. https://doi.org/10.1016/j.jia.2022.07.013

134. Yang L, Song W, Xu C, Sapey E, Jiang D, Wu C. Effects of high night temperature on soybean yield. Front Plant Sci. 2023;14:1065604. https://doi.org/10.3389/fpls.2023.1065604

135. Hu XY, Zhang ZG, Dai YJ, Qian ZY, Chen BL, Wang YH. Effect of increased temperature on cotton fiber yield and quality. Yingyong Shengtai Xuebao. 2013;24:3501–7.

136. Rykaczewska K. Effect of high temperature on potato yield and tuber defects. Am J Potato Res. 2015;92:339–49. https://doi.org/10.1007/s12230-015-9436-x

137. Ji H, Xiao L, Xia Y, Song H, Liu B, Tang L, et al. Effects of low temperature stress on wheat yield. Agric For Meteorol. 2017;243:33–42. https://doi.org/10.1016/j.agrformet.2017.04.016

138. Žydelis R, Weihermüller L, Herbst M, Klosterhalfen A, Lazauskas S. Effects of water and cold stress on maize development. Agric For Meteorol. 2018;263:169–79. https://doi.org/10.1016/j.agrformet.2018.08.011

139. Unan R, Genctan T, Pedroso RM. Cold stress reduces rice grain yield. Rev Bras Eng Agric Ambient. 2022;26:947–52. https://doi.org/10.1590/1807-1929/agriambi.v26n12p947-952

140. Staniak M, Czopek K, Stępień-Warda A, Kocira A, Przybyś M. Cold stress alters soybean yield and seed quality. Agronomy. 2021;11:2059. https://doi.org/10.3390/agronomy11102059

141. Zhao Y, Zhu Y, Feng S, Zhao T, Wang L, Zheng Z, et al. Impact of temperature on cotton yield in Xinjiang. NPJ Sustain Agric. 2024;2:43. https://doi.org/10.1038/s44264-024-00043-z

142. Chang DC, Sohn HB, Cho JH, Im JS, Jin YI, Do GR, et al. Freezing and frost damage of potato plants. Potato Res. 2014;57:99–110. https://doi.org/10.1007/s11540-014-9253-5

143. Singh S, Aggarwal PK. Effect of heavy metals on crop biomass and yield. Indian J Agric Sci. 2006;76:688–91.

144. Arif N, Sharma NC, Yadav V, Ramawat N, Dubey NK, Tripathi DK, et al. Heavy metal stress in rice crops. J Plant Biol. 2019;62:239–53. https://doi.org/10.1007/s12374-019-0112-4

145. Vasilachi IC, Stoleru V, Gavrilescu M. Heavy metal impacts on cereal crop development. Agriculture. 2023;13:1983. https://doi.org/10.3390/agriculture13101983

146. Tyagi V, Nagargade M, Singh RK. Agronomic interventions for drought management. In: Rakshit A, Singh HB, Singh AK, Singh US, Fraceto L, editors. New frontiers in stress management for durable agriculture. Singapore: Springer; 2020. p. 461–76. https://doi.org/10.1007/978-981-15-1322-0_24

147. Shao Y, Xie Y, Wang C, Yue J, Yao Y, Li X, et al. Soil conservation tillage effects on wheat–maize systems. Eur J Agron. 2016;81:37–45. https://doi.org/10.1016/j.eja.2016.08.014

148. Bhan S, Behera UK. Conservation agriculture in India. Int Soil Water Conserv Res. 2014;2:1–12. https://doi.org/10.1016/S2095-6339(15)30053-8

149. Triplett GB Jr, Dick WA. No-tillage crop production. Agron J. 2008;100:S153–65. https://doi.org/10.2134/agronj2007.0005c

150. Teame G, Tsegay A, Abrha B. Effect of organic mulching on sesame yield. Int J Agron. 2017;2017:4767509. https://doi.org/10.1155/2017/4767509

151. Mandal TK, Maitra S, Goswami S, Das P. Impact of abiotic stress on crops. In: Sairam M, Santosh DT, Gaikwad DJ, Maitra S, editors. Advances in modern agricultural practices. New Delhi: New Delhi Publishers; 2024. p. 83.

152. Singh A, Singh D, Kang J, Aggarwal N. Management practices to mitigate heat stress in wheat. IIOAB J. 2011;2:11–22.

153. Ding Z, Kheir AMS, Ali OAM, Hafez EM, ElShamey EA, Zhou Z, et al. Vermicompost and deep tillage improve saline soils. J Environ Manage. 2021;277:111388. https://doi.org/10.1016/j.jenvman.2020.111388

154. Rehman A, Farooq M, Ozturk L, Asif M, Siddique KHM. Zinc nutrition in wheat-based systems. Plant Soil. 2018;422:283–315. https://doi.org/10.1007/s11104-017-3507-3

155. Abedi T, Gavanji S, Mojiri A. Lead and zinc uptake and toxicity in maize. Plants. 2022;11:1922. https://doi.org/10.3390/plants11151922

156. Wallander S, Aillery M, Hellerstein D, Hand M. Role of conservation programs in drought adaptation. Econ Res Serv ERR. 2013;148.

157. Ramakrishna A, Tam HM, Wani SP, Long TD. Effect of mulch on groundnut yield. Field Crops Res. 2006;95:115–25. https://doi.org/10.1016/j.fcr.2005.01.030

158. Bobojonov I, Lamers JPA, Bekchanov M, Djanibekov N, Franz-Vasdeki J, Ruzimov J, et al. Crop diversification in Uzbekistan. Agroecol Sustain Food Syst. 2013;37:788–811. https://doi.org/10.1080/21683565.2013.775539

159. Swapna S, Shylaraj KS. Osmotic stress responses in rice varieties. Rice Sci. 2017;24:253–63. https://doi.org/10.1016/j.rsci.2017.04.004

160. Zhang C, Shi S, Liu Z, Yang F, Yin G. Drought tolerance mechanisms in alfalfa. J Plant Physiol. 2019;232:226–40. https://doi.org/10.1016/j.jplph.2018.10.023

161. Wang B, Wang G, van Dam J, Yang X, Ritsema C, Siddique KHM, et al. Crop rotation improves soil moisture and yield. Agric Water Manag. 2024;294:108721. https://doi.org/10.1016/j.agwat.2024.108721

162. Hassan MU, Chattha MU, Khan I, Chattha MB, Barbanti L, Aamer M, et al. Heat stress in cultivated plants. Plant Biosyst. 2021;155:211–34. https://doi.org/10.1080/11263504.2020.1727987

163. Oyebamiji Y, Adigun B, Aziz N, Asmuni MI, Ahmad Malike F, Lateef A. Advancements in mitigating abiotic stresses in crops. Horticulturae. 2024;10:156. https://doi.org/10.3390/horticulturae10020156

164. Adhikari L, Baral R, Paudel D, Min D, Makaju SO, Poudel HP, et al. Cold stress tolerance strategies in forage crops. Plant Stress. 2022;4:100081. https://doi.org/10.1016/j.stress.2022.100081

165. Hussain I, Afzal S, Ashraf M, Rasheed R, Saleem MH, Alatawi A, et al. Effects of metals on wheat growth and remediation. J Plant Growth Regul. 2022;42:2258–82. https://doi.org/10.1007/s00344-022-10700-7

166. Burges A, Alkorta I, Epelde L, Garbisu C. From phytoremediation of soil contaminants to phytomanagement of ecosystem services in metal-contaminated sites. Int J Phytoremediation. 2018;20(4):384-94. https://doi.org/10.1080/15226514.2017.1365340

167. Dhanwal P, Kumar A, Dudeja S, Chhokar V, Beniwal V. Recent advances in phytoremediation technology. In: Kumar R, Sharma AK, Ahluwalia SS, editors. Advances in environmental biotechnology. Singapore: Springer; 2017. p. 227-41. https://doi.org/10.1007/978-981-10-4041-2_14

168. Fageria NK, Stone LF, Santos ABD. Breeding for salinity tolerance. In: Fritsche-Neto R, Borém A, editors. Plant breeding for abiotic stress tolerance. Berlin: Springer; 2012. p. 103-22. https://doi.org/10.1007/978-3-642-30553-5_7

169. Thorve SB, Upadhye SK, Surve SP, Kadam JR. Impact of life-saving irrigation on yield of *Rabi* sorghum (*Sorghum bicolor* L.). Int J Agric Sci. 2009;5(1):53-4.

170. Ramamurthy V, Patil NG, Venugopalan MV, Challa O. Effect of drip irrigation on productivity and water-use efficiency of hybrid cotton (*Gossypium hirsutum*). Indian J Agric Sci. 2009;79(2):118-21.

171. Muniyappa M. Influence of depth and interval of drip irrigation on yield, water-use efficiency and economics of chickpea (*Cicer arietinum* L.). Int J Pure Appl Biosci. 2017;5:771-6. https://doi.org/10.18782/2320-7051.2504

172. Dring C, Devlin J, Boag G, Sunohara M, Fitzgibbon J, Topp E, et al. Incentives and disincentives influencing adoption of controlled tile drainage in eastern Ontario, Canada. Water Qual Res J Can. 2016;51(1):1-12. https://doi.org/10.2166/wqrjc.2015.047

173. Choudhury PN, Kumar V. Sensitivity of growth and yield of dwarf wheat to water stress at three growth stages. Irrig Sci. 1980;1(4):223-31. https://doi.org/10.1007/BF00277627

174. Li SX, Wang ZH, Malhi SS, Li SQ, Gao YJ, Tian XH. Nutrient and water management effects on crop production in dryland China. In: Advances in agronomy. Vol 102. San Diego: Academic Press; 2009. p. 223-65. https://doi.org/10.1016/S0065-2113(09)01007-4

175. Hussain S, Maqsood M, Lal R, Hussain M, Sarwar A, Bashair M, et al. Integrated nutrient management to alleviate drought stress in hybrid maize. Rom Agric Res. 2017;34:233-42.

176. Noreen S, Fatima Z, Ahmad S, Athar HR, Ashraf M. Foliar micronutrients in mitigating abiotic stress. In: Hasanuzzaman M, Fujita M, Oku H, Nahar K, Hawrylak-Nowak B, editors. Plant nutrients and abiotic stress tolerance. Singapore: Springer; 2018. p. 95-117. https://doi.org/10.1007/978-981-10-9044-8_3

177. Machado R, Serralheiro R. Salt stress alleviation through fertilization in fruit crops. In: Fruit crops. London: Elsevier; 2020. p. 465-80. https://doi.org/10.1016/B978-0-12-818732-6.00033-2

178. Zong-An H, Jiang D, Yang Y, Sun JW, Jin SH. Effects of nitrogen deficiency on gas exchange and antioxidant enzymes in rice. Photosynthetica. 2004;42(3):357-64. https://doi.org/10.1023/B:PHOT.0000046153.08935.4c

179. Peck AW, McDonald GK. Zinc nutrition alleviates heat stress in bread wheat. Plant Soil. 2010;337:355-74. https://doi.org/10.1007/s11104-010-0532-x

180. Kleinhenz M, Palta J. Root-zone calcium modulates heat stress response in potato. Physiol Plant. 2002;115(1):111-8. https://doi.org/10.1034/j.1399-3054.2002.1150113.x

181. Jungers J, Kaiser D, Lamb J, Noland R, Samac D, Wells S, et al. Potassium fertilization affects yield and persistence of alfalfa. Agron J. 2019;111(6):2843-52. https://doi.org/10.2134/agronj2019.01.0011

182. Undersander D, Cosgrove D, Cullen E, Grau C, Rice ME, Renz M, et al. Alfalfa management guide. Madison: Am Soc Agron; 2011. https://doi.org/10.2134/2011.alfalfamanagementguide

183. Pang J, Ross J, Zhou M, Mendham N, Shabala S. Foliar nutrients alleviate waterlogging stress in barley. Funct Plant Biol. 2007;34(4):221-7. https://doi.org/10.1071/FP06158

184. Farooq M, Basra S, Rehman H, Saleem B. Seed priming improves chilling tolerance in late-sown wheat (*Triticum aestivum* L.). J Agron Crop Sci. 2008;194(1):55-60. https://doi.org/10.1111/j.1439-037X.2007.00287.x

185. Manavalan LP, Guttikonda SK, Tran LS, Nguyen HT. Physiological and molecular approaches to improve drought resistance in soybean. Plant Cell Physiol. 2009;50(7):1260-76. https://doi.org/10.1093/pcp/pcp082

186. Anderson M, Habiger J. Identification of productivity-associated rhizobacteria in wheat. Appl Environ Microbiol. 2012;78(12):4434-46. https://doi.org/10.1128/AEM.07466-11

187. Abd El-Daim I, Bejai S, Meijer J. Improved heat stress tolerance in wheat seedlings by bacterial seed treatment. Plant Soil. 2014;379:337-50. https://doi.org/10.1007/s11104-014-2063-3

188. Ueno D, Rombolà A, Iwashita T, Nomoto K, Ma JF. Novel phytosiderophores secreted by perennial grasses. New Phytol. 2007;174(2):304-10. https://doi.org/10.1111/j.1469-8137.2007.02056.x

189. Rasheed R, Wahid A, Farooq M, Hussain I, Basra SMA. Proline and glycine betaine improve heat tolerance in sugarcane buds. Plant Growth Regul. 2011;65(1):35-45. https://doi.org/10.1007/s10725-011-9572-3

190. Kaushal N, Gupta K, Bhandhari K, Kumar S, Thakur P, Nayyar H. Proline induces heat tolerance in chickpea (*Cicer arietinum* L.). Physiol Mol Biol Plants. 2011;17(3):203-13. https://doi.org/10.1007/s12298-011-0078-2

191. Wang LJ, Li SH. Thermotolerance induced by heat acclimation and salicylic acid in grape (*Vitis vinifera* L.). Plant Growth Regul. 2006;48:137-44. https://doi.org/10.1007/s10725-005-6146-2

192. Kumar S, Sirhindi G, Bhardwaj R, Kumar M, Arora P. Role of 24-epibrassinolide in heat stress tolerance of *Brassica juncea* L. Plant Stress. 2012;6:55-8.

193. Sattar A, Cheema M, Farooq M, Wahid M, Wahid A, Babar B. Performance of wheat cultivars under late-sown conditions. Int J Agric Biol. 2010;12(4):561-8.

194. Wahid A, Shabbir A. Induction of heat tolerance in barley by seed treatment with glycine betaine. Plant Growth Regul. 2005;46:133-41. https://doi.org/10.1007/s10725-005-8379-5

195. Adedapo A, Jimoh F, Koduru S, Afolayan A, Masika PJ. Antibacterial and antioxidant properties of *Calpurnia aurea*. BMC Complement Altern Med. 2008;8:53. https://doi.org/10.1186/1472-6882-8-53

196. Yeh CH, Kaplinsky N, Hu C, Charng Y. Phenotyping to explore thermotolerance diversity. Plant Sci. 2012;195:10-23. https://doi.org/10.1016/j.plantsci.2012.06.004

197. Sharma J, Kumar N, Singh N, Santal A. Phytoremediation technologies for heavy-metal removal. Front Plant Sci. 2023;14:1076876. https://doi.org/10.3389/fpls.2023.1076876

198. Wani OA, et al. Biochar as a tool to mitigate abiotic stress. In: Bahar FA, Bhat MA, Mahdi SS, editors. Secondary agriculture. Cham: Springer; 2022. p. 97-108. https://doi.org/10.1007/978-3-031-09218-3_9

199. Tang H, Wang S, Liu Y, Hassan MU, Song Y, Huang G, et al. Biochar mitigates heavy-metal toxicity in plants. Not Bot Horti Agrobo. 2022;50(3):12778. https://doi.org/10.15835/nbha50312778

200. Huang M, Yin X, Chen J, Cao F. Biochar mitigates heat stress in rice (*Oryza sativa* L.). Front Plant Sci. 2021;12:711725. https://doi.org/10.3389/fpls.2021.711725

201. Wu Y, Wang X, Zhang L, Zheng Y, Liu X, Zhang Y. Role of biochar in mitigating drought and salinity stress. Front Plant Sci. 2023;14:1163451. https://doi.org/10.3389/fpls.2023.1163451

202. Kanwal S, Ilyas N, Shabir S, Saeed M, Gul R, Zahoor M, et al. Biochar mitigates salinity stress in wheat (*Triticum aestivum* L.). J Plant Nutr. 2018;41(4):526-38. https://doi.org/10.1080/01904167.2017.1392568

203. Yuan J, Meng J, Liang X, Yang X, Chen W. Biochar leachates improve cold tolerance in rice seedlings. Front Plant Sci. 2017;8:1624. https://doi.org/10.3389/fpls.2017.01624

204. Mahmoudian M, Rahemi M, Karimi S, Yazdani N, Tajdini Z, Sarikhani S, et al. Kaolin improves drought tolerance in Persian walnut. J Saudi Soc Agric Sci. 2021;20(6):409-16. https://doi.org/10.1016/j.jssas.2021.05.002

205. Mnyika A, Mbuvi S, Gogo E. Superabsorbent polymer and rabbit manure improve eggplant growth (*Solanum melongena* L.). NASS J Agric Sci. 2020;2(1):13-20.

206. Ostrand MS, DeSutter TM, Daigh ALM, Limb RF, Steele DD. Superabsorbent polymers: properties and applications. Agrosyst Geosci Environ. 2020;3(1):e20074. https://doi.org/10.1002/agg2.20074

207. Goyal V, Kumari A, Avtar R, Baliyan V, Mehrotra S. Orthosilicic acid and seaweed extract alleviate heat stress in *Brassica juncea*. Silicon. 2023;15(11):4909-19. https://doi.org/10.1007/s12633-023-02376-9

208. Hussein MH, Eltanahy E, Al Bakry AF, Elsafty N, Elshamy MM. Seaweed extracts alleviate salinity stress in *Vigna sinensis* and *Zea mays*. J Appl Phycol. 2021;33(2):1273-91. https://doi.org/10.1007/s10811-020-02330-x

209. Shukla PS, Shotton K, Norman E, Neily W, Critchley AT, Prithiviraj B. Seaweed extract improves drought tolerance in soybean. AoB Plants. 2018;10(1):plx051. https://doi.org/10.1093/aobpla/plx051

210. El Boukhari MEM, Barakate M, Drissi B, Bouhia Y, Lyamlouli K. Seaweed biostimulants mitigate drought stress in faba bean (*Vicia faba* L.). J Plant Growth Regul. 2023;42(9):5642-52. https://doi.org/10.1007/s00344-023-10945-w

211. Anjos Neto AP, Oliveira GRF, Mello SCDC, Silva MSD, Gomes-Junior FG, Novembre ADLC, et al. Seaweed extract seed priming mitigates heat stress in spinach. Bragantia. 2020;79(4):502-11. https://doi.org/10.1590/1678-4499.20200127

212. Babaousmail M, Nili MS, Brik R, Saadouni M, Yousif SKM, Omer RM, et al. Improving salinity tolerance in lettuce (*Lactuca sativa* L.). Life. 2022;12(10):1538. https://doi.org/10.3390/life12101538

213. Yousef EAA, Ali MAM. Yeast extract and glycine betaine alleviate cold stress in tomato. Egypt J Hortic. 2019;46(1):117-31. https://doi.org/10.21608/ejoh.2019.8020.1096

214. Seleiman MF, Al-Suhaibani N, Ali N, Akmal M, Alotaibi M, Refay Y, et al. Drought stress impacts and mitigation strategies. Plants. 2021;10(2):259. https://doi.org/10.3390/plants10020259

215. Iqbal S, Waheed Z, Naseem A. Nanotechnology and abiotic stresses. In: Javad S, editor. Nanoagronomy. Cham: Springer; 2020. p. 37-52. https://doi.org/10.1007/978-3-030-41275-3_3

216. El-Saadony MT, Saad AM, Soliman SM, Salem HM, Desoky ESM, Babalghith AO, et al. Nanoparticles enhance crop tolerance to abiotic stress. Front Plant Sci. 2022;13:946717. https://doi.org/10.3389/fpls.2022.946717

217. Sadak MS, Dawood MG. Biofertilizers alleviate salinity stress in wheat. Gesunde Pflanzen. 2023;75(4):1207-19. https://doi.org/10.1007/s10343-022-00783-3

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