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Phytohormone-Based Biostimulants as an Alternative Mitigating Strategy for Horticultural Plants Grown Under Adverse Multi-Stress Conditions: Common South African Stress Factors

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Abstract

Worldwide, it has been recorded extensively that plants are subjected to severe abiotic and biotic stressors. The scientific research community has widely reported that multi-abiotic stressors cause horticultural crop losses, accounting for at least 50 to 70% of the crop yield and quality losses. Therefore, this review focused on the detrimental effects caused by abiotic stress factors occurring in single-, combined- and multi-cell stresses on horticultural plants worldwide, along with the best production systems practices for mitigation during and post-single and combined abiotic or multi-stress damages. A conclusion and recommendation could be reached using the pool of research material, which constituted research articles, reviews, book chapters, thesis, research short communications and industrial short communications from at least twenty-five years ago. Findings showed that some of the leading abiotic stresses are single- and combined abiotic stressors like water deficit, salinity, soil pH, phosphate deficiency, wounding, soil density and pot size. Established commercial and smallholder farmers are globally adapting to plant growth regulators and biostimulants as part of their production systems. However, as much as the effectiveness of biostimulants containing humic acids, algal extracts, plant growth-promoting microorganisms and phytohormones has been reported to promote plant development under multi-stress, only a few studies are focusing on organic phytohormone-based biostimulants on horticultural crops grown under adverse multi stress factoring. In conclusion, the review recommends alternative solutions for emerging South African farmers and growers who cannot afford agricultural insurance options and energy alternatives on the common single- and combined abiotic- or multi-stress-factors.

Keywords: abiotic stress; moisture stress; plant growth regulators; salinity stress; wounding stress

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INTRODUCTION

Environmental factors such as salinity, drought, cold, moisture stress, and a variety of biotic stresses, including herbivory, are estimated to lower plant growth and crop yield by up to 50% worldwide (Khetsha, 2020; Habib et al., 2021; Turan et al., 2021; Ramzan and Younis, 2022). According to Franzoni (2020), only 3.5% of the worldwide geographical area is unaffected by

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limits on the environment and salinity because of different water qualities, water deficit, and moisture stress. The wounding, mineral deficiencies, and soil pH stresses are common abiotic multi-stress-factors affecting the development and management of the yield and quality of horticultural crops in South Africa (Sedibe et al., 2013; Bulgari et al., 2015; Liebenberg et al., 2020; Aslam et al., 2022). However, these environmental stress factors are more detrimental when occurring in combinations and as multi-stress (Pandey et al., 2017).

In recent studies, multi-stress has been reported and attributed to the increasing global climate change, for example, Warren et al. (2018) and Numan et al. (2021) reported that a combination of drought stress and higher temperatures has led to a significant decrease in crop production in the African countries. Lesk et al. (2022) also reported the detrimental effects of heat and extreme moisture stress leading to crop losses due to various crop physiological interactions, with the latter attributed primarily to climate change. In Nepal, climate change did not only detrimentally affect crop production through multi-stress. However, led to a weak social welfare system and contributed to poverty, a similar challenge encountered by most African countries, a key goal specified in the Sustainable Development Goals (SDG: 1, 2 and 6) (Lim et al., 2018); thus, cheaper alternative strategies to improve the optimization of crop production are needed (Chalise et al., 2017). Therefore, the detrimental impact of climate change on crop yields can be better understood by investigating the effects of individual climate change components on plants and crops, especially growing under adverse multi-stress conditions.

Multiple strategies have been implemented to meet rising food demand that improve horticulture plant development, resistance, and crop productivity under severe environmental conditions. These mitigation strategies include several tools such as agronomical techniques (Franzoni, 2020), *in-vitro* selection, tissue culture, and genetic engineering (Kumar et al., 2020), biofertilizers and xenobiotic agrochemicals (Rana et al., 2022), insect pest, protected cultivation, use of compounds or substances applied on leaves to reduce moisture loss, and biostimulants or specific bioactive compounds (Franzoni, 2020). The biostimulant industry is commonly composed primarily of humic acids, fulvic acids, algal extracts, silicon, and plant growth-promoting microorganisms, bio-inhibitors, and phytohormone in South Africa (Khetsha et al., 2022).

For example, Canellas et al. (2015) extensively recorded the effects of humic and fulvic acid on various vegetables, which improved the yield and quality of vegetables grown under various adverse abiotic stress conditions. Plant growth-promoting microorganisms have been the central focus of the biostimulant industry since 1940. Thus, this area of research has been overly explored. On the other hand, Kapoore et al. (2021) provided explicit sustainable production systems using algae and silicon-based biostimulants, showing the potential for vegetables grown under adverse multi-stress conditions. However, much has been extensively researched on single stress factors, lacking novelty. Khetsha et al. (2020; 2023) also reported explicitly on the recovery response mechanism of a simulated hail-damaged medicinal and aromatic plant, *Pelargonium graveolens* (L.), using bio-inhibitors; promising future research to explore under adverse multi-stress factoring for vegetables. Therefore, new novel approaches using organic plant-based/phytohormones-based biostimulants are the eco-friendly approaches to explore, as described by Habib et al. (2021). However, there is limited scientific proven work on phytohormones-based biostimulants as an alternative strategy in stimulating plant recovery and development by acting on primary or secondary metabolism and acting as a stress repair mechanism while promoting tolerance against abiotic-multi stress factors. Therefore, this review explicitly unpacks the common South African single-, combined-, and multi-stress factors affecting vegetables and further provides alternative strategies to mitigate these adverse abiotic challenges as well as future studies and trends in South Africa.

MATERIALS AND METHOD

This review article was developed by examining studies on the impact of biostimulants on plant stress, with a primary emphasis on plant development, crop yields, and crop quality worldwide, and cascading to South African studies. Therefore, the authors conducted a desktop review focusing on various vegetables and other commercial crops globally. At most, the authors maintained twenty-five years of research material, constituting research articles, reviews, book chapters, thesis, research short communications, and industrial short communications. All material reviewed was analyzed and discussed based on the primary objective, with the conclusion leading to the recommended future studies to lay a foundation for the sustainable agricultural production systems strategy in South Africa.

RESULTS AND DISCUSSION

Common abiotic stressors affecting horticultural plants in South Africa

Abiotic stressors such as drought, temperature extremes, radiation, floods, edaphic factors, and the physical and biological components (Minhas et al., 2017) hurt agricultural production and productivity. Yuan et al. (2017) state that abiotic factors, such as drought, changes in temperature, and water quality, significantly impact the production of tomatoes (*Solanum lycopersicum* L.). Soil salinity quickly increases, reducing crop productivity by more than 20%. It also reduces the output capacity of an additional 20 to 46 million ha (FAO, 2016). Numerous research studies have been conducted on plant responses to single stressors. The consequences of coupled stressors on plant physiological and metabolic systems, on the other hand, have received far less attention (Sack and Buckley, 2020). The mechanisms of environmental stress resistance are mostly noticed in seed plants, and little is known about how non-flowering plants adapt to abiotic challenges (Pietrak et al., 2023).

Plants wither due to many soil-related factors, for example, acidic soils and the solubility of toxic elements. While soil pH is a helpful indicator in assessing acidity conditions in the soil to optimize revegetation, the breakdown of toxic compounds under acidic conditions should be considered. For instance, Al, which makes up around 7% of the Earth’s mass, is rapidly released in water when the pH shifts, directly impeding plant growth (Jaiswal et al., 2018). Aluminum is found in soils as $Al(OH)_3$, which dissolves in water as Al^{3+} under acidic conditions, with at least a pH of 4.5 and is liberated as $Al(OH)_4$ under alkaline ones. Because Al^{3+} rapidly interacts with phosphoric acid, it causes P shortage in plants by forming insoluble $AlPO_4$ in soils (Li et al., 2009).

Plants growing with pH under 5.5 tend to have P, N, K^+, Ca^{2+}, and Mg^{2+} deficits and toxicities of H^+, Al^{3+}, and Mn^{2+}; soil pH impacts plant nutrient availability (Peterson, 2020). Chemically, Mn^{4+} is converted to Mn^{2+} at low pH values, and toxicity results when plants consume excessive Mn^{2+}. Manganese taken by plants may function as a harmful agent, reducing photosynthesis and, as a result, yield. Manganese insufficiency occurs when acidic soils have high levels of Fe, especially when the pH is less than 5.6 (Peterson, 2020). Acidic soils can also inhibit root development and impair the activity of beneficial soil microbes. Globally, P shortage is a significant abiotic stress factor restricting crop output and plant growth (Wissuwa, 2003). It is linked to extremely weathered soils, a high capacity to fix P in forms often unavailable to plants, and limited fertilizer use, especially in regions where resource-poor farmers are typically found. The ability of rice (*Oryza sativa* L.) cultivars to withstand P deficit has been targeted in part due to the discovery that there is significant genetic heterogeneity in GenBank accessions about the ability to absorb P from a highly P-fixing soil (Wissuwa, 2003).

Plants may also exhibit comparable phytochemical reactions in response to P deficiency (Galieni et al., 2015). Research has revealed that nutrient deficiency can yield negative results on growth and yield. For instance, Galieni et al. (2015) found that the imposed restricting growth conditions substantially impacted the development and production of lettuce (*Lactuca sativa* L.). The stress treatments, except for the no P application treatment, significantly reduced the number of leaves to 29. For example, leaf length increased by 56.7% in low light compared to control but decreased by 21% in 0 kg ha^{-1} N. Water stress and 0 kg ha^{-1} P did not trigger any variations in leaf length. In the 0 kg ha^{-1} N treatment, the fresh biomass of lettuce leaves was considerably reduced.

According to Stagnari et al. (2014), water stress diminished the storage root weight by 62% and 75% at W50% and W30% treatments, respectively. Red beetroot leaf water content also showed comparable trends. Furthermore, Stagnari et al. (2014) observed that moisture stress increased total phenolic content, betacyanin, and betaxanthin by 86%, 52%, and 70%, respectively, resulting in higher antioxidant activity. Minerals such as Mg, P, and especially Zn in W50% and W100% treatments, respectively, and Fe in W30% and W100% treatments, respectively, were highly concentrated in water-stressed roots, as were neutral detergent fiber and acid-detergent fiber. In other crops, such as parsley, the severity of the water stress response varies with the cultivar and the plant density (Petropoulos, 2020).

Plants may demonstrate strategic defense responses that differ from their reaction to individual stress when drought and salinity occur concurrently. However, plants also become prone to ionic stress during ongoing salt contact, resulting in leaf senescence and photosynthesis, which leads to a decrease in addition to dehydration (Ma et al., 2020). These stresses are significant problems for agriculture, livestock, fishery, and other commodity production. Only 9% of the world's agricultural land is suitable for crop production, while the remaining 91% is subject to various stressors. While abiotic pressures cause losses of more than 50% of agricultural productivity, their intensity and negative impact are anticipated to increase exponentially due to climate change and natural resource exploitation. Dryland agroecosystems are vulnerable to severe consequences (Minhas et al., 2017).

The extent of salinity as a potential stress factor

According to the United Nations Food and Agriculture Organisation (FAO), soil salinization takes 1.5 million ha of agriculture out of production annually. It may significantly reduce production potential by up to 46 million ha annually. Furthermore, annual agricultural output losses due to salinization are estimated to be $31 million. Salinization of soil and water happens naturally, but human influence, such as land removal and incorrect irrigation practices, accentuates this occurrence. When the soil's electrical conductivity (EC) exceeds 4 dS m^{-1}, it is deemed salt-affected. Rainwater can contain up to 650 mg kg^{-1} of NaCl, which may also raise the salinity of the soil (Riaz et al., 2018).

The impact of salinity varies based on the species or varieties studied, the salt content and stress duration. Salinity has been shown to impact fruits' nutritional and nutraceutical characteristics by causing metabolic alterations in reaction to stressful conditions (Rouphael et al., 2018). The impact of salt on tomato fruit and other significant fruit crops has been extensively researched. According to the same study, salinity did not affect the expression of numerous essential genes involved in antioxidant synthesis in ripe fruit. In specific tomato genotypes, salinity stress resulted in a two- to three-fold rise in lycopene concentration. At the same time, salt had a varied effect on total anthocyanin accumulation in two anthocyanin-rich tomato genotypes (Rouphael et al., 2018).

Furthermore, salt stress reduces tomato output at all phases of plant development. Seed priming is an efficient approach for reducing salt stress that can boost performance and growth. This strategy allows for controlled hydration of seeds while preserving metabolic activity and preventing radicle protrusion (Mundaya Narayanan et al., 2023).

Numerous attempts have been made to manage salinity stress sustainably, such as by modifying farming systems to include perennials in rotation with annual crops, mixed plantings, or site-specific plantings (Al Murad et al., 2020). However, the execution is hampered by expenses and a surplus of high-quality water. Other approaches to reducing the adverse impacts of salinity stress include the development of salt-tolerant and transgenic crops, using microorganisms in mineral leaching, and drip irrigation techniques to optimize water use (Malhotra et al., 2018).

Several studies have shown that plant hormones (phytohormones) like cytokinins (CKs), auxin, gibberellins (GAs), salicylic acid (SA), and the abscisic acid (ABA) can play a critical role in metabolic engineering targets for producing crops with abiotic stress tolerance (Wani et al., 2016). Furthermore, key genes affect plant growth and response to various abiotic stress situations. Previous research focused less on understanding the molecular alterations connected with the grafting process and the molecular mechanism of graft union formation (Mo et al., 2018).

The extent of wounding as a potential stress factor

Palms that are constantly over-pruned become frail and frequently break in the wind. Removing leaves exhibiting deficient symptoms of mobile minerals, such as K and Mg, should be avoided so these nutrients can be moved to other plant sections (Schuch and Quist, 2023). Palms' photosynthetic surface area is effectively concentrated due to their huge leaves; therefore, a single extra cut can dramatically diminish the tree's potential to support healthy growth and repair. When deciding how much to prune, a decent rule of thumb is to limit trimming to no more than 25% of the living canopy in a season and to avoid pruning more than once every season. Wounds are persistent because no cambium covers them, leaving the tree vulnerable to disease infestation (Schuch and Quist, 2023).

Plant wounding is the injury or damage caused to the plant by grazing animals, insect pests, and parasitic plants, resulting in disturbance of plant growth, development, and yield (Savatin et al., 2014). The restorative cell divisions are triggered by wounding predominately in the cells at the inner adjacent side of the eliminated cells

(Vega-Muñoz et al., 2020). Pruning of plants is a common technique used to remove excessive parts of the plants. Excessive shoots, branches, buds, flowers, fruit, and roots are targeted to improve and optimize plant growth and development. Its role in crop production is to remove excessive plant parts to redirect energy to those parts that can bear fruit, have a better root-to-shoot ratio, and improve plant quality and yield (Alam et al., 2016).

According to Maboko and Plooy (2008), shoots emerging from leaf axils are pruned to create plant structures to make plant management easier. Tarigan et al. (2011) carried out research to compare pruning quality and how it affects crop yield and quality optimization. Two kinds of pruning are employed: branches pruning is conducted by cautiously removing the branch collar to prevent the bark from tearing. Alternatively, branches were pruned on the branch's collar, and the bark was pulled to create an opening. Tarigan et al. (2011) observed that careful and rough pruning methods resulted in wounds in *Acacia mangium* and *A. crassicarpa*. All rough pruning procedures caused larger wounds than meticulous pruning. Another method includes the removal of the dead lower fronds, which often remain and tend to fall off later. Lower fronds usually senesce and turn brown as new foliage emerges from the terminal bud. These dead lower fronds may remain or fall off. When they persist, they form a “shag” or “skirt” that can be kept for trunk protection or historical character, or it can be clipped to reduce the risk of falling debris or to improve the tree's beauty. Pruning rules in all circumstances include (1) defining a clear rationale for each cut, (2) pruning at the proper time, and (3) adopting correct techniques such as those stated in the ANSI pruning standards available through the International Society of Arboriculture (Schuch and Quist, 2023).

Plant responses to wounding are divided into local and systemic and include molecules that simulate regeneration, participate in signaling pathways, and change gene expression (Al-Khayri et al., 2023). Plants activate numerous defense mechanisms to respond to wounding, which include strengthening the cell walls, inducing the defense-related genes, synthesizing antinutritional compounds, and antimicrobial and wounding healing processes (Wielkopolan et al., 2022). Under biotic stresses, plants respond through inducible basal defense networks stimulated by the correlated pathogen-associated molecular patterns (PAMPs) (Al-Khayri et al., 2023). Meents et al. (2019) used a mechanical caterpillar (MecWorm28) to inflict persistent mechanical wounding on sweet potato (*Ipomoea batatas* (L.) Lam.) to imitate herbivory without its stimulant oral secretion. In this study, mechanical damage for 18 hours led to the emission of more compounds. The combination of mechanical wounding and the contribution of herbivory attributed to molecular patterns provided by oral discharge may account for this increase. In wounded plants, reactive oxygen species (ROS) is primarily produced by the activity of NADPH oxidases that can be activated by Ca^{2+} ions (Mostafa et al., 2022). A few minutes after wounding, the ROS are synthesized, and the cytoplasmic Ca pool increases (Fiorucci et al., 2022). Plants with midrib and lamina injury demonstrated a substantial increase in 2,2-diphenyl-1-picryl-hydrazyl-hydrate (DPPH) scavenging rate compared to the control plants. Plant leaves with midrib injury produced higher levels of DPPH scavenging rate by 46.6% at 48 hours compared with leaf lamina injury and control (Sabina and Jithesh, 2021). DPPH scavenging rate is measured to study the antioxidant activity of plant extracts. In the case of herbivory harm, volatile compounds are released to deter pests and draw predators and parasitoids (Khetsha et al., 2022).

The extent of soil acidity as a potential stress factor

Soil pH can be calculated chemically as the negative logarithm of the active hydrogen (H^+) or hydroxyl ion concentration (OH) (Jackson et al., 2018). Because of water shortages, low precipitation, and potential evapotranspiration, soils in semi-arid and arid areas are commonly alkaline, as evidenced by the inverse associations between soil temperature and pH as well as the soil pH and moisture (Beheiry et al., 2023). As a result of their close relationship, soil pH impacts the adsorption/absorption and availability of nutrients in the soil. Furthermore, most of the soil's chemical, fertility, and biological properties are strongly related to soil pH, which affects plant growth and development.

The available data on the strong relationship between soil pH and nutrient availability indicates the ability of plants to assimilate nutrients through their root systems (Beheiry et al., 2023), as well as the fixation/adsorption capacity, which limits the assimilation by plants and is affected by soil pH values either being extremely acidity or alkalinity. According to some studies, the soil pH in Egypt varies from neutral to strongly alkaline as an inherent characteristic of the soil, owing to the nature of the parent material and the prevailing climatic conditions (Al-Soghir et al., 2022). Awad et al. (2021) explored the response of sweet potato (Beauregard cv.) plants grown in calcareous soil ($CaCO_3$ = 10.8 to 11.3%) to foliar nourishment with ZnO nanoparticles (ZnONPs) and ascorbic acid (ASA) applied individually or in a mixture over two summer seasons. The highest values of Fe and Mn contents were recorded in both seasons of data collection. In contrast, the highest values of P and Cu were recorded in the second season, with ZnONPs applied at 1500 mg l^{-1}. The results indicate that the low availability of some nutrients, particularly P and other micronutrients, is strongly related to an increase in soil pH.

Soil acidity is a serious concern in South African agricultural farming. Peterson (2020) conducted a study of breeding maize for tolerance to acidic soils to improve maize yields. The findings revealed a highly significant and positive correlation between ear diameter (0.9), ear length (0.9), and leaf area (0.7), with 1000 kernel weight, indicating that these attributes could be beneficial when determining genotypes that are tolerant to soil acidity under field conditions. Zharare and Vilane (2021) reported a deficiency of P in Manguzi soils, as compared to the index levels (8 to 10 mg kg^{-1}) for healthy growth of groundnut (*Arachis hypogaea* L.), which is associated with soil acidity in the Lowveld in South Africa. Furthermore, Awkes (2010) reported that foliar observations showed increased foliar Ca and Mg levels with decreasing soil acidity; however, a decline in foliage K levels with lower soil acidity in maize production in South Africa's highveld was also observed.

The extent of water deficit as a potential stress factor

Global water consumption doubles every 20 years and is expected to increase by 56% by 2030 (Caparas et al., 2021). As a result of droughts caused by global warming, commercial farmers use a variety of water sources, including surface-level water, groundwater, municipality water, and rainwater (Hajihashemi et al., 2020) to meet plant water requirements. However, the scarcity of water leads to water deficit stress. Water stress is a critical agricultural problem, leading to lethal crop losses worldwide. Besides water stress as a global concern, soil bulk density represents a significant challenge as a valuable indicator of soil compaction. Soil compaction can reduce crop yields by 25% and up to 75% when combined with water deficit stress, as roots find it difficult to penetrate compacted soils (Huang et al., 2022). Soil moisture is determined by the highest and lowest values of potting water holding capacity when comparing crop performance in response to water stress, which differs from soil texture and bulk density (Koehler et al., 2022). Water stress triggers plants to have lower evapotranspiration, leading to water stress symptoms and modifications in biochemical and physiological processes (Parkash and Singh, 2020). Water scarcity affects plant growth and development, as well as agri-food production, all over the world (Rezaei-Chiyaneh et al., 2023). Exposure to water deficit can here be defined as a lack of plant-available water for a sustained period. Moisture stress inhibits plant growth and development by altering physiological and biochemical activities, decreasing productivity and quality, e.g., declining photosynthetic rates, shortened root systems, and high leaf senescence (Ibrahim et al., 2018; Raza et al., 2021).

Water deficit is the significant abiotic stress that occurs due to the lack of soil water to maintain plant growth and respiration demand, which leads to reduced plant water potential (Dong et al., 2022). Moisture stress can cause various morphological, physiological, and biochemical changes in plants, including stomatal conductance variation, leaf expansion, decreased development of plants, and elongation of the plant stem (Kumar et al., 2020). Water stress causes stomatal closure and an interruption in water flow from the xylem to the surrounding cells, which inhibits cell elongation and affects sensitive physiological processes such as protein synthesis and transportation of nutrients (Al-Quraan et al., 2021). During the critical growth stages, moisture stress decreases leaf turgor and the stomatal opening, ultimately resulting in stunted growth (Inoue et al., 2021). In situations where plants are stressed by moisture deficit, an increased transpiration rate reduces turgor pressure and results in wilting of leaves, which lowers light interception (Bhattacharya, 2021). Water deficit hinders cell division, roots, and shoot expansion, leading to stunted plants (Kumar et al., 2020).

The extent of P deficiency as a potential stress factor

Moisture stress can cause various morpho-physiological and biochemical changes in plants, including stomatal conductance variation, leaf expansion, decreased plant development, and plant stem elongation. Phosphorus is one of the macronutrients crucial for plant growth, being a highly required resource after N to improve the productive performance of several crops, particularly in highly weathered soils. However, many nutrients applied as fertilizers become fixed in the soil and cannot be assimilated by plants. Adjusting P use is critical for environmental sustainability and socioeconomic development (Silva et al., 2023). As a result, possibilities for managing this nutrient are required, and using a phytohormone-based biostimulant is one option for optimizing its use by crops, allowing the exploration of less available fractions of the nutrient in soils and reducing the demand for P fertilizers. Phosphorus is found in sugars, nucleic acids, lipids, and other plant compounds. It synthesizes carbohydrate mediators and plays a role in enzyme activation and inactivation in metabolism. It also promotes germination, root development, flowering, and seed formation (Malhotra et al., 2018). It even participates in energy transfer processes like photosynthesis and is a component of molecules like adenosine triphosphate (ATP) and guanosine triphosphate (GTP) (Bisson et al., 2017).

Phosphorus is less soluble in wet soils than N and K, limiting plant-available P. Fertilizer-P material is generally quickly fixed and immobilized in soil by reaction with cations under acidic and alkaline soil pH conditions. Phosphorus is not readily available to plants and is rapidly immobilized upon application, so a pH between 5 and 7 is generally optimal for P availability. Phosphorus is frequently over-applied to ensure sufficient P is available for crops (Weil and Brady, 2016). Several studies have identified P as a limiting factor in plant growth, with deficiency causing cellular and physiological changes (Dokwal et al., 2021; Meng et al., 2021; Silva et al., 2023). According to Meng et al. (2021), P availability influenced the growth of pummelo (*Citrus grandis* (Burm.) Merr.), where its absence restricted the accumulation of dry matter in the leaves and branches. According to Silva et al. (2023), low P also inhibits plant growth by limiting nutrient assimilation, decreasing the photosynthetic rate, and subsequently increasing the production of ROS. As a result, the availability of P nutrients in the soil directly impacts crop productivity (Silva et al., 2023).

Phosphorus is deficient in at least 40% of the world's cultivated land and has become one of the main limiting factors for crop growth due to P nutrient loss caused by high temperatures and heavy rain, or rather acidic rain caused by industries and mining releasing some S gases, and P fixation by Fe and Al_2O_3 in the soil. Additionally, inorganic P efficiently produces complex oxides and hydroxides of Fe and Al in acidic soils and with Ca in alkaline soils, rendering up to 80% of P applied as fertilizer unavailable to most crops. This situation is exacerbated by insufficient and unbalanced fertilizer use, which results in reduced nutrient availability for crop growth (Meng et al., 2021). According to the available literature, P deficiency significantly reduced the drying weight of lettuce roots and shoots, as well as the leaf number of Chinese milk vetch (*Astragalus sinicus* L.), alfalfa (*Medicago sativa* L.), lettuce, tomato, and marigold (*Tagetes erecta* L.) (Yoneyama et al., 2012; Meng et al., 2021). According to Zhang et al. (2018), P deficiency reduced the photosystem II reaction center's net photosynthesis rate and energy capture efficiency in sunflowers (*Helianthus annuus* L.) and maize. Phosphorus deficiency has also been linked to a decrease in photosynthesis rate in sugar beetroot (*Beta vulgaris* L.), soybean (*Glycine max* L.) Merr.), and tobacco (*Nicotiana tabacum* L.) (Meng et al., 2021). Muneer and Jeong (2015) discovered that short-term P deprivation reduced P concentration, total chlorophyll, and carotenoid content in tomato seedlings.

The extent of pot size and soil density as a potential stress factor

The bulk density is essential for calculating and comprehending other critical substrate characteristics for plant growth, such as aeration space, total porosity, and available water (Haase et al., 2021). According to Yakti et al. (2023), factors that interfere with water availability in the growth medium, including bulk density and substrate evaporation, could also influence the availability of nutrients and the microbiome. Increasing bulk density decreases porosity and aeration space and increases substrate available water and remaining water (Yakti et al., 2023). It is probably caused by the increase in substrate particles occupying more air space due to the rise in mass, leading to the reduction of porosity and change of pore size distribution. Low total porosity and volume of substrates require great care in irrigation management to prevent water deficit (Isa et al., 2021). According to Lu et al. (2021), the amount of water available for transpiration was significantly affected by pot size, with the total average water transpired from the 2.3 and 4.1 l pots being equivalent to 1217 and 1239 g, respectively. Individual pot sizes' total transpirable soil water corresponded closely to the pot's volume and weight (Lu et al., 2021). The substrate dry density and potting size can affect the formation of new roots (Yakti et al., 2023).

In small pot sizes, the root system becomes dense, branched, and matted (Lu et al., 2021). Plant roots are critical in the uptake of nutrient-rich water and the regulation of shoot extension by phytohormones. In addition, plant roots rely on shoots for fixed carbon from photosynthesis, and shoots depend on roots for the supply of water and minerals. In the soil, the lettuce roots reach a depth of only 300 mm. Thus, it is necessary to confine the nutrients and moisture requirements of lettuce to this moderately small volume of soil (Gruda, 2019). Small pots are often used for experiments in a controlled environment due to limited space. Pot size, bulk density, porosity, nutrient status, and water status of the root media influence the formation and growth of plant roots.

Root media bulk density is an important soil property that makes identifying root penetration problems, soil aeration, water infiltration, and soil aeration easier. The substrate bulk density can negatively affect the substrate's physical properties and hamper plant growth (Isa et al., 2021). The soil bulk density influences root growth through soil penetration resistance (Lu et al., 2021). The high soil bulk density caused compaction, decreased pore volume, air circulation, infiltration of water, and increased drainage, all of which resulted in the loss of useful soil nutrients (Isa et al., 2021). Soils with high porosity have a small capillary perimeter of saturated soil, a low capacity to retain water and drain fast, and plants quickly use up the limited available water to the point where they acquire significant water deficit (Turner, 2019; Isa et al., 2021).

The compacted soil in plants may cause inadequate soil aeration, reducing photosynthetic activity and sugar-metabolizing enzyme activities and affecting transpiration and soil water content (Lu et al., 2021). The limited rooting space in small pots stunted the growth of plant shoots because plants produced few and small tillers in small pots (Sondhi, 2023). The number of potatoes indicated that the volume of 3.8 l pots had a significantly higher number of potatoes and total weight per pot than 2.0 and 1.5 l (Balali et al., 2008). Inadequate rooting volume reduces the photosynthetic capacity of plants (Benamirouche et al., 2020). When pot volume dimensions hamper root growth, the carboxylation efficiency tends to increase in response to CO_2 enhancement, suggesting that ribulose-1,5-bisphosphate carboxylase activity may be responsive to plant source-Z balance rather than CO_2 concentration as a single element (Lu et al., 2021).

Multi-abiotic stress factors affecting horticultural plants in South Africa

Adverse environmental stressors such as moisture deficit, soil acidity, wounding, soil and root media density, and nutrient deficiency, particularly P, threaten food security as a combined multi-stress due to climate change. The contemporary agricultural sector is in an impoverished state in which innovative approaches for sustainable food production must be developed, and it is a known phenomenon that plants remain constantly subjected to abiotic stresses (Nephali et al., 2020). Abiotic stress in plants is defined as the external condition that negatively reduces crop productivity. Stress significantly triggers plant physiological responses like altering gene expression, broad metabolic activities, and changing crop yields and quality (Verma et al., 2022). Crops have shown difficulties adapting to these types of abiotic stress, which causes poor morphological, physiological, and biochemical modifications such as water alignment with the consequences of climate conditions.

The rising temperature caused by global warming has significantly impacted plant growth and development over the last few decades and continues to do so today. Erratic climatic conditions caused by global warming will increase abiotic and biotic stresses on plants, reducing crop quality and productivity. Stress can inhibit the development and growth of crops, and plants will respond to stress in various ways, such as changes in cell metabolism, decreased growth rates and yields, changes in gene transcription, and so on, as a way for plants to adapt to stress. Stress can be categorized as either biotic or abiotic, depending on the nature of the inducing factor. Biotic stress is caused by biological factors that affect plant development and productivity (Dewi et al., 2023). In addition, globally, around 20 to 40% of agricultural crop yield losses occur due to factors such as strong wind, radiation, mechanical damage, chemical treatment with heavy metals, herbivores, and infection by damaging host cells like fungi, bacteria, or viruses at different stages of plant growth (Al-Khayri et al., 2023).

According to Hanus-Fajerska et al. (2023) and McKay et al. (2022), forecast scenarios predict a 1.5 to 2 ºC increase in average annual air temperature over the next few decades. For a given area, the number of days with temperatures below the mean for the year is expected to drop by half, while the number of days with maximum temperatures is expected to double. On a global basis, prolonged droughts will increase, as will the frequency of tropical cyclones and floods, particularly in the coastal regions. These are not conditions conducive to plant growth and development in the scenarios described. As a result, the global human population's food supply is seriously threatened (Kwak, 2019). For this reason, research work on the response of plants to multi-stress conditions is constantly being undertaken, and attempts are being made to obtain lines with an increased degree of tolerance to various types of abiotic stresses (Numan et al., 2021).

When a variety of two or more stressful factors occur, a severe decline in successive plant growth and survival happens. Multiple abiotic stresses reduce enzyme activities and cause chlorophyll deterioration, organic molecule damage, and lipid peroxidation harm (Zulfiqar et al., 2020). Moisture stress, soil density, pot size, and wounding stress impact plants' critical biological and physiological processes (Sehgal et al., 2022). Morpho-physiological and biochemical parameters of horticultural species were negatively affected and reduced by water deficit (Repke et al., 2022), soil properties, and wounding stress (Wielkopolan et al., 2022).

According to reports, a plant wound is a critical feature of moisture stress; thus, combining moisture stress and mechanical wounding increases ROS levels (Becerra-Moreno et al., 2015; Gao and Farmer, 2023). Sabina and Jithesh (2021) observed during the quantitative analysis of H_2O_2 levels that types of mechanical wounding caused a quick response, reaching the highest level at 4 hours of stress, followed by a reduction in H_2O_2 after 24 and 48 hours, respectively. It shows that mechanical wounding contributes to water deficit stress. Moisture and wounding stress reduce the photosynthesis rate by stomate closure, decreasing the efficacy of the carbon-fixing process, thereby inhibiting leaf development and inducing leaf shed on cabbage (Kiremit et al., 2022; Sehgal et al., 2022).

Lu et al. (2021) investigated the effects of moisture stress on tomato quality parameters. The authors took the soil texture and soil bulk density into account in the study and found that soil bulk density on lycopene differed from that of vitamin C when water was scarce. They increased by 17.84% in soil with a bulk density of 1.4 g cm^{-1} but not in a bulk density of 1.2 to 4 g cm^{-1}. Under water-deficit stress, most miniature pots dry much more quickly, and these plants (Million and Yeager, 2022). When multiple stressors co-exist, it requires different metabolic and physiological responses and causes severe consequences for horticultural species' plant growth and quality attributes (Kiremit et al., 2022; Sehgal et al., 2022). According to Bilal et al. (2023), physiological and biochemical processes initiated by a particular stress condition differ from those triggered by different compositions of adverse environmental stresses. For instance, Hoque and Kobata (2000) investigated agronomic and yield parameters and the water use on various rice cultivars in response to different soil bulk density levels during the vegetative and reproductive stages under water deficit conditions. The results revealed that plants adversely suffered from soil desiccation at the reproductive stage, which reduced the dry weight at the maturity stage by 46 to 62% due to the increase in soil bulk density. In this study, the yield reduction was caused by the curb and diminution of root development and moisture uptake rate. In rice pot trials, water deficit and a high soil bulk density raised sterility and consequently decreased fertile spikelets (Hoque and Kobata, 2000). Increasing bulk density decreases the soil aerobic bacteria, actinomycetes, and fungi populations.

Large pots retain more substrate and moisture better than small containers, even when subjected to sudden temperature fluctuations and water stress (Balliu et al., 2021). Small pots dry out quickly due to reduced water-holding capacity; as a result, plant water status can be adversely affected. Different container sizes and root restrictions significantly impact shoot growth (Melrose and Normandeau, 2021). When the roots of seedling roots are restricted by polybag, they become spiral and deformed, decreasing plant growth and leading to stress resistance (Benamirouche et al., 2020). After transplanting, seedlings with spiral roots may not sufficiently anchor the plant and may have limited water and nutrient intake (Benamirouche et al., 2020; Haase et al., 2021).

Jan et al. (2022) reported that the drought and UV radiation interaction reduced the length of the shoot by 26% and 16% on Wt+D+UV (non-transgenic treated rice plants exposed to drought and UV radiation) and OxF3H+D+UV (transgenic treated rice plants exposed to drought and UV radiation) treatment, respectively, and this is compared with the control. The leaf area of Wt+D+UV plants had been significantly decreased by 42%, followed by OxF3H+D+UV by 36%. According to the same study, combined stress caused the most leaf-tip burn in wild-type plants, followed by individual drought stress in OxF3H plants. The response of plants to abiotic stresses is determined by stress time of day, length, frequency, extent, the response of harmed tissues, and crop growth stages (Venugopal et al., 2023).

Studies have revealed positive results on combinations of multiple stresses in horticultural crops. For example, in tomato plants, salt stress causes the accumulation of proteinase inhibitors and the activation of other wound-related genes (Delgado et al., 2021). Under deficit irrigation, the β-carotene content of cherry tomatoes increased by 10.68% (Lu et al., 2021). Moisture stress caused a 20- and 14-fold increase in the relative expression of 3-deoxy-D-arabino-heptulosonate synthase and phenylalanine ammonia-lyase genes in wounded carrot tissue (Becerra-Moreno et al., 2015). Plants convey different strategies to adapt or avoid the adverse effects of multi-stress (Aslam et al., 2022). Hence, crop management needs to implement alternative strategies to cope with the impact of water deficiency under deficit irrigation techniques on plant growth and development.

Ever since the irrational climate change, plants have had to physiologically respond and regulate various abiotic stresses, including deficit or excessive water, nutrient shortages or imbalances, soil acidity or alkalinity and others related such as low or high temperature (Ambrosini et al., 2021). As a result, extreme stresses tend to cause significant crop yield losses, mainly attributed to recent climate change (Wani et al., 2016; Ambrosini et al., 2021). When these stresses combine, the negative impact on plant growth is exacerbated. For example, drought and heat stress were responsible for up to 40% of the reduction in crop yield for maize (Daryanto et al., 2016) and up to 68% for cowpea (*Vigna unguiculata* (L.) Walp.) (Farooq et al., 2017). Furthermore, water scarcity and soil salinity trigger oxidative and temperature stresses, posing yet another significant challenge to productivity (Landi et al., 2017). Nutritional imbalances directly reduce the growth of plants and, thus, productivity by affecting nutrient assimilation and dissemination within the plant (Rouphael et al., 2018). Despite conflicting reports on the effects of nutrient supply on plant growth under water-deficient conditions, it is generally accepted that increased nutrient supply will not improve plant growth when the nutrient is already present in sufficient quantities in the soil, and the water deficit is severe.

Furthermore, it is generally known that nutrient availability requires water for solubility, transport, and distribution, and its availability is pH-dependent. Other studies found that a field experiment to study the effects of individual or combined water and nutrient deficiencies on photosynthesis has decreased wheat grain yield and leaf photosynthetic rate (Kang et al., 2023). When plants endure exposure to water stress regimes, agronomic and yield parameters decrease significantly, while primary metabolites increase in response to moisture stress (Sultan et al., 2023).

Phytohormone-based biostimulants as stimulatory substances for horticultural plants

du Jardin (2015) defined “biostimulants” as substances that enhance the accessibility and assimilation of essential nutrients from soil while allowing for greater tolerance of biological and environmental stresses. According to science, a more precise definition of biostimulant products is any substance or microorganism applied to plants to enhance nutrition efficiency, abiotic stress tolerance and crop quality traits, regardless of nutrient content (du Jardin, 2015). Alternatively, a biologically developed product enhances plants’ productivity due to the complex components’ unique attributes rather than the presence of known essential nutrients for plants, phytohormones or bioinhibitors (Yakhin et al., 2017).

According to Yakhin et al. (2017), biostimulants are natural stimulants, organic compounds, biostimulators, or plant growth regulators. The term “biostimulants” was first used in 1951 (Yakhin et al., 2017), but only in the past 25 years have researchers investigated how biostimulants might lessen the effects of global climate change (Yakhin et al., 2017; Rai et al., 2021; Khetsha et al., 2023). Due to recent extreme temperatures and weather patterns, abiotic stresses, such as drought, are becoming increasingly significant threats to food production.

Organic-based or plant-based biostimulants have consistently increased their relevance among emerging innovations and crop optimization techniques in recent years, and the revenue is expected to grow further. The market availability of many biostimulant products with various origins and putative functions may be interpreted as a good demonstration of their practical effectiveness and dependability as agronomic tools. Even though many integrated and organic production techniques for horticultural products have already been implemented, they are currently inadequate, exact, and backed by science on the effectiveness of plant-based biostimulants. This lack of clarity is undoubtedly due to the nature of these products, whose composition frequently precludes detailed analysis and quantification of all components. Furthermore, the composition of the same product category can vary significantly depending on the material used and the manufacturing conditions (Andreotti et al., 2022).

Abou-Sreea et al. (2021) reported that plant biostimulants like honeybee (HB) and silymarin (Sm) are a strategic trend for managing stressed crops by promoting nutritional and hormonal balance and regulating osmotic protectors, antioxidants, and genetic potential, reflecting plant growth and productivity. Thus, they applied diluted HB and silymarin-enriched HB-Sm as foliar nourishment to investigate their improving influences on growth, yield, nutritional and hormonal balance, various osmoprotectants levels, different components of the antioxidant system, and genetic potential of chili pepper plants grown under NaCl-salinity stress (10 dS m^{-1}). Honeybees significantly promoted the examined attributes, and HB-Sm conferred optimal values, including growth, productivity, K^+/Na^+ ratio, capsaicin, and Sm contents. The antioxidative defense components were significantly better than those obtained with HB alone. Conversely, oxidative stress markers (superoxide ions and hydrogen peroxide) and parameters related to membrane damage (malondialdehyde level, stability index, ionic leakage, Na^+, and Cl^- contents) were significantly reduced. HB-Sm significantly affects inactive gene expression as a natural biostimulator silencing active gene expression. As a natural multi-bio stimulator, HB-Sm can attenuate salt stress effects in chili pepper plants by remodeling the antioxidant defense system and ameliorating plant productivity.

Effect of phytohormone-based biostimulants on plant growth and development grown under various stress factors

Phytohormones are small organic molecules produced naturally by plants or synthesized in laboratories to induce metabolic activities and regulate local and distant plant growth processes within plant cells at low endogenous concentrations (Khetsha et al., 2022; Verma et al., 2022). Phytohormones, namely auxins, CKs, GAs, auxins, brassinosteroids (BRs), and ethylene (ET) are categorized under plant growth regulators and ABA, Jasmonic acid (JA) and SA as bio-inhibitors (Chen et al., 2016; Iqbal et al., 2020; Jiménez-Arias et al., 2022; Verma et al., 2022; Wei et al., 2023). Phytohormones can induce an array of physio-biochemical processes and control the transcription of genes for adaptive plant responses to abiotic and biotic stresses (Nephali et al., 2020; Turan et al., 2021; Rana et al., 2022; Clément et al., 2023). Some plant hormones are essential biostimulant compounds used by the crop and horticultural industries (Tadele and Zerssa, 2023). The positive effects of plant biostimulants with traces of phytohormones on yield, fruit diameter, length, chlorophyll content, and overall functional quality have been reported on horticultural crops such as tomato, pepper (*Capsicum annuum* L.) and spinach (*Spinacia oleracea* L.) (Turan et al., 2021). Biostimulants have been authenticated to encourage the growth and development of plants, as well as pathogen defense and decrease the spread and severity of some diseases (Khetsha, 2020; Habib et al., 2021; Turan et al., 2021; Ramzan and Younis, 2022).

Foliar application of these phytohormones in stressed plants influences the accumulation of secondary metabolism and participation in defense responses (Mostafa et al., 2022). For example, the exogenous application of JA and SA triggered the most vigorous systemic immunity to the tobacco mosaic virus in *Nicotiana benthamiana* (L.) plants (Kudoyarova et al., 2022). Phytohormone signaling and build-up are altered in response to environmental stress factors to sustain and promote plant growth. Phytohormones, either directly or indirectly, modulate plants' protective responses to abiotic and biotic stress (Iqbal et al., 2020). Nephali et al. (2020) indicated that phytohormones influence plant growth and development by integrating numerous stress signaling molecules that trigger complex signaling cascades and control the transcription of stress-responsive genes, eventually leading to multiple stress tolerance. A complex network of synergistic and malicious interactions is influenced by the signaling pathways of one another (Nephali et al., 2020).

ABA as an elicitor regulating moisture stress

ABA is essential for plant responses to environmental stress factors (Arif et al., 2018), such as water stress, soil bulk density, mechanical density, mechanical wounding, or plant pathogen infection. ABA is essential in response to stress caused by moisture through morpho-physiological processes in plants (Chen et al., 2016). The action of ABA, which accumulates during stress and attaches to its identical receptor family, the pyrabactin Resistance1 (PYR1)/ PYR1-LIKE (PYL)/ABA Receptor Regulatory Components (RCAR), is linked to the response to plant stress (Wielkopolan et al., 2022). ABA levels in rice root tip tissues were determined on plants grown in non-compacted soil with a bulk density of 1.1 g cm^{-1} and compacted soil with a bulk density of 1.6 g cm^{-1}, revealing that ABA levels increased threefold in compacted soil versus non-compacted soil conditions. In response to high bulk-density conditions, ABA biosynthesis is required to promote radial root extension (Huang et al., 2022).

Protein receptors (PYR/PIL/RCAR) bind to ABA in the ABA-dependent signaling pathway by suppressing protein phosphatases 2C (PP2C) activity, which enables SNF1-related protein kinase 2 (SnRK2) activation through autophosphorylation (González-Morales et al., 2021). Indeed, the ABA-PYR/PYL complex muddles to PP2Cs and consequently hinders PP2Cs, whereby, in the lack of ABA, dephosphorylate and retain subclass III Sucrose non-fermenting-1 (SNF1)-related protein kinases 2 (SnRK2s) inactivated (González-Morales et al., 2021). Activated SnRK2s phosphorylate transcription factors called ABA-Responsive Element (ABRE) Binding Proteins (AREBs)/ ABRE Binding factor (ABFs), which control the manifestation of target genes to improve plant response to moisture stress (Liu et al., 2022). The ABA homologous responsive genes include IA19, IA20, and IA24, and thus, IA20 encodes TF WRKY20, which regulates ABA signaling and improves water stress tolerance (González-Morales et al., 2021). Another signaling pathway that water and osmotic pressure activate is ABA-independent and involves Growth-Regulating Factor7 (GRF7) (Guo et al., 2022).

During water deficiency, ABA controls the quick response to stomatal closure governed by a complex network of signaling pathways (Shomali et al., 2022). ABA, ET phytohormones, and H_2O_2 and Ca ions signal messengers can be involved in guard-cell signal transduction and stomatal mobilization (Zhang et al., 2020). Water deficit triggers ABA accumulation, which activates response mechanisms through diverse ABA-responsive genes, resulting in the immediate closure of stomata and synthesis of osmoprotectants. In an experiment by Jiménez-Arias et al. (2022), water deficit induced SlNCED2 transcription in tomato seedlings after 10 hours of treatment, an ABA biosynthetic pathway gene that encodes 9-*cis*-epoxy carotenoid dioxygenase. Therefore, this caused an evident ABA accumulation in seedling leaves after 24 hours of treatment. DWARF14 (D14) and KARRIKIN IN-SENSITIVE 2 (KAI2) are strigolactone and karrikin receptors that modulate ABA responsiveness, proliferation of the anthocyanin, the stomatal conductance, cell wall, and biosynthesis of the cuticle *Arabidopsis thaliana* (Liu et al., 2022). The root restrictions in the small pots induced ABA production by the roots (Turner, 2019).

SA as an elicitor regulating moisture, wounding, and salinity stress

SA is a signaling molecule uncovered organically in plants and has a key role in bioinhibition reactions against pathogen infection (Cunha et al., 2023). SA is a phenolic plant growth regulator compound that regulates plant physiological processes like mineral assimilation by plant roots and stomate closure when plants are exposed to stresses (Khattak et al., 2021). Tomato plants treated with phytohormone-based biostimulant showed enhanced toleration to ROS-mediated oxidative inequality, such as collaborative action of SA, hydroxycinnamic amide signaling, carotenoids, prenyl quinone radical scavenging, and declined tetrapyrrole biosynthesis (Hossain et al., 2021). Aazami et al. (2023) soaked the wheat seeds in 0.05 mM SA solution for 3 hours. Results revealed that SA treatment ultimately prevented the ABA build-up and the diminishing levels of IAA and CKs in seedlings induced by salinity and water deficit. It indicates that pre-sowing treatment with SA may be necessary for wheat seedlings to recover and resume proliferating under water deficit and salinity stresses.

Liu et al. (2022) found that the mechanisms relating to photosynthetic processes and the metabolism of CKs and BRs are mediated by the SL and KAR/KL pathways in plant responses to water deficiency. Overexpression of OsF3H in rice reduced the building up of SA during drought and UV-B radiation stress (Jan et al., 2022). The SA moderates the reaction to water stress by regulating the production of ROS and the redox balance by antagonistically depressing ABA (Khattak et al., 2021). The SA-dependent signaling pathway is activated in response to herbivores and biotrophic pathogens that typically cause tissue disruption in plants, like piercing-sucking (Wielkopolan et al., 2022). Khattak et al. (2021) evaluated the effects of SA on sunflower yield and yield attributes under water deficit stress. The authors reported that the exogenous application of SA at 5 mg l^{-1} rate effectively improved the moisture stress state of the sunflower varieties, yield, and yield attributes, as well as the seed quality.

JA as an elicitor regulating moisture and salinity stress

JA is a lipid-derived phytohormone synthesized from a-linolenic acid. Herbivore insect feeding tends to damage the plant by inflicting wounds on plant-damaged parts; therefore, plants' responses follow a generation of a wounding reaction interceded proteinase inhibitors and polyphenol oxidases within the plant, which is a JA synthesizing protective substance (Meents et al., 2019; Cunha et al., 2023). The JA signaling pathway is key for the growth responses to lesions (Cunha et al., 2023). Wounded MT and jai1-1 plants significantly had shooter shoots than unwounded control MT and jai1-1 plants, indicating a wound-inducing decrease in growth in tomatoes, and this is most likely due to an applicable JA signaling pathway (Cunha et al., 2023). JA controls the generation and emission of herbivore-induced plant volatiles (HIPVs). HIPVs produce and release terpenoids from green leaf volatiles, which may draw in herbivore parasitoids and predators that prevent the infestation (Meents et al., 2019).

Guan et al. (2022) found that the genetic products involved in plants' metabolic processes and physiological reactions conveyed a high percentage in response to aphid feeding and mechanical wounding, respectively, by at least 40% and 39%. A gene encoding the small subunit of ribulose-1,5-bisphosphate carboxylase/ oxygenase (RuBisCo) was routinely up-regulated in plant leaves after aphid feeding and mechanical wounding (Guan et al., 2022). In rice, the antisense expression of OsPLD4 and -5 lowered the expression levels of OsHI-LOX, OsMPK3, OsHPL3, and OsACS2 under water deficit (Jan et al., 2022). Following this, OsPLD4 and OsPLD5 expression may impact the oxylipin pathway by simulating LeA, the typical substrate for biosynthesis of JA and GLVs, or altering LOX activity MAPK signaling, in turn, controlling the biosynthesis of JA and GLVs. The higher level of expression of the genetic material encoding the NINJA protein regulators, which minimize gene transcription factors that influence the transcription of JA-responsive genes, was found in plants damaged by the larvae with the bacterial flora in the JA-dependent signaling pathway (Wielkopolan et al., 2022).

CK as a plant growth regulator on multi-stress

Cytokinin significantly responds to abiotic stresses such as temperature, water osmotic, and salt stress, requiring a functioning CK signaling route (Hai et al., 2020). Cytokinins are the likely biostimulants responsible for growth enhancement because they regulate the proliferation of cells and chloroplast synthesis (Jiménez-Arias et al., 2022). Numerous organs, including plants and pathogens, obviously use adenine derivatives as signaling molecules contained by the CK hormone. Hence, CKs are optimal for communication between phytopathogens and plants. Cytokinin signaling has evolved into an intercellular transmission network system required for crosstalk with other botanical hormones and their controlling pathways in regulating plant response to moisture stress (Hai et al., 2020).

The CK signaling in plants includes two classical component approaches combining histidine kinases and histidine phosphotransfer proteins (Hai et al., 2020). In *A. thaliana*, the D14 pathway regulated CK and BR metabolism. In contrast, in response to water scarcity, the D14 and KAI2 pathways control the metabolic processes associated with glucosinolates and trehalose (Li et al., 2020). During the wounding recovery process after the grafting in tomatoes, the auxin and CK act simultaneously; however, at various locations, they act above and below the graft junction (Cui et al., 2021). The application of biostimulant on tomato under water deficit showed that it helped antioxidant defense and exercised a significant hormonal consequence in leaves by raising indole-3-acetic acid (auxin), JA, and *trans*-zeatin (CK) (Turan et al., 2021).

Abou-Sreea et al. (2021) soaked maize grains in *cis*-(c-Z-Ck) or *trans*-zeatin-type CK (t-Z-Ck) solutions at a concentration of 50 or 40 µM, respectively. The total carotenoid content, the growth and yield components, relative water content, membrane stability index, photochemical activity, gas exchange, K^+ and chlorophyll contents, K^+/Na^+ ratio, and photosynthetic efficiency were significantly improved by c-Z-Ck pretreatment and further enhanced by t-Z-Ck pretreatment compared with the corresponding controls. Furthermore, the contents of proline, soluble sugars, ascorbate, glutathione, and enzymatic antioxidant activities were significantly elevated by 75 or 150 mM NaCl salt stress concentrations. They increased more by both biostimulators compared to the control. Compared to c-Z-Ck, t-Z-Ck was superior in mitigating the harmful effects of the high H_2O_2 levels caused by salt stress on malondialdehyde and ion leakage levels compared to the control. Under normal or stress conditions, t-Z-Ck pretreatment was better than c-Z-Ck pretreatment, while both positively affected maize hormonal contents. As a result, t-Z-Ck is recommended to enhance the growth and productivity of maize plants by suppressing the effects of oxidative stress caused by saline water irrigation.

Auxins as a plant growth regulator on various stress factors

The auxin phytohormone conforms to numerous crucial processes in plant growth, development, and environmental adaptation (Jogawat et al., 2021). In various physiological processes, the functions of auxins can be comprehensively regulated via three primary regulatory actions: auxin-directed transport, signal transduction, and auxin biosynthesis and inactivation (Zhang et al., 2020). Auxins act as a chemical messenger that influences the expression of genes via the nuclear signaling module identified as SCFTIR1/AFB-Aux/IAA-ARF transcription with DNA-binding auxin response factors (ARFs) (Verma et al., 2022). Auxin penetration typically initiates with TIR1/AFB receptors (Jogawat et al., 2021). Auxin receptor, the F-box proteins AFB1-AFB5/TIR1, which DNA ligases activate the type of ARF transcription factors as well as the Aux/IAA transcriptional repressors Aux/IAA (Cui et al., 2021).

The ARF gene expression regulates plant adaptation to water stress. Auxin-responsive, induced proteins, ARF, small auxin-upregulated RNA (SAUR), auxin-responsive Gretchen Hagen3 (GH3), and YUCCA genes are involved in the auxin signaling pathway (Jogawat et al., 2021). The transcription factor WUSCHEL-related homeobox 11 (WOX11) functions primarily with WOX12 to allow four days after the cut for the transition of local cambium cells to root founder cells, which is directly triggered by the accumulation of auxin in one day at the wound site (Vega-Muñoz et al., 2020). Auxin regulates gene transcription through Aux/IAA proteins, can interact with ARF transcription factors, and hinders auxin signaling (Jogawat et al., 2021). In an experiment by Cui et al. (2021), IAA was linked to SlARF4 as well as SlARF10B, ME-IAA was linked to SlARF6B and SlARF10B, and ICAld was linked to SlARF5 and SlARF7B. It reveals that the AUX/IAA gene family-related genes related to IAA and ME-IAA were moderately similar.

Auxin is transported by two dissimilar linked systems in higher plants, namely a non-directional flow with photoassimilates in the phloem and slowly directed intercellular polar auxin transport (PAT) (Zhang et al., 2022). In addition, the PAT creates an auxin gradient that controls vital processes in organ patterning, cell division, and elongation (Verma et al., 2022). Reactivating cell division is necessary for tissue reunion after perforation or grafting to bridge the gap and permit vascular tissue reconnection (Vega-Muñoz et al., 2020). Cui et al. (2021) reported that the polar auxin transport of PIN1 and PIN6 maps in the drafting process was improved at 312 HAG, indicating that the transcription of snRNA-related genes is related to the build-up of auxin above the graft junction wound in tomato. Auxin accumulates at the plant wound site, triggering a repair process that protects wounds and promotes tissue regeneration (Vega-Muñoz et al., 2020).

ET as a plant growth regulator on various stress factors

Plant ET production can be regulated when plants endure biotic and abiotic stresses. Plants produce ET during germination, leaf abscission, fruit ripening, and floral senescence developmental stages, and it can be secreted in roots, seeds, leaves, flowers, and even in fruits (Baharudin and Osman, 2023). The C_2H4 or $H_2C=CH_2$ is a formula representing the flammable colorless gas ET. Ethylene, a gaseous hormone, is used by plant roots to detect soil compaction (Huang et al., 2022). In a lettuce study, Aires et al. (2020) reported that the ethylene response factor1 (LsERF1) transcription factor was absorbed under high-temperature stresses and assisted lettuce in germinating. LsERF1 is a transcription factor involved in the ET signaling pathway.

As plants' impaired oxylipin and ET signaling enhanced the enactment of striped stem borer (SSB) and the brown rice planthopper *Nilaparvata lugens* and decreased the appealing nature of plants to an SSB larval parasitoid, *Apanteles chilonis*, and it also lowered the levels of volatiles and trypsin protease inhibitors that are induced by herbivores (Mostafa et al., 2022). In lettuce, postharvest cut ET and auxin-related genes were up-regulated at day 0 by 55 to 60%, respectively, whereas 26% was up-regulated at day 7 (Mostafa et al., 2022). These observations indicate a vigorous mobilization of auxin and ET responding pathways instantly after the cut stress. The ET and JA signaling pathways defend plants against biotic factors such as insects (Wielkopolan et al., 2022). Instead, ET and ABA regulate plant responses to herbivores by modifying JA signaling components (Wielkopolan et al., 2022).

GA as a plant growth regulator on various stress factors

Cui et al. (2021) investigated the effects of foliar application of IAA and 6-BA on xylem and phloem reconnection after tomato grafting. They found that both hormones initially facilitated xylem and phloem reconnection and hampered their reconnection at a later stage as the concentration increased. On faba bean (*Vicia faba* L.), Wei et al. (2023) observed that 45 mg l^{-1} dose of IAA phytohormone promotes the chlorophyll (a + b), and carotenoid contents of leaves by 25%, 14%, and 27%, respectively than control. Furthermore, these authors reported that applying IAA significantly promoted key physio-morphological parameters, e.g., net photosynthetic rate, stomatal conductance, and relative water content of bean plant leaves under water-deficit conditions. Declined ET dispersal in compacted soil induces ET signaling to accumulate in tip root tissues, activating the stabilization of OsEIL1, which up-regulates the expression of OsYUC8-mediated auxin biosynthesis (Huang et al., 2022).

Even though plants lack a central nervous system, they must respond to the environmental stress factors for survival, using environmental cues to control growth and organ development. Plants use small molecule signals that strike with neurotransmitters, thereby preventing the genome that encodes the fundamental change and development program, which is altered by environmental stress factors. Environmental signals such as water, energy, light, and temperature influence plant hormone biosynthesis, catabolism, and translocation. Plants use systemic signals to respond to environmental cues. The production of phytoalexins, other secondary metabolites, and structural defenses, such as increased trichome production and cell wall strengthening, can protect the plant from recurring damage once activated (Savatin et al., 2014). Besides, hormone-receptor bonds interact with F-box proteins, resulting in a degradation of transcriptional repressors by the 26S proteasome. This type of signaling alters protein activities and gene transcription, resulting in plant development and physiology changes. Hormones have such profound effects that we produced high-yielding, nutritious, and resilient crops in the twentieth century through breeding and agrochemical approaches. Plant hormones are being looked to in the twenty-first century to aid the increasing food production demand under increasingly adverse environmental cues.

Plant growth regulators are effective when associated with a crosstalk network between synergic and antagonistic metabolic processes. For example, Cato and Macedo (2013) found that tomatoes treated with GA (5 mg l^{-1}) developed longer internodes and delayed flowering, whereas plants treated with only CK (5 mg l^{-1}) formed no axillary buds. In the same study, the fresh matter increased when GA and CK were paired. The crosstalk between major phytohormones can physiologically improve antagonistic interactions between the significant growth stimulants.

The biosynthetic pathways of most plant hormones that have been identified have shown that the genes encoded by many of the enzymes that trigger the biosynthetic steps are cloned. However, due to redundant pathways for its production, the exact processes involved in synthesizing IAA remain unknown. Plant hormones control many aspects of plant growth and development and their responses to their surroundings.

When GAs is not present, their receptor gibberellin-insensitive dwarf1 (GID1) becomes inactive, and the repressor DELLA-contained protein (DELLA) inhibits the activity of the transcription factor Phytochrome-interacting factor (PIF), repressing GA responses. The bioactive GAs can alter the conformation of their receptor GID1, increasing the affinity between GID1 and DELLA and forming the GA-GID1-DELLA complex. As a result, the complex increases the connection between DELLA and SLEEPY1/2 (SLY1/2). Therefore, DELLA is degraded through the SCFSLY1/2 complex by the ubiquitin-proteasome pathway. PIFs are released during the degradation of DELLA, allowing the GA responses. During hormone perception, including the perception of auxin, co-receptor complexes are formed (Hernández-García et al., 2021).

Plant responses to stress follow complex mechanisms, which consist of numerous pathways communicating with one another. For example, when an event of stress occurs, signal transduction cascades are activated, which interact with phytohormone-mediated pathways. Natural phytohormones regulate plant growth and help plants adapt by modulating plant physiology and molecular responses. Co-receptor complexes are formed during hormone perception, including the perception of auxin. Hormone perception can result in signal transmission via protein phosphorylation cascades (Calderon-Villalobos et al., 2010).

GA regulates plant germination, shoot development, and elongation with auxins, as well as the reproduction determination of the plant. SPINDLY inhibits GA responses by possibly stabilizing the DELLA protein. The response to wound-induced damage is rapid, such as the oxidative burst and gene expression related to defense, such as the callus deposition and accumulation of protein base inhibitors and hydrolytic enzymes (Chen et al., 2016). Plant growth regulators have a variety of economic implications in the agricultural field. Their significance has been a boon and benefit to farmers and horticulturists. They took advantage of the practical impact and consequences of these hormones and growth regulators to earn money. The assignment focuses on the economic significance of plant growth regulators.

BR as a plant growth regulator on various stress factors

Teasterone and cathasterone are two BRs linked to several signaling networks, including stress from abiotic sources response, cell membrane advancement, and lignin formation (Jan et al., 2022). The BR biosynthesis-related genes CYP90A1 and CYP90D1 are suppressed by water deficit, indicating that plants adapt to drought by declining BR concentration

Table 1. Examples of commercial biostimulants containing phytohormones as declared on the labels

Product	Composition	Stress factor	Citation
Kepstar®	Extract of seaweed *Ecklonia maxima* containing the following phytohormone-based biostimulants: Auxin (11 mg l^{-1}) and CK (0.03 mg l^{-1}).	Severe drought stress	Sabatino et al. (2023)
Pa-penfuss Kelpak®	Extract of brown seaweed *E. maxima* containing the following phytohormone-based biostimulants: Auxins (11 mg kg^{-1}), CKs (0.03 mg kg^{-1}), an Auxin: CK ratio (367:1), amino acids (2.5 g kg^{-1}), vitamin B1 (0.9 mg kg^{-1}), B2 (0.1 mg kg^{-1}), C (20 mg kg^{-1}), and E (0.7 mg kg^{-1}).	Water-deficit stress	Jiménez-Arias et al. (2022)
Boosten and Megafol®	The two products contain the following phytohormone-based biostimulants: Traces of undisclosed amounts of amino acids, betaines, proteins, vitamins, auxin, GA, and CK.	Extremely low or high-temperature stress	Niu et al. (2022)
MC-Extra®	Derived from *Ascophyllum nodosum* comprises the following phytohormone-based biostimulants: Mannitol (4%), betaines (0.2%), and CKs.	Reduced mineral strength	Loconsole et al. (2023)
Stimplex®	The extract contains 99% *A. nodosum* extract and includes the following phytohormone-based biostimulants: 0.01% Kinetin.	NaCl stress	Ali et al. (2018)
Seasol®	Seaweed extract from *Durvillea potato-rum* and *A. nodosum* species contains minerals and 7 % (w/v) total laminarins, 154 µg l^{-1} total auxins, 36 µg l^{-1} total CKs and 382 µg l^{-1} total betaines.	Reduced mineral strength	Mattner et al. (2023)
ComCat®	It is based on two Nrs: 24-epi-secasterone and 24-epicastasterone.	Drought and nutrient deficiency stress	Gerhards et al. (2021)
Lucky Plant®	It is based on the GK, BRs and traces of CKs.	Simulated hail damage	Khetsha et al. (2022)

(Li et al., 2020). Researchers identified that BRs balance ROS production, JA signal, and the ABA response and are involved in the resistance to moisture and osmotic stress (Kumar et al., 2020).

In a maize study, Gerhards et al. (2021) discovered that BRs functioned as regulating agents in producing vitamin E, which indirectly secured cell membranes from free radical harm, particularly under water stress. The authors also found that BRs are involved in plant growth and development, particularly root development, through cell elongation and division. BR hormones regulate senescence mechanisms in fresh-cut vegetables by changing the lipid composition of cells (Li et al., 2020). Guo et al. (2022) discovered 175 putative IbNAC genes, 15 genomes, and multiple hormone-related cis-elements in sweet potato promoters. In wheat leaves, the transcription levels of transcripts encoding WRKY62, NPR1-type protein 2, PR-4-like, MAPK 3, and the AOC were lower in response to antibiotics-untreated larvae feeding than in plants injured by antibiotics-treated larvae (Wielkopolan et al., 2022).

As illustrated in Table 1, the latest list of phytohormone-based biostimulants has been adapted to alleviate various stress factors. However, it remains a challenge for growers and emerging farmers who cannot afford agricultural insurance on how these phytohormones can combat the novel multi-stress. From this review, it could be noted that warranted future studies should focus on investigating suitable biostimulants on phytohormones in horticultural plants.

CONCLUSIONS

From this review, it could be deduced that using phytohormone-based biostimulants can improve horticultural crops grown under multi-stress conditions, and a few sources could be suggested in South Africa. In addition, this review further proved that future studies should focus on developing phytohormone-based biostimulants as a sustainable tool to mitigate the adverse effects of multi-stress. Therefore, the use and development of natural biostimulants containing phytohormones as an alternative production technique strategy for horticultural plants such as vegetables grown under extreme multi-stress conditions are vital for South African emerging farmers and growers, especially those who cannot afford agricultural insurance options. Currently, studies in the development of phytohormone-based biostimulants for vegetable producers under multi-stress conditions should focus on improving the recovery response mechanism of vegetables using phytohormone-based biostimulants grown under salinity stress conditions following pruning, determining the recovery response mechanism of vegetables to multi stress using phytohormone-based biostimulants as a mitigation strategy; evaluating eco-organic soilless culture combined with phytohormones-based biostimulants as an alternative production system to grow vegetables under multi stress conditions; and assessing the effectiveness of phytohormone-based biostimulant and P application to improve the soil available P, growth, and yield of vegetables grown under multi stress conditions.

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REFERENCES

Aazami, M. A., Maleki, M., Rasouli, F., & Gohari, G. (2023). Protective effects of chitosan based salicylic acid nanocomposite (CS-SA NCs) in grape (*Vitis vinifera* cv. ‘Sultana’) under salinity stress. *Scientific Reports*, *13*(1), 883. https://doi.org/10.1038/s41598-023-27618-z

Abou-Sreea, A. I. B., Azzam, C. R., Al-Taweel, S. K., Abdel-Aziz, R. M., Belal, H. E. E., Rady, M. M., Abdel-Kader, A. A. S., Majrashi, A., & Khaled, K. A. M. (2021). Natural biostimulant attenuates salinity stress effects in chili pepper by remodeling antioxidant, ion, and phytohormone balances, and augments gene expression. *Plants*, *10*(11), 2316. https://doi.org/10.3390/plants10112316

Aires, E. S., Aragão, C. A., Gomes, I. L. S., De Souza, G. N., De Andrade, I. G. V., De Oliveira, A. B. N., Bezerra, W. C., & Yuri, J. E. (2020). Growth and production of crisphead lettuce cultivars in protected cultivation and high temperatures. *Revista Brasileirade*

Ciencias Agrarias, *15*(1), 1–9. https://doi.org/10.5039/AGRARIA.V15I1A6288

Al Murad, M., Khan, A. L., & Muneer, S. (2020). Silicon in horticultural crops: Crosstalk, signaling, and tolerance mechanism under salinity stress. *Plants*, *9*(4), 460. https://doi.org/10.3390/plants9040460

Alam, M., Islam, N., Ahmad, S., Hossen, M., & Islam, M. (2016). Effect of different staking methods and stem pruning on yield and quality of summer tomato. *Bangladesh Journal of Agricultural Research*, *41*(3), 419–432. https://doi.org/10.3329/bjar.v41i3.29714

Ali, O., Ramsubhag, A., & Jayaraman, J. (2018). *Ascophyllum nodosum* (Linnaeus) Le Jolis seaweed extract improves seed germination in tomato and sweet pepper under NaCl-induced salt stress. *Tropical Agriculture*, *95*(2), 141–147. Retrieved from https://journals.sta.uwi.edu/ojs/index.php/ta/article/view/7053

Al-Khayri, J. M., Rashmi, R., Toppo, V., Chole, P. B., Banadka, A., Sudheer, W. N., Nagella, P., Shehata, W. F., Al-Mssallem, M. Q., Alessa, F. M., Almaghasla, M. I., & Rezk, A. A. S. (2023). Plant secondary metabolites: The weapons for biotic stress management. *Metabolites*, *13*(6), 716. https://doi.org/10.3390/metabo13060716

Al-Quraan, N. A., Al-Ajlouni, Z. I., & Qawasma, N. F. (2021). Physiological and biochemical characterization of the gaba shunt pathway in pea (*Pisum sativum* L.) seedlings under drought stress. *Horticulturae*, *7*(6), 125. https://doi.org/10.3390/horticulturae7060125

Al-Soghir, M. M. A., Mohamed, A. G., El-Desoky, M. A., & Awad, A. A. M. (2022). Comprehensive assessment of soil chemical properties for land reclamation purposes in the Tochka area, Egypt. *Sustainability*, *14*(23), 15611. https://doi.org/10.3390/su142315611

Ambrosini, S., Sega, D., Santi, C., Zamboni, A., Varanini, Z., & Pandolfini, T. (2021). Evaluation of the potential use of a collagen-based protein hydrolysate as a plant multi-stress protectant. *Frontiers in Plant Science*, *12*, 600623. https://doi.org/10.3389/fpls.2021.600623

Andreotti, C., Rouphael, Y., Colla, G., & Basile, B. (2022). Rate and timing of application of biostimulant substances to enhance fruit tree tolerance toward environmental stresses and fruit quality. *Agronomy*, *12*(3), 603. https://doi.org/10.3390/agronomy12030603

Arif, M., Jan, T., Riaz, M., Fahad, S., Arif, M. S., Shakoor, M. B., Amanullah, & Rasul, F. (2018). Advances in rice research for abiotic stress tolerance: Agronomic approaches to improve rice production under abiotic stress. *Advances in Rice Research for Abiotic Stress Tolerance*, 585–614. https://doi.org/10.1016/B978-0-12-814332-2.00029-0

Aslam, M., Khubaib, H. M., Awan, B. A., Ali, A., Fatima, S., Ashraf, A., Ikhlaque, H. Z., & Bilal, H. (2022). Agricultural insights for development of genetically modified foods, horticultural crops and role of nanotechnology. *Haya: The Saudi Journal of Life Sciences*, *7*(5), 158–162. https://doi.org/10.36348/sjls.2022.v07i05.003

Awad, A. A. M., Sweed, A. A. A., Rady, M. M., Majrashi, A., & Ali, E. F. (2021). Rebalance the nutritional status and the productivity of high $CaCO_3$-stressed sweet potato plants by foliar nourishment with zinc oxide nanoparticles and ascorbic acid. *Agronomy*, *11*(7), 1443. https://doi.org/10.3390/agronomy11071443

Awkes, M. M. (2010). *Comparison of calcium ameliorants and coal ash in alleviating the effects of subsoil acidity on maize root development near Middelburg, Mpumalanga* (Doctoral dissertation). Stellenbosch: University of Stellenbosch. Retrieved from https://scholar.sun.ac.za/items/9c2c7e67-e781-4435-81db-86845c89fd86

Baharudin, N. F., & Osman, N. I. (2023). Plant development, stress responses, and secondary metabolism under ethylene regulation. *Plant Stress*, *7*, 100146. https://doi.org/10.1016/j.stress.2023.100146

Balali, G. R., Hadi, M. R., Yavari, P., Bidram, H., Naderi, A. G., & Eslami, A. (2008). Effect of pot size, planting date and genotype on minituber production of Marfona potato cultivar. *African Journal of Biotechnology*, *7*(9), 1265–1270. Retrieved from https://www.ajol.info/index.php/ajb/article/view/58660

Balliu, A., Zheng, Y., Sallaku, G., Fernández, J. A., Gruda, N. S., & Tuzel, Y. (2021). Environmental and cultivation factors affect the morphology, architecture and performance of root systems in soilless grown plants.

Horticulturae, *7*(8), 24. https://doi.org/10.3390/horticulturae7080243

Bhattacharya, A. (2021). Effect of soil water deficit on growth and development of plants: A review. *Soil Water Deficit and Physiological Issues in Plants*, pp. 393–488. Springer, Singapore. https://doi.org/10.1007/978-981-33-6276-5_5

Becerra-Moreno, A., Redondo-Gil, M., Benavides, J., Nair, V., Cisneros-Zevallos, L., & Jacobo-Velázquez, D. A. (2015). Combined effect of water loss and wounding stress on gene activation of metabolic pathways associated with phenolic biosynthesis in carrot. *Frontiers in Plant Science*, *6*, 837. https://doi.org/10.3389/fpls.2015.00837

Beheiry, H. R., Awad, A. A. M., & Hussein, H. A. Z. (2023). Response of multi-stressed *Olea europaea* trees to the adjustment of soil pH by acidifying agents: Impacts on nutrient uptake and productivity. *Agronomy*, *13*(2), 539. https://doi.org/10.3390/agronomy13020539

Benamirouche, S., Chouial, M., Guechi, W., & Nanfack, R. F. (2020). Radicle length and container size effects on root deformities in the mediterranean oak quercus suber l. *Bois & Forets Des Tropiques*, *343*, 17–26. https://doi.org/10.19182/bft2020.343.a31669

Bilal, S., Shahzad, R., Asaf, S., Imran, M., Al-Harrasi, A., & Lee, I. J. (2023). Efficacy of endophytic SB10 and glycine betaine duo in alleviating phytotoxic impact of combined heat and salinity in *Glycine max* L. via regulation of redox homeostasis and physiological and molecular responses. *Environmental Pollution*, *316*, 120658. https://doi.org/10.1016/j.envpol.2022.120658

Bisson, C., Adams, N. B. P., Stevenson, B., Brindley, A. A., Polyviou, D., Bibby, T. S., Baker, P. J., Hunter, C. N., & Hitchcock, A. (2017). The molecular basis of phosphite and hypophosphite recognition by ABC-transporters. *Nature Communications*, *8*(1), 1746. https://doi.org/10.1038/s41467-017-01226-8

Bulgari, R., Cocetta, G., Trivellini, A., Vernieri, P., & Ferrante, A. (2015). Biostimulants and crop responses: A review. *Biological Agriculture and Horticulture*, *31*(1), 1–17. https://doi.org/10.1080/01448765.2014.964649

Calderon-Villalobos, L. I., Tan, X., Zheng, N., & Estelle, M. (2010). Auxin perception-structural insights. *Cold Spring Harbor Perspectives in Biology*, *2*(7), a005546. https://doi.org/10.1101/cshperspect.a005546

Canellas, L. P., Olivares, F. L., Aguiar, N. O., Jones, D. L., Nebbioso, A., Mazzei, P., & Piccolo, A. (2015). Humic and fulvic acids as biostimulants in horticulture. *Scientia Horticulturae*, *196*, 15–27. https://doi.org/10.1016/j.scienta.2015.09.013

Caparas, M., Zobel, Z., Castanho, A. D. A., & Schwalm, C. R. (2021). Increasing risks of crop failure and water scarcity in global breadbaskets by 2030. *Environmental Research Letters*, *16*(10), 104013. https://doi.org/10.1088/1748-9326/ac22c1

Cato, S. C., & Macedo, W. R. (2013). Sinergism among auxins, gibberellins and cytokinins in tomato cv. Micro-Tom *Horticultura Brasileira*, *31*, 549–553. https://doi.org/10.1590/S0102-05362013000400007

Chalise, S., Naranpanawa, A., Bandara, J. S., & Sarker, T. (2017). A general equilibrium assessment of climate change–induced loss of agricultural productivity in Nepal. *Economic Modelling*, *62*, 43–50. https://doi.org/10.1016/j.econmod.2017.01.014

Chen, L., Sun, B., Xu, L., & Liu, W. (2016). Wound signaling: The missing link in plant regeneration. *Plant Signaling and Behavior*, *11*(10), e1238548. https://doi.org/10.1080/15592324.2016.1238548

Clément, J., Delisle-Houde, M., Nguyen, T. T. A., Dorais, M., & Tweddell, R. J. (2023). Effect of biostimulants on leafy vegetables (Baby Leaf lettuce and Batavia lettuce) exposed to abiotic or biotic stress under two different growing systems. *Agronomy*, *13*(3), 879. https://doi.org/10.3390/agronomy13030879

Cui, Q., Xie, L., Dong, C., Gao, L., & Shang, Q. (2021). Stage-specific events in tomato graft formation and the regulatory effects of auxin and cytokinin. *Plant Science*, *304*, 110803. https://doi.org/10.1016/j.plantsci.2020.110803

Cunha, A. F. A., Rodrigues, P. H. D., Anghinoni, A. C., de Paiva, V. J., Pinheiro, D. G. da S., & Campos, M. L. (2023). Mechanical wounding impacts the growth versus defense balance in tomato (*Solanum lycopersicum*). *Plant*

Science, *329*, 111601. https://doi.org/10.1016/j.plantsci.2023.111601

Daryanto, S., Wang, L., & Jacinthe, P. A. (2016). Global synthesis of drought effects on maize and wheat production. *PLoS ONE*, *11*(5), e0156362. https://doi.org/10.1371/journal.pone.0156362

Delgado, C., Mora-poblete, F., Ahmar, S., Chen, J. T., & Figueroa, C. R. (2021). Jasmonates and plant salt stress: Molecular players, physiological effects, and improving tolerance by using genome-associated tools. *International Journal of Molecular Sciences*, *22*(6), 3082. https://doi.org/10.3390/ijms22063082

Dewi, W. S., Amalina, D. D., & Romadhon, M. R. (2023). Microbial biofilm for soil health, plant growth, and productivity under multi stress. A Review. *IOP Conference Series: Earth and Environmental Science*, *1162*(1), 012008. https://doi.org/10.1088/1755-1315/1162/1/012008

Dokwal, D., Romsdahl, T. B., Kunz, D. A., Alonso, A. P., & Dickstein, R. (2021). Phosphorus deprivation affects composition and spatial distribution of membrane lipids in legume nodules. *Plant Physiology*, *185*(4), 1847–1859. https://doi.org/10.1093/plphys/kiaa115

Dong, X., Tang, H., Zhang, Q., Zhang, C., & Wang, Z. (2022). Transcriptomic analyses provide new insights into jujube fruit quality affected by water deficit stress. *Scientia Horticulturae*, *291*, 110558. https://doi.org/10.1016/j.scienta.2021.110558

du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae*, 196, 3–14. https://doi.org/10.1016/j.scienta.2015.09.021

FAO. (2016). *The state of food and agriculture. Climate change, agriculture and food security*. Rome-Italy: Food and Agriculture Organization of the United States. Retrieved from https://www.fao.org/3/i6030e/i6030e.pdf

Farooq, M., Gogoi, N., Barthakur, S., Baroowa, B., Bharadwaj, N., Alghamdi, S. S., & Siddique, K. H. M. (2017). Drought stress in grain legumes during reproduction and grain filling. *Journal of Agronomy and Crop Science*, *203*(2), 81–102. https://doi.org/10.1111/jac.12169

Fiorucci, A. S., Michaud, O., Schmid-Siegert, E., Trevisan, M., Petrolati, L. A., Ince, Y. Ç., & Fankhauser, C. (2022). Shade suppresses wound-induced leaf repositioning through a mechanism involving PHYTOCHROME KINASE SUBSTRATE (PKS) genes. *PLoS Genetics*, *18*(5), e1010213. https://doi.org/10.1371/journal.pgen.1010213

Franzoni, G. (2020). *Mechanisms of action of biostimulants in crops* (Doctoral dissertation). Institutional Research Information System - AIR Archivio Istituzionale della Ricerca. Retrieved from https://air.unimi.it/handle/2434/703322

Galieni, A., Di Mattia, C., De Gregorio, M., Speca, S., Mastrocola, D., Pisante, M., & Stagnari, F. (2015). Effects of nutrient deficiency and abiotic environmental stresses on yield, phenolic compounds and antiradical activity in lettuce (*Lactuca sativa* L.). *Scientia Horticulturae*, *187*, 93–101. https://doi.org/10.1016/j.scienta.2015.02.036

Gao, Y. Q., & Farmer, E. E. (2023). Osmoelectric siphon models for signal and water dispersal in wounded plants. *Journal of Experimental Botany*, *74*(4), 1207–1220. https://doi.org/10.1093/jxb/erac449

Gerhards, R., Ouidoh, F. N., Adjogboto, A., Avohou, V. A. P., Dossounon, B. L. S., Adisso, A. K. D., Heyn, A., Messelhäuser, M., Santel, H. J., & Oebel, H. (2021). Crop response to leaf and seed applications of the biostimulant ComCat® under stress conditions. *Agronomy*, *11*(6), 1161. https://doi.org/10.3390/agronomy11061161

González-Morales, S., Solís-Gaona, S., Valdés-Caballero, M. V., Juárez-Maldonado, A., Loredo-Treviño, A., & Benavides-Mendoza, A. (2021). Transcriptomics of biostimulation of plants under abiotic stress. *Frontiers in Genetics*, *12*, 583888. https://doi.org/10.3389/fgene.2021.583888

Gruda, N. S. (2019). Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy*, *9*(6), 298. https://doi.org/10.3390/agronomy9060298

Guan, W., Edwards, M. G., Gatehouse, J. A., & Gatehouse, A. M. R. (2022). Responses of wheat (*Triticum aestivum*) to grain aphid (*Sitobion avenae*) infestation and mechanical wounding using a cDNA subtractitve library approach. *Agricultural Sciences*, *13*(06), 715–740. https://doi.org/10.4236/as.2022.136047

Guo, M., Wang, X. S., Guo, H. D., Bai, S. Y., Khan, A., Wang, X. M., Gao, Y. M., & Li, J. S. (2022). Tomato salt tolerance mechanisms and their potential applications for fighting salinity: A review. *Frontiers in Plant Science, 13*, 949541. https://doi.org/10.3389/fpls.2022.949541

Haase, D. L., Bouzza, K., Emerton, L., Friday, J. B., Lieberg, B., Aldrete, A., & Davis, A. S. (2021). The high cost of the low-cost polybag system: A review of nursery seedling production systems. *Land*, *10*(8), 826. https://doi.org/10.3390/land10080826

Habib, S., Lwin, Y. Y., & Li, N. (2021). Article down-regulation of slgras10 in tomato confers abiotic stress tolerance. *Genes*, *12*(5), 623. https://doi.org/10.3390/genes12050623

Hai, N. N., Chuong, N. N., Tu, N. H. C., Kisiala, A., Hoang, X. L. T., & Thao, N. P. (2020). Role and regulation of cytokinins in plant response to drought stress. *Plants*, *9*(4), 422. https://doi.org/10.3390/plants9040422

Hajihashemi, S., Mbarki, S., Skalicky, M., Noedoost, F., Raeisi, M., & Brestic, M. (2020). Effect of wastewater irrigation on photosynthesis, growth, and anatomical features of two wheat cultivars (*Triticum aestivum* L.). *Water*, *12*(2), 607. https://doi.org/10.3390/w12020607

Hanus-Fajerska, E., Kępka, K., Kruszyna, C., & Kamińska, I. (2023). Plant-based solutions for non-productive sites useful in the management of dry land. *Plants*, *12*(3), 537. https://doi.org/10.3390/plants12030537

Hernández-García, J., Briones-Moreno, A., & Blázquez, M. A. (2021). Origin and evolution of gibberellin signaling and metabolism in plants. *Seminars in Cell and Developmental Biology, 109*, 46–54. https://doi.org/10.1016/j.semcdb.2020.04.009

Hoque, M. M., & Kobata, T. (2000). Effect of soil compaction on the grain yield of rice (*Oryza sativa* L.) under water-deficit stress during the reproductive stage. *Plant Production Science*, *3*(3), 316–322. https://doi.org/10.1626/pps.3.316

Hossain, A., Pamanick, B., Venugopalan, V. K., Ibrahimova, U., Rahman, M. A., Siyal, A. L., Maitra, S., Chatterjee, S., & Aftab, T. (2021). Emerging roles of plant growth regulators for plants adaptation to abiotic stress-induced oxidative stress. *Emerging Plant Growth Regulators in Agriculture: Roles in Stress Tolerance*, pp. 1–72. https://doi.org/10.1016/B978-0-323-91005-7.00010-2

Huang, G., Kilic, A., Karady, M., Zhang, J., Mehra, P., Song, X., Sturrock, C. J., Zhu, W., Qin, H., Hartman, S., Schneider, H. M., Bhosale, R., Dodd, I. C., Sharp, R. E., Huang, R., Mooney, S. J., Liang, W., Bennett, M. J., Zhang, D., & Pandey, B. K. (2022). Ethylene inhibits rice root elongation in compacted soil via ABA- and auxin-mediated mechanisms. *Proceedings of the National Academy of Sciences of the United States of America, 119*(30), e2201072119. https://doi.org/10.1073/pnas.2201072119

Ibrahim, A., Harrison, M., Meinke, H., Fan, Y., Johnson, P., & Zhou, M. (2018). A regulator of early flowering in barley (*Hordeum vulgare* L.). *PLoS ONE*, *13*(7), e0200722. https://doi.org/10.1371/journal.pone.0200722

Inoue, T., Sunaga, M., Ito, M., Yuchen, Q., Matsushima, Y., Sakoda, K., & Yamori, W. (2021). Minimizing VPD fluctuations maintains higher stomatal conductance and photosynthesis, resulting in improvement of plant growth in lettuce. *Frontiers in Plant Science*, *12*, 646144. https://doi.org/10.3389/fpls.2021.646144

Iqbal, M. S., Singh, A. K., & Ansari, M. I. (2020). Effect of drought stress on crop production. *New Frontiers in Stress Management for Durable Agriculture*, pp. 35–47. Springer, Singapore. https://doi.org/10.1007/978-981-15-1322-0_3

Isa, M. M., Kasim, K. F., Muttalib, M. F. A., & Jaafar, M. N. (2021). Physical and chemical properties of different media mixture as D growing medium for containerized plant. *AIP Conference Proceedings*, *2339*, 020122. https://doi.org/10.1063/5.0044253

Jackson, K., Meetei, T. T., Jackson, K., & Meetei, T. T. (2018). Influence of soil pH on nutrient availability: A Review. *International Journal of Emerging Technologies and Innovative Research*, *5*(12), 707–713. Retrieved from http://www.jetir.org/papers/JETIRDZ06090.pdf

Jaiswal, S. K., Naamala, J., & Dakora, F. D. (2018). Nature and mechanisms of aluminium toxicity, tolerance and amelioration in symbiotic legumes and rhizobia. *Biology and Fertility of Soils*, *54*(3), 309–318. https://doi.org/10.1007/s00374-018-1262-0

Jan, R., Khan, M. A., Asaf, S., Lubna, Waqas, M., Park, J. R., Asif, S., Kim, N., Lee, I. J., & Kim, K. M. (2022). Drought and UV radiation stress tolerance in rice is improved by overaccumulation of non-enzymatic antioxidant flavonoids. *Antioxidants*, *11*(5), 917. https://doi.org/10.3390/antiox11050917

Jiménez-Arias, D., Morales-Sierra, S., Borges, A. A., Herrera, A. J., & Luis, J. C. (2022). New biostimulants screening method for crop seedlings under water deficit stress. *Agronomy*, *12*(3), 728. https://doi.org/10.3390/agronomy12030728

Jogawat, A., Yadav, B., Chhaya, Lakra, N., Singh, A. K., & Narayan, O. P. (2021). Crosstalk between phytohormones and secondary metabolites in the drought stress tolerance of crop plants: A review. *Physiologia Plantarum*, *172*(2), 1106–1132. https://doi.org/10.1111/ppl.13328

Kang, J., Chu, Y., Ma, G., Zhang, Y., Zhang, X., Wang, M., Lu, H., Wang, L., Kang, G., Ma, D., Xie, Y., & Wang, C. (2023). Physiological mechanisms underlying reduced photosynthesis in wheat leaves grown in the field under conditions of nitrogen and water deficiency. *Crop Journal*, *11*(2), 638–650. https://doi.org/10.1016/j.cj.2022.06.010

Kapoore, R. V., Wood, E. E., & Llewellyn, C. A. (2021). Algae biostimulants: A critical look at microalgal biostimulants for sustainable agricultural practices. *Biotechnology Advances*, *49*, 107754. https://doi.org/10.1016/j.biotechadv.2021.107754

Khattak, A., Ullah, F., Shinwari, Z. K., & Mehmood, S. (2021). The effect of titanium dioxide nanoparticles and salicylic acid on growth and biodiesel production potential of sunflower (*Helianthus annuus* L.) under water stress. *Pakistan Journal of Botany*, *53*(6), 1987–1995. https://doi.org/10.30848/PJB2021-6(42)

Khetsha, Z. P. (2020). *Using agricultural plant growth regulators as a mitigating strategy for hail-damaged rose geranium (Pelargonium graveolens L'Hér.)* (Doctoral dissertation). Central University of Technology. Retrieved from http://ir.cut.ac.za/handle/11462/2346

Khetsha, Z. P., Mahmood Sedibe, M., Johannes Pretorius, R., Caiphus Rathebe, P., & Moloantoa, K. (2022). Using biostimulants containing phytohormones to recover hail-damaged essential oil plants. *IntechOpen*. https://doi.org/10.5772/intechopen.102398

Khetsha, Z. P., Sedibe, M. M., & Pretorius, R. J. (2020). Effects of abscisic acid and methyl jasmonate on the recovery of hail damaged rose geranium (*Pelargonium graveolens*) plants. *Acta Horticulturae*, 1287, 31–40. https://doi.org/10.17660/ActaHortic.2020.1287.5

Khetsha, Z. P., Sedibe, M. M., Pretorius, R. J. & Van Der Watt, E. (2023). Biostimulants improve the leaf micro-morphology and essential oil biosynthesis of simulated hail-damaged *Pelargonium graveolens* (L'Hér.). *Acta Horticulturae*, 1372, 283–294. https://doi.org/10.17660/ActaHortic.2023.1372.37

Kiremit, M. S., Osman, H. M., & Arslan, H. (2022). Response of yield, growth traits, and leaf nutrients of garden cress to deficit saline irrigation waters. *Journal of Plant Nutrition*, *46*(6), 1050–1065. https://doi.org/10.1080/01904167.2022.2072333

Koehler, T., Moser, D. S., Botezatu, Á., Murugesan, T., Kaliamoorthy, S., Zarebanadkouki, M., Bienert, M. D., Bienert, G. P., Carminati, A., Kholová, J., & Ahmed, M. (2022). Going underground: Soil hydraulic properties impacting maize responsiveness to water deficit. *Plant and Soil*, *478*(1–2), 43–58. https://doi.org/10.1007/s11104-022-05656-2

Kudoyarova, G., Veselov, D., Yemelyanov, V., & Shishova, M. (2022). The role of aquaporins in plant growth under conditions of oxygen deficiency. *International Journal of Molecular Sciences*, *23*(17), 10159. https://doi.org/10.3390/ijms231710159

Kumar, S., Bhushan, B., Wakchaure, G. C., Meena, K. K., Kumar, M., Meena, N. L., & Rane, J. (2020). Plant phenolics under water-deficit conditions: Biosynthesis, accumulation, and physiological roles in water stress alleviation. *Plant Phenolics in Sustainable Agriculture*, *1*, 451–465.

https://doi.org/10.1007/978-981-15-4890-1_19

Kwak, S. S. (2019). Biotechnology of the sweetpotato: Ensuring global food and nutrition security in the face of climate change. *Plant Cell Reports*, *38*(11), 1361–1363. https://doi.org/10.1007/s00299-019-02468-0

Landi, S., Hausman, J. F., Guerriero, G., & Esposito, S. (2017). Poaceae vs. abiotic stress: Focus on drought and salt stress, recent insights and perspectives. *Frontiers in Plant Science*, *8*, 1214. https://doi.org/10.3389/fpls.2017.01214

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K. F., & Konar, M. (2022). Compound heat and moisture extreme impacts on global crop yields under climate change. *Nature Reviews Earth and Environment*, *3*(12), 872–889. https://doi.org/10.1038/s43017-022-00368-8

Li, W., Gupta, A., Tian, H., Nguyen, K. H., Tran, C. D., Watanabe, Y., Tian, C., Li, K., Yang, Y., Guo, J., Luo, Y., Miao, Y., & Phan Tran, L. S. (2020). Different strategies of strigolactone and karrikin signals in regulating the resistance of *Arabidopsis thaliana* to water-deficit stress. *Plant Signaling and Behavior*, *15*(9), 1789321. https://doi.org/10.1080/15592324.2020.1789321

Li, X. F., Zuo, F. H., Ling, G. Z., Li, Y. Y., Yu, Y. X., Yang, P. Q., & Tang, X. L. (2009). Secretion of citrate from roots in response to aluminum and low phosphorus stresses in Stylosanthes. *Plant and Soil*, *325*(1), 219–229. https://doi.org/10.1007/s11104-009-9971-7

Liebenberg, A., van der Nest, J. R., Hardie, A. G., Labuschagne, J., & Swanepoel, P. A. (2020). Extent of soil acidity in no-tillage systems in the western Cape province of South Africa. *Land*, *9*(10), 361. https://doi.org/10.3390/land9100361

Lim, M. M. L., Søgaard Jørgensen, P., & Wyborn, C. A. (2018). Reframing the sustainable development goals to achieve sustainable development in the anthropocene—a systems approach. *Ecology and Society*, *23*(3), 22. https://doi.org/10.5751/ES-10182-230322

Liu, J., Shu, D., Tan, Z., Ma, M., Guo, N., Gao, S., Duan, G., Kuai, B., Hu, Y., Li, S., & Cui, D. (2022). The Arabidopsis IDD14 transcription factor interacts with bZIP-type ABFs/AREBs and cooperatively regulates ABA-mediated drought tolerance. *New Phytologist*, *236*(3), 929–942. https://doi.org/10.1111/nph.18381

Loconsole, D., Cristiano, G., & De Lucia, B. (2023). Biostimulant application, under reduced nutrient supply, enhances quality and sustainability of ornamental containerized transplants. *Agronomy*, *13*(3), 765. https://doi.org/10.3390/agronomy13030765

Lu, J., Shao, G., Gao, Y., Zhang, K., Wei, Q., & Cheng, J. (2021). Effects of water deficit combined with soil texture, soil bulk density and tomato variety on tomato fruit quality: A meta-analysis. *Agricultural Water Management*, *243*, 106427. https://doi.org/10.1016/j.agwat.2020.106427

Ma, Y., Dias, M. C., & Freitas, H. (2020). Drought and salinity stress responses and microbe-induced tolerance in plants. *Frontiers in Plant Science*, *11*, 591911. https://doi.org/10.3389/fpls.2020.591911

Maboko, M. M., & Plooy, C. P. du. (2008). Effect of pruning on yield and quality of hydroponically grown cherry tomato (*Lycopersicon esculentum*). *South African Journal of Plant and Soil*, *25*(3), 178–181. https://doi.org/10.1080/02571862.2008.10639914

Malhotra, H., Vandana, Sharma, S., & Pandey, R. (2018). Phosphorus nutrition: Plant growth in response to deficiency and excess. *Plant Nutrients and Abiotic Stress Tolerance*, pp. 171–190. Springer, Singapor. https://doi.org/10.1007/978-981-10-9044-8_7

Mattner, S. W., Villalta, O. N., McFarlane, D. J., Islam, M. T., Arioli, T., & Cahill, D. M. (2023). The biostimulant effect of an extract from *Durvillaea potatorum* and *Ascophyllum nodosum* is associated with the priming of reactive oxygen species in strawberry in south-eastern Australia. *Journal of Applied Phycology*, *35*(4), 1789–1800. https://doi.org/10.1007/s10811-023-02979-0

McKay, D. A., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Updated assessment suggests >1.5°C global warming could trigger multiple climate tipping points. *Earth and Space Science Open Archive*, pp. 1–80.

Retrieved from https://d197for5662m48.cloudfront.net/documents/publicationstatus/98433/preprint_pdf/25c0099969d2b05f790906b2c8023572.pdf

Meents, A. K., Chen, S. P., Reichelt, M., Lu, H. H., Bartram, S., Yeh, K. W., & Mithöfer, A. (2019). Volatile DMNT systemically induces jasmonate-independent direct anti-herbivore defense in leaves of sweet potato (*Ipomoea batatas*) plants. *Scientific Reports*, *9*(1), 17431. https://doi.org/10.1038/s41598-019-53946-0

Melrose, J., & Normandeau, S. (2021). The prairie gardener's go-to for small spaces. *Touchwood Editions*. Retrieved from https://books.google.co.id/books?hl=id&lr=&id=7nIOEAAAQBAJ&oi=fnd&pg=PT5&dq=The+prairie+gardener%27s+go-to+for+small+spaces&ots=XRIt9a0UrI&sig=ffYU1ryq0m3MYQYFaZ92ZzzUN98&redir_esc=y#v=onepage&q=The%20prairie%20gardener's%20go-to%20for%20small%20spaces&f=false

Meng, X., Chen, W. W., Wang, Y. Y., Huang, Z. R., Ye, X., Chen, L. S., & Yang, L. T. (2021). Effects of phosphorus deficiency on the absorption of mineral nutrients, photosynthetic system performance and antioxidant metabolism in *Citrus grandis*. *PLoS ONE*, *16*, e0246944. https://doi.org/10.1371/journal.pone.0246944

Million, J. B., & Yeager, T. H. (2022). Fabric containers increased irrigation demand but decreased leachate loss of nitrogen and phosphorus compared with conventional plastic containers during production of dwarf Burford Holly. *HortScience*, *57*(7), 743–749. https://doi.org/10.21273/HORTSCI16570-22

Minhas, P. S., Rane, J., & Pasala, R. K. (2017). Abiotic stresses in agriculture: An overview. *Abiotic Stress Management for Resilient Agriculture*, pp. 3–8. Springer, Singapore. https://doi.org/10.1007/978-981-10-5744-1_1

Mo, Z., Feng, G., Su, W., Liu, Z., & Peng, F. (2018). Transcriptomic analysis provides insights into grafting union development in pecan (*Carya illinoinensis*). *Genes*, *9*(2), 71. https://doi.org/10.3390/genes9020071

Mostafa, S., Wang, Y., Zeng, W., & Jin, B. (2022). Plant responses to herbivory, wounding, and infection. *International Journal of Molecular Sciences*, *23*(13), 7031. https://doi.org/10.3390/ijms23137031

Mundaya Narayanan, J., Viswanathan, V., Tirumalai Ramanujam, T., & Nagendra Rao, K. (2023). Improving tomato productivity for changing climatic and environmental stress conditions. *Tomato Cultivation and Consumption - Innovation, Sustainability and Health*. IntechOpen. https://doi.org/10.5772/intechopen.112251

Muneer, S., & Jeong, B. R. (2015). Proteomic analysis provides new insights in phosphorus homeostasis subjected to pi (inorganic phosphate) starvation in tomato plants (*Solanum lycopersicum* L.). *PLoS ONE*, *10*(7), e0134103. https://doi.org/10.1371/journal.pone.0134103

Nephali, L., Piater, L. A., Dubery, I. A., Patterson, V., Huyser, J., Burgess, K., & Tugizimana, F. (2020). Biostimulants for plant growth and mitigation of abiotic stresses: A metabolomics perspective. *Metabolites*, *10*(12), 505. https://doi.org/10.3390/metabo10120505

Niu, C., Wang, G., Sui, J., Liu, G., Ma, F., & Bao, Z. (2022). Biostimulants alleviate temperature stress in tomato seedlings. *Scientia Horticulturae*, *293*, 110712. https://doi.org/10.1016/j.scienta.2021.110712

Numan, M., Serba, D. D., & Ligaba-Osena, A. (2021). Alternative strategies for multi-stress tolerance and yield improvement in millets. *Genes*, *12*(5), 739. https://doi.org/10.3390/genes12050739

Pandey, P., Irulappan, V., Bagavathiannan, M. V., & Senthil-Kumar, M. (2017). Impact of combined abiotic and biotic stresses on plant growth and avenues for crop improvement by exploiting physio-morphological traits. *Frontiers in Plant Science*, *8*, 00537. https://doi.org/10.3389/fpls.2017.00537

Parkash, V., & Singh, S. (2020). A review on potential plant-basedwater stress indicators for vegetable crops. *Sustainability*, *12*(10), 3945. https://doi.org/10.3390/SU12103945

Peterson, M. T. (2020). *Screening of ten maize genotypes for tolerance to acid soils using various methods* (Doctoral dissertation). University of South Africa. Retrieved from https://uir.unisa.ac.za/handle/10500/26855

Petropoulos, S. A. (2020). Practical applications of plant biostimulants in greenhouse vegetable crop production. *Agronomy, 10*(10), 1569. https://doi.org/10.3390/agronomy10101569

Pietrak, A., Salachna, P., & Łopusiewicz, Ł. (2023). Changes in growth, ionic status, metabolites content and antioxidant activity of two ferns exposed to shade, full sunlight, and salinity. *International Journal of Molecular Sciences*, *24*(1), 296. https://doi.org/10.3390/ijms24010296

Rai, N., Rai, S. P., & Sarma, B. K. (2021). Prospects for abiotic stress tolerance in crops utilizing phyto- and bio-stimulants. *Frontiers in Sustainable Food Systems*, *5*, 754853. https://doi.org/10.3389/fsufs.2021.754853

Ramzan, F., & Younis, A. (2022). Use of biostimulants in tolerance of drought stress in agricultural crops. *Emerging Plant Growth Regulators in Agriculture*, pp. 429–446. https://doi.org/10.1016/B978-0-323-91005-7.00001-1

Rana, V. S., Sharma, S., Rana, N., & Sharma, U. (2022). Sustainable production through biostimulants under fruit orchards. *CABI Agriculture and Bioscience*, *3*(1), 38. https://doi.org/10.1186/s43170-022-00102-w

Raza, M. A., Gul, H., Wang, J., Yasin, H. S., Qin, R., Bin Khalid, M. H., Naeem, M., Feng, L. Y., Iqbal, N., Gitari, H., Ahmad, S., Battaglia, M., Ansar, M., Yang, F., & Yang, W. (2021). Land productivity and water use efficiency of maize-soybean strip intercropping systems in semi-arid areas: A case study in Punjab Province, Pakistan. *Journal of Cleaner Production*, *308*, 127282. https://doi.org/10.1016/j.jclepro.2021.127282

Repke, R. A., Silva, D. M. R., dos Santos, J. C. C., & de Almeida Silva, M. (2022). Alleviation of drought stress in soybean by applying a biostimulant based on amino acids and macro- and micronutrients. *Agronomy*, *12*(10), 2244. https://doi.org/10.3390/agronomy12102244

Rezaei-Chiyaneh, E., Mahdavikia, H., Alipour, H., Dolatabadian, A., Battaglia, M. L., Maitra, S., & Harrison, M. T. (2023). Biostimulants alleviate water deficit stress and enhance essential oil productivity: A case study with savory. *Scientific Reports*, *13*(1), 720. https://doi.org/10.1038/s41598-022-27338-w

Riaz, M., Arif, M. S., Ashraf, M. A., Mahmood, R., Yasmeen, T., Shakoor, M. B., Shahzad, S. M., Ali, M., Saleem, I., Arif, M., & Fahad, S. (2018). A comprehensive review on rice responses and tolerance to salt stress. *Advances in Rice Research for Abiotic Stress Tolerance*, 133–158. https://doi.org/10.1016/B978-0-12-814332-2.00007-1

Rouphael, Y., Raimondi, G., Lucini, L., Carillo, P., Kyriacou, M. C., Colla, G., Cirillo, V., Pannico, A., El-Nakhel, C., & De Pascale, S. (2018). Physiological and metabolic responses triggered by omeprazole improve tomato plant tolerance to NaCl stress. *Frontiers in Plant Science*, *9*, 00249. https://doi.org/10.3389/fpls.2018.00249

Sabatino, L., Consentino, B. B., Rouphael, Y., Baldassano, S., De Pasquale, C., & Ntatsi, G. (2023). Ecklonia maxima-derivate seaweed extract supply as mitigation strategy to alleviate drought stress in chicory plants. *Scientia Horticulturae, 312,* 111856. https://doi.org/10.1016/j.scienta.2023.111856

Sabina, S., & Jithesh, M. N. (2021). Mechanical wounding of leaf midrib and lamina elicits differential biochemical response and mitigates salinity induced damage in tomato. *Journal of Applied Horticulture*, *23*(1), 3–10. https://doi.org/10.37855/jah.2021.v23i01.01

Sack, L., & Buckley, T. N. (2020). Trait multi-functionality in plant stress response. *Integrative and Comparative Biology*, *60*(1), 98–112. https://doi.org/10.1093/icb/icz152

Savatin, D. V., Gramegna, G., Modesti, V., & Cervone, F. (2014). Wounding in the plant tissue: The defense of a dangerous passage. *Frontiers in Plant Science*, *5*, 00470. https://doi.org/10.3389/fpls.2014.00470

Schuch, U. K., & Quist, T. M. (2023). *Arizona landscape palms and their management*. The University of Arizona Cooperative Extension Press, pp. 1–14. Retrieved from https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az2021-2023.pdf

Sedibe, M. M., Khetsha, Z. P., & Malebo, N. (2013). Salinity effects on external and internal morphology of rose geranium (*Pelargonium graveolens* L.) leaf. *Life Science Journal*, *10*(11), 99–103. Retrieved from http://hdl.handle.net/11462/1515

Sehgal, A., Reddy, K. R., Walne, C. H., Barickman, T. C., Brazel, S., Chastain, D., & Gao, W. (2022). Individual and interactive effects of multiple abiotic stress treatments on early-season growth and development of two

Brassica species. *Agriculture*, *12*(4), 453. https://doi.org/10.3390/agriculture12040453

Shomali, A., Das, S., Arif, N., Sarraf, M., Zahra, N., Yadav, V., Aliniaeifard, S., Chauhan, D. K., & Hasanuzzaman, M. (2022). Diverse physiological roles of flavonoids in plant environmental stress responses and tolerance. *Plants*, *11*(22), 3158. https://doi.org/10.3390/plants11223158

Silva, L. I. da, Pereira, M. C., Carvalho, A. M. X. de, Buttrós, V. H., Pasqual, M., & Dória, J. (2023). Phosphorus-solubilizing microorganisms: A key to sustainable agriculture. *Agriculture*, *13*(2), 462. https://doi.org/10.3390/agriculture13020462

Sondhi, S. (2023). Applications of bioplastic in composting bags and planting pots. *Handbook of Bioplastics and Biocomposites Engineering Applications*, 605–617. https://doi.org/10.1002/9781119160182.ch28

Stagnari, F., Galieni, A., Speca, S., & Pisante, M. (2014). Water stress effects on growth, yield and quality traits of red beet. *Scientia Horticulturae*, *165*, 13–22. https://doi.org/10.1016/j.scienta.2013.10.026

Sultan, K., Perveen, S., Parveen, A., Atif, M., & Zafar, S. (2023). Benzyl Amino Purine (BAP), moringa leaf extract and ascorbic acid induced drought stress tolerance in pea (*Pisum sativum* L.). *Gesunde Pflanzen*, *75*(6), 2423–2436. https://doi.org/10.1007/s10343-023-00890-9

Tadele, K. T., & Zerssa, G. W. (2023). Biostimulants and phytohormones improve productivity and quality of medicinal plants under abiotic stress. *Medicinal Plants: Their Response to Abiotic Stress*, pp. 335–362. Springer, Singapore. https://doi.org/10.1007/978-981-19-5611-9_13

Tarigan, M., Wingfield, M. J., van Wyk, M., Tjahjono, B., & Roux, J. (2011). Pruning quality affects infection of *Acacia mangium* and *A. crassicarpa* by *Ceratocystis acaciivora* and *Lasiodiplodia theobromae*. *Southern Forests*, *73*(3–4), 187–191. https://doi.org/10.2989/20702620.2011.639498

Turan, M., Yildirim, E., Ekinci, M., & Argin, S. (2021). Effect of biostimulants on yield and quality of cherry tomatoes grown in fertile and stressed soils. *HortScience*, *56*(4), 414–423. https://doi.org/10.21273/HORTSCI15568-20

Turner, N. C. (2019). Imposing and maintaining soil water deficits in drought studies in pots. *Plant and Soil*, *439*(1–2), 45–55. https://doi.org/10.1007/s11104-018-3893-1

Vega-Muñoz, I., Duran-Flores, D., Fernández-Fernández, Á. D., Heyman, J., Ritter, A., & Stael, S. (2020). Breaking bad news: Dynamic molecular mechanisms of wound response in plants. *Frontiers in Plant Science*, *11*, 610445. https://doi.org/10.3389/fpls.2020.610445

Venugopal, D., Vishwakarma, S., Kaur, I., & Samavedi, S. (2023). Electrospun fiber-based strategies for controlling early innate immune cell responses: Towards immunomodulatory mesh designs that facilitate robust tissue repair. *Acta Biomaterialia*, *11*, 228–247. https://doi.org/10.1016/j.actbio.2022.06.004

Verma, P. K., Verma, S., & Pandey, N. (2022). Root system architecture in rice: impacts of genes, phytohormones and root microbiota. *3 Biotech*, *12*(9), 239. https://doi.org/10.1007/s13205-022-03299-9

Wani, S. H., Kumar, V., Shriram, V., & Sah, S. K. (2016). Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. *Crop Journal*, *4*(3), 162–176. https://doi.org/10.1016/j.cj.2016.01.010

Warren, R., Price, J., Graham, E., Forstenhaeusler, N., & VanDerWal, J. (2018). The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, *360*(6390), 791–795. https://doi.org/10.1126/science.aar3646

Wei, X., Liao, R., Zhang, X., Zhao, Y., Xie, Z., Yang, S., Su, H., Wang, Z., Zhang, L., Tian, B., Wei, F., & Yuan, Y. (2023). Integrative transcriptome, miRNAs, degradome, and phytohormone analysis of *Brassica rapa* L. in response to *Plasmodiophora brassicae*. *International Journal of Molecular Sciences*, *24*(3), 2414. https://doi.org/10.3390/ijms24032414

Weil, R. R., & Brady, N. C. (2016). *The nature and properties of soils, ed*. Columbus, Ohio: Pearson, 910. Retrieved from https://scholar.google.co.id/scholar?cites=6066109438040124111&as_sdt=2005&sciodt=0,5&hl=id

Wielkopolan, B., Frąckowiak, P., Wieczorek, P., & Obrępalska-Stęplowska, A. (2022). The impact of *Oulema melanopus*—Associated bacteria on the wheat defense response to the feeding of their insect hosts. *Cells*, *11*(15), 2342. https://doi.org/10.3390/cells11152342

Wissuwa, M. (2003). How do plants achieve tolerance to phosphorus deficiency? Small causes with big effects. *Plant Physiology*, *133*(4), 1947–1958. https://doi.org/10.1104/pp.103.029306

Yakhin, O. I., Lubyanov, A. A., Yakhin, I. A., & Brown, P. H. (2017). Biostimulants in plant science: A global perspective. *Frontiers in Plant Science*, *7*, 2049. https://doi.org/10.3389/fpls.2016.02049

Yakti, W., Müller, M., Klost, M., Mewis, I., Dannehl, D., & Ulrichs, C. (2023). Physical properties of substrates as a driver for *Hermetia illucens* (L.) (Diptera: Stratiomyidae) larvae growth. *Insects*, *14*(3), 266. https://doi.org/10.3390/insects14030266

Yoneyama, K., Xie, X., Kim, H. Il, Kisugi, T., Nomura, T., Sekimoto, H., Yokota, T., & Yoneyama, K. (2012). How do nitrogen and phosphorus deficiencies affect strigolactone production and exudation? *Planta*, *235*(6), 1197–1207. https://doi.org/10.1007/s00425-011-1568-8

Yuan, L. B., Dai, Y. S., Xie, L. J., Yu, L. J., Zhou, Y., Lai, Y. X., Yang, Y. C., Xu, L., Chen, Q. F., & Xiao, S. (2017). Jasmonate regulates plant responses to postsubmergence reoxygenation through transcriptional activation of antioxidant synthesis. *Plant Physiology*, *173*(3), 1864–1880. https://doi.org/10.1104/pp.16.01803

Zhang, F., He, J. D., Ni, Q. D., Wu, Q. S., & Zou, Y. N. (2018). Enhancement of drought tolerance in trifoliate orange by mycorrhiza: Changes in root sucrose and proline metabolisms. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *46*(1), 270–276. https://doi.org/10.15835/nbha46110983

Zhang, L., Li, D., Yao, Y., & Zhang, S. (2020). H_2O_2, Ca^{2+}, and K^+ in subsidiary cells of maize leaves are involved in regulatory signaling of stomatal movement. *Plant Physiology and Biochemistry*, *152*, 243–251. https://doi.org/10.1016/j.plaphy.2020.04.045

Zhang, Q., Gong, M., Xu, X., Li, H., & Deng, W. (2022). Roles of auxin in the growth, development, and stress tolerance of horticultural plants. *Cells*, *11*(17), 2761. https://doi.org/10.3390/cells11172761

Zharare, G. E., & Vilane, N. M. (2021). Soil fertility management for groundnut in the Lowveld of Mpumalanga and north coastal plain of KwaZulu-Natal provinces of South Africa. *South African Journal of Agricultural Extension*, *49*(2), 59–69. https://doi.org/10.17159/2413-3221/2021/v49n2a12801

Zulfiqar, F., Casadesús, A., Brockman, H., & Munné-Bosch, S. (2020). An overview of plant-based natural biostimulants for sustainable horticulture with a particular focus on moringa leaf extracts. *Plant Science*, *295*, 110194. https://doi.org/10.1016/j.plantsci.2019.110194