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REVIEW ARTICLE

Integrated strategies against biotic and abiotic stress: A physiological and molecular roadmap for sustainable food security

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Abstract

Global agriculture faces the dual challenge of increasing food production amidst accelerating climate change. This review hypothesizes that an integrated understanding and management of the complex interplay between biotic (e.g., pathogens) and abiotic (e.g., salinity, drought) stresses is fundamentally more effective than addressing each stressor in isolation. The urgency of this investigation is underscored by the critical need for resilient crops capable of withstanding multiple, concurrent environmental challenges. Through a critical review of existing literature, we explore the interconnected physiological and molecular mechanisms governing plant responses to combined stresses, focusing on the crosstalk between defense signaling pathways, metabolic regulation and antioxidant machinery. This reveals a significant knowledge gap in studies addressing the synergistic or antagonistic outcomes of co-occurring stresses. This review presents a breakthrough by revealing overlooked interdisciplinary connections, paving the way for integrated management strategies that merge advanced plant breeding (e.g., CRISPR-Cas9), bio stimulant application and precision agriculture. Key business opportunities lie in developing "smart" cultivars and inputs that respond effectively to environmental cues. Future research should focus on translating molecular insights into economically viable field applications. We conclude that this integrated approach is the cornerstone of achieving sustainable food security.

Keywords: biotic and abiotic stress; food security; integrated pest and disease management; plant diseases; plant hormones; plant physiology; stress resistance; synergistic interactions

Introduction

Plant physiology, which investigates the vital functions of plants, food security and agricultural stability (1). Physiological processes are strongly influenced by biotic factors, which include living organisms and abiotic factors, referring to non-life environmental conditions (2, 3). For a global leadership, biotic stresses are defined as damage inflicted by other living organisms (e.g., fungi, viruses, insects), while abiotic stresses are caused by non-living environmental factors (e.g., salinity, drought, extreme temperatures). Plant diseases greatly limit productivity and affect global food security (4) (Fig. 1).

Pathogenic fungi such as *Rhizoctonia solani* and *Fusarium* spp. cause significant economic losses to a wide range of crops (5, 6). Plant viruses such as Tomato Yellow Leaf Curl Virus (TYLCV) disrupt plant physiological processes, including viral regulation (7, 8). Plants interact with these pathogens through complex defense mechanisms, including the production of pathogenesis-related proteins (PRS) and activation of signaling pathways (9). In addition, plants cause direct and indirect damage by ingesting insects and transmitting pathogens (10, 11). Weeds compete with crops for important resources, thereby reducing growth and yield (12). In contrast, beneficial organisms such as Trichoderma play an important role in promoting plant growth and controlling diseases (13-15).

Water stress in plants, whether due to excess or insufficient water, is one of the important factors affecting photosynthesis and growth and development, which can limit plant productivity (3). High and low temperatures can damage important proteins and enzymes (16). Salt stress can hinder the plant's absorption of water and nutrients, leading to the accumulation of toxic ions in plant tissues (3). Deficiencies in key nutrients such as nitrogen, phosphorus and potassium can hinder photosynthesis and plant growth (17-19).

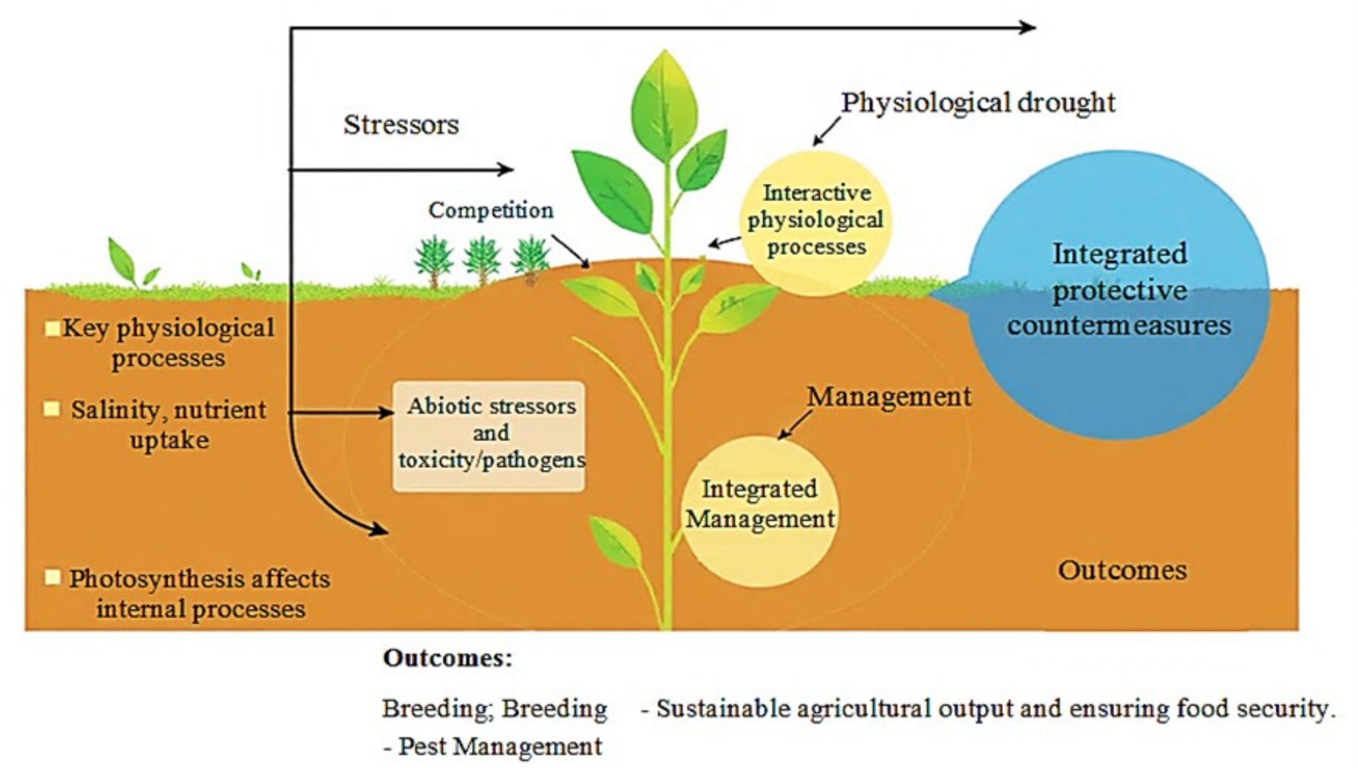

Fig. 1. Conceptual framework illustrating the integrated impact of biotic and abiotic stressors on plant physiology and food security. The diagram shows how different stressors (e.g., salinity, drought, pathogens) interact to affect key physiological processes (photosynthesis, nutrient uptake) and how integrated management strategies (breeding, IPM, soil health) can mitigate these negative impacts to ensure sustainable agricultural output.

A more intense metabolism, facilitated by enhanced nutrient availability, is a prerequisite for higher yield. Recent trends show that soil amendments like biochar can enhance plant-microbe interactions, leading to more efficient nutrient use and reduced greenhouse gas emissions, thus paving the way for more sustainable fertilization practices. Furthermore, it must be emphasized that for any crop production technology to be viable, it must demonstrate not only environmental but also economic sustainability and profitability. An examination from an investor's perspective is crucial for the real-world adoption of new agricultural technologies. In competitive ecosystems, early growth and establishment provide a significant advantage; innovative techniques such as the application of silica nanoparticles to improve germination economics are a testament to this principle.

Different types of environmental pollution, such as air, water and soil pollution, can have a negative impact on plant physiology and productivity (4). This intricate relationship among biotic and abiotic processes impacts upon food security and agricultural sustainability (4). In the quest for sustainable food security, holistic agricultural policies should be developed that consider all these multifunctional factors (20). These alternative strategies are based on the breeding in plant populations, resulting in breeding populations which commonly exhibit the resistance/tolerance to diseases and abiotic stress factors (21). Integrated insect and disease management (IPM) apply a number of strategies for pest and disease management (22-24).

Suitable water and nutrient management should be applied for resource loss and mitigating plant stress (17). The practice of sustainable agriculture, organic farming and crop rotation can also improve soil health and reduced dependency on exogenous inputs (25-27). Plant-based agriculture via gene and gene editing approaches can be employed to increase productivity and the tolerance of crop plants to the toxicant (28, 29). Phytosanital actions also help to curb the cross-border spread of pests and diseases and ensure global food security (30). Compliance with international trade on Agro-food can increase food availability and must be coupled with stringent compliance to Phytosanitary standards (31).

The novelty of this review lies in its critical synthesis of disparate research fields. While most reviews focus on a single stress factor, a clear research gap exists in understanding the cross-talk and synergistic effects of concurrent biotic and abiotic stressors. By connecting findings from molecular biology, agronomy and plant physiology, this paper establishes a novel, integrated framework to guide future research toward developing truly resilient agricultural systems.

Physiological responses of plants to salt stress and the effects of salinity on photosynthesis, water and nutrient metabolism and growth

Photosynthesis, in turn, as well as water and nutrient metabolism are fundamentally influenced by salinity and all three factors contribute to dramatically decreased plant growth. Salt stress also causes stunted growth, leaf dwarfing, leaf abscission and reduced yield in crops (1, 3). Salinity changes the allocation of carbon in the plant, decreasing root growth and negatively impacting the plant's ability to take up water and nutrients (17).

Specifically, salt stress tolerance has been developed by exclusion of toxic ions (na+ and Cl-) through limiting the uptake of sodium and chloride ions in roots and ion compartmentalization - the sequestration of ions in vacuoles (1). Accumulation of compatible solutes, such as proline and glycine betaine, to maintain cell osmotic potential (16) and increase the production of antioxidants capable of neutralizing Reactive Oxygen Species (ROS) (3).

Mitigation strategies for salt stress, improvement of irrigation handling through talented methods such as drip irrigation, soil rehabilitation with organic modifications (25, 27), Salt-tolerant varieties (20) and applying bioremediation using beneficial microorganisms (14).

The novelty of this review lies in its critical synthesis of disparate research fields. While most reviews focus on a single stress factor, a clear research gap exists in understanding the cross-talk and synergistic effects of concurrent biotic and abiotic stressors (Table 1). By connecting findings from molecular biology, agronomy and plant physiology, this paper establishes a novel, integrated framework to guide future research toward developing truly resilient agricultural systems.

The impact of fungi and viruses on plant physiology and their role in disrupting photosynthesis, energy and nutrient metabolism and growth inhibition

Fungi and viruses are one of the most important causes of plant diseases, adversely affecting major physiological processes in plants and causing considerable production losses (4, 7). These pathogens impair photosynthesis, disrupt energy and nutrient metabolism, inhibit growth and thus considerably influence the health and yield of plants (1). Fungi are one of the main parasites of many plants; A parasite is an organism that feeds on the host to live and as these fungi feed they take nutrients and energy from the plant and this parasitic relationship interfere with normal physiological processes (2). Fungi infection destroys plant tissues like (e.g., leaves, stem and roots) reducing the plant's capability in performing photosynthesis (1). For instance, fungal species such as *Rhizoctonia solani* and *Fusarium* spp. cause roots rot and leaves wilting which lead to inhibit water and nutrient absorption and also adverse effect on photosynthesis (5, 32). Also, some fungi produce mycotoxins that disturb and inhibit enzymatic processes and disturb energy metabolism in plants (33).

This physical disorder not only inhibits the plant's ability to grow and flourish, but also leads to important agriculture and economic loss. Understanding mechanisms such as fungi and virus plant affects physiology, it is important to reduce the effect of them and develop effective strategies to protect crop health. Plant viruses invade host cells by co-opting the host's cellular machinery to generate more viral copies, interfering with typical cellular operations (1). They hinder photosynthesis by suppressing the chlorophyll levels in leaves or spitting negative on the enzymes play a role in carbon fixation. For instance, tomato yellow leaf curl virus (TYLCV) decreases the levels of plant hormones and alters the concentrations of certain minerals and vitamins in tomato fruits, thereby impairing fruit quality and nutritional value (8, 34, 35). Furthermore, viruses can interfere with nutrient transport in plants, which results in ionic imbalance and repression of plant growth. Viral infections also modify the plant's metabolism, leading to the buildup of select compounds and the depletion of others (36, 37).

In general, fungal and viral infections cause a variety of side effects on physiological processes in plants. These include a reduction in chlorophyll content, damage to chloroplast membrane and dissolution of photosynthesis through loss of enzymes involved in carbon fixation. In addition, the infection irritates energy and nutritional metabolism by reducing water and nutrients, disrupting the transport of nutrients and interfering with enzymatic activities (1). Ultimately, these physical disorders suppress the growth of plants, which manifest itself as increased growth, manifested as stunted growth, increases abscission and reduction in crop productivity (1).

Control of such plant diseases needs integrated approaches of preventive and curative measures (2). These strategies include using of resistant varieties with intrinsic ability to resist fungal and viral diseases. Crop rotation, adequate soil drainage and removal of infected crop residues are other examples of good agricultural practices that mitigate disease spread (2). Another efficient way to manage fungal pathogens is the use of beneficial microorganisms such as the fungi Trichoderma for biological control (14, 15). Finally, chemical control through the use of fungicides and insecticides (to control virus vectors) should only be used judiciously and according to technical recommendations (38). Thus, integrated control strategies should be adopted for both preventive and curative measures to maintain plant health and agricultural crop productivity as fungi and viruses adversely affect plant physiology (1, 2).

However, it is crucial to explain that not all plant-fungus and plant-virus interactions are negative. Many plants form symbiotic relationships with beneficial microorganisms. Arbuscular mycorrhizal fungi (AMF), for instance, colonize plant roots and vastly improve the uptake of water and nutrients like phosphorus. In return, the plant provides the fungi with carbohydrates. Similarly, many endophytic fungi live within plant tissues without causing disease, often producing compounds that protect the host from pathogens and herbivores. Furthermore, soil amendments like biochar can improve plant metabolism and overall soil health, creating an environment that is less conducive to pathogenic organisms and more favorable for beneficial ones.

The Impact of salinity and plant diseases on crop physiology and integrated management strategies

Agricultural crops are continuously exposed to a diverse array of biotic and abiotic stresses that curtail their productive potential and compromise their qualitative attributes. The interplay between these stresses constitutes a complex factor that intensifies the challenges confronting plants (1). Frequently, these stresses interact in non-linear manners, leading to intricate and unforeseen effects on the physiological processes of the plant (39).

Table 1. Examples of combined stress impacts on major crops

Crop	Combined Stress	Observed Physiological/ Yield Impacts	Reference
Tomato	Salinity + TYLCV	Severe reduction in photosynthesis, disruption of hormonal and mineral balance, significant yield loss.	AL-Abedy et al. (8)
Wheat	Drought + Fusarium crown rot	Reduced biomass, impaired nutrient uptake, increased mycotoxin accumulation in grains.	Aljuaifari et al. (21)
Rice	Salinity + Brown spot disease	Synergistic negative impact on growth, chlorophyll content and grain yield greater than individual stresses.	Kumar (40)
Maize	Heat + Aphid infestation	Compounded reduction in photosynthetic efficiency, increased oxidative stress and drastic yield decline.	Munir (51)

Salinity and plant disorders stand out as good examples of these stresses, where their contemporary influence can have serious effects on crop physiology and their ability to grow and give (40).

Salinity triggers a series of detrimental physiological alterations in plants such as decreased intake of water and vital nutrients, imbalance of cellular ionic homeostasis as well as the enhanced generation of ROS. This leads to oxidative stress which can lead to substantial damage to cells and tissues (3). In contrast, plant diseases cause direct damage to tissues, impair photosynthesis-the key way in which organisms produce energy and alter energetics and nutrient metabolism. They, too, trigger the signaling of plant defense mechanisms that are costly for the plant and invoke its limited resources (2, 23). When crops experience salinity and disease together, the physiological damage accumulates, leading to a significant decrease in growth and yield (4, 41) (Table 1).

Interactions between salinity and plant diseases and their adverse impact on vital physiological processes in plants

Photosynthesis

Various processes contribute to the reduction of photosynthesis efficiency under salinity stress, including stomatal closure to prevent excessive transpiration and impairment of primary carbon fixation enzymes (1). Simultaneously, plant diseases, especially those that target leaves, decrease the surface area available for photosynthesis and damage chloroplast membranes, aggravating the crucial process (1). For example, it has been shown that infection with tomato yellow leaf curl virus (TYLCV) under conditions of salinity can markedly reduce the photosynthetic rate in tomato plants, leading to an impact on their growth and productivity (8, 34, 35).

Water and Nutrient metabolism

High salinity hampers its absorption of water and micronutrients from the soil, leading to physiological-apparent drought and deficiency of micronutrients (3). Plant diseases further aggravate these challenges by damaging the plant's vascular system, which lowers the supply of water and nutrients to aerial organs including leaves and stems (1). This interaction can increase the imbalance in both water stress and nutrients, which can have negative effects on plant production and total productivity (17).

Growth

Simultaneous exposure to salinity and plant diseases leads to significant growth suppression (1). Salinity stress alters carbon allocation, often reducing root development and compromising the plant's ability to acquire water and nutrients from the soil (17). Additionally, plant pathogens cause tissue damage and disrupt fundamental metabolic processes, compounding growth inhibition (1). For example, infections by fungal pathogens such as *Rhizoctonia solani* and *Fusarium* spp. under saline conditions have been shown to significantly reduce yields in various crops, highlighting the importance of integrated management for such stress combinations (5, 6).

Though these conditions pose serious challenges, some plants developed adaptive strategies to deal with salinity and phytopathological pressure. Among them, these are the exclusion of toxic ions, regulation of their uptake, accumulation of compatible solutes which provide protection to the cells and enhanced production of antioxidants to counter oxidative stress (1, 3). Plant tolerance to combined stresses is often limited, highlighting the need to ensure sustainable management strategies to maintain and enhance productivity under multiple stress conditions (39).

Promising management strategies for mitigating the combined effects of salinity and plant diseases

To address the complex challenge of combined stresses, a multi-pronged approach is necessary. This involves not only reactive measures but also proactive strategies to build resilience in agricultural systems. Several integrated strategies have shown promise in addressing the complex challenges posed by the interaction of salinity and plant diseases (Table 2):

Plant Breeding

A key strategy to respond to this challenge is to develop genetically improved cultivars resistant to both salinity and plant pathogens (21). These cultivars combine tolerance traits with disease resistance, which could keep them productive under stress conditions.

Integrated management

However, multi stressors can be efficiently controlled via a holistic approach, including various types of practices, including good agricultural practices that aim to promote both soil and plant health, biological control of pathogens with beneficial organisms and the rational use of chemical pesticides, if necessary (14).

Improved irrigation and Drainage management

Precision irrigation techniques, such as drip irrigation, are paramount in reducing water loss and preventing the accumulation of salts in the root zone. Effective drainage systems are equally critical to leach excess salts away from the plant, preventing toxic build-up.

Table 2. Integrated management strategies for mitigating combined plant stresses

Strategy	Mechanism of Action	Practical Application	Reference
Advanced Plant Breeding	Stacking genes for tolerance to multiple stresses (e.g., salinity and disease resistance).	Use of molecular markers and gene-editing tools like CRISPR-Cas9 to develop multi-stress tolerant cultivars.	Yadav et al. (27)
Integrated Pest Management (IPM)	A holistic approach using biological, cultural and chemical controls judiciously.	Combining crop rotation, use of resistant varieties and biological control agents (Trichoderma spp.) to manage pests and diseases.	AL-Abedy et al. (8)
Biostimulants & Biological Control	Application of beneficial microbes or their metabolites to enhance plant growth and defense.	Seed treatment or soil application with Trichoderma spp. or PGPR to suppress pathogens and improve nutrient uptake.	AL-Abedy et al. (14)
Nanotechnology	Controlled delivery of nutrients and biopesticides to enhance efficiency and reduce environmental loss.	Encapsulating fertilizers or fungicides in nanoparticles for slow, targeted release.	Munir et al. (51)

Soil rehabilitation

The application of organic amendments, such as compost and biochar, improves soil structure, water-holding capacity and nutrient cycling. This not only mitigates the effects of drought and salinity but also enhances the activity of beneficial soil microorganisms. The combined effect of salinity with the plant diseases is an adaptable challenge to crop physiology leading to the photosynthesis, water and nutritional metabolism and overall growth (1, 3). To meet that challenge a broad approach, including conventional breeding, integrated control, improving water and drainage management and soil rehabilitation is needed. That would be necessary, if the aim is to maintain the productivity of the crop under stress, avoid famine and ensure food security for the future (20).

Plant enzymes as central regulators of stress response: their role in physiological processes and defense mechanisms against diseases

Plants experience various environmental stresses including biotic (i.e., due to pathogens) and abiotic (salt and drought) stress, for which the natural defenses of plants are constantly challenged (42). In this sense, plant enzymes are critical in adaptation and response to stress. They serve as master switch of the photosynthesis and respiration paths as well as disease-defending methods and internal cellular homeostasis (3, 16).

Enzymes modify photosynthesis and respiratory routes to fit widespread environmental conditions. For example, salt stress can prevent activity of Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase), an important enzyme in carbon dioxide fixation can reduce an important enzyme, photosynthetic efficiency (43). Conversely, plants can adapt to the expression of enzymes included in alternative photosynthetic routes such as C4 and CAM, which increases the use of water in a dry environment (20).

Moreover, responses can also be subjected to shifts in path of cellular respiration for enhanced energy generation and to secondary products production towards metabolic paths related to resistance by environmental stresses (17). Through these enzymatic modifications, the plant can tolerate and response to a wide range of environmental and pathogenic challenge. Enzymes are significant components of plant defense mechanisms against pathogens. When a plant is under attack, it employs a wide range of PRS proteins, which are key players in lowering the MAMP-triggered response (9).

These include chitinases, which break down chitin, the primary structural component of fungal cell (32, 44), the primary structural component of glucancases, which break glucans and proteases, aimed at the pathogenic protein (2).

Beyond degrading pathogens directly, some enzymes involved in synthesizing antimicrobial compounds including phytoalexins and phenolic compounds that have anti-pathogen action (45, 46). In addition, several beneficial fungi in the field of biological control, like *Trichoderma* spp, secreted enzymes that decompose the cell walls of pathogenic fungi thereby enhancing plant protection (13, 15).

Enzymes are also included in the induced systemic resistance (ISR) passage, where pre -rich to a pathogenic or specific chemical triggers a systemic immune response. This increasing defense position equipped the plant for better resistance to subsequent attacks (47).

Enzymes like phenylalanine amm-onia-lyase (PAL) have a significant role in this system by catalyzing the formation of cinnamic acid, which is a precursor compound in the growth of several defensive compounds (48). Environmental stress also induces the generation of ROS, which causes oxidative stress and damage to the cells (3). The antioxidant system of plants, including SOD, CAT, POD and GR, can scavenge the ROS and reduce the ROS-induced damage (16). Stress can enhance the activity of these enzymes promoting plant tolerance to less favorable environments (49).

There is a possibility to access stress tolerance by transgenic tool targeting the genes whose enzymes are interconnected in biochemical terms. Other resources to apply are gene manipulation of major good enzymes or transformation of the resistance to stress of some genes, collected based on microorganisms used (29). Furthermore, DNA- based markers are employed to identify and select for plant genotypes which are homozygous to the desirable allele of stress enzymes to hasten breeding process (50).

The positive impact of nanoparticles on the activity of antioxidant enzymes, with the subsequent enhancement of stress tolerance in plants, is emerging as a new approach for mitigating stress in plants (51, 52). In brief, plant enzymes play an important role in the stress response, which synergizes developmental and defense pathways converge, determining the principles of plant survival and productivity through the regulation of central physiological processes, the development of defense mechanisms and the stability of cell homeostasis. An improved understanding of the molecular mechanisms regulating enzyme activity under stress would aid in the identification of strategies to improve crop resilience and secure our food supply on a global food security (4, 40).

From an industrial and agricultural perspective, this knowledge is highly valuable. It drives the development of commercial bio stimulants-products containing compounds (e.g., seaweed extracts, humic acids, or microbial metabolites) that trigger or enhance the activity of these defensive enzyme systems. Farmers can apply these products to "prime" their crops, making them more prepared and resilient to subsequent stress events, thereby offering a sustainable alternative or supplement to conventional chemical pesticides.

Integrated hormonal responses to stress in plants under biotic and abiotic conditions

Plant hormone - Plant hormones, also known as growth regulators, are af diverse group of endogenous organic compounds that perform a crucial duty in regulating growth, development and other physical responses, in plants (1). The group contains auxins, cytokinin, gibberellins, ethylene and abscisic acid (ABA), as well as other signaling molecules like jasmonic acid (JA) and salicylic acid (SA) (17).

Given the continuous risk of plants for a wide range of environmental tension - both biotic (generated from pathogens and insects) and abiotic (such as drought, salinity and extreme temperature) plant hormones are central to regulating adaptive reactions that ensure existence and productivity under these harsh conditions (3).

Hormones are important regulators of many developmental processes like cellular activities (division, elongation and differentiation), organ growth and aging (27). Auxins possessing abilities to elongate cells and induce root initiation and cytokinins promoting cell division and inhibiting leaf senescence effects (53). Key regulators of seed germination, stem elongation, and floral initiation, gibberellins (GA) are phytochemicals that promote these processes. For instance, salinity stress significantly inhibits growth and dramatically decreases crop yield (43). As a result, plants have evolved strategies to modulate hormone levels to enhance tolerance to stress. conditions.

Specific hormones are critical for plants responding to biotic stressors like pathogens and pests (2). Plants activate a complex signaling network of hormonal pathways upon attack with pathogens that result in a range of defense responses (9). Salicylic acid (SA) classically functions in resistance to biotrophic pathogens, while jasmonic acid (JA) and ethylene are primarily involved in responses to necrotrophic pathogens and herbivorous pests (47). Interestingly, certain pathogens have acquired advanced abilities to alter the plant endogenous hormone concentrations which in turn increase their pathogenicity (54). Infected tomato plants are compromised in their immune responses because infection with tomato yellow leaf curl virus (TYLCV) has been shown to modulate hormone content (8, 34, 35). Apart from their involvement in biotic defense, also plant hormones have a central role in mediating responses to abiotic stresses such as drought, salinity and temperature extremes (3). Abscisic acid (ABA), this is one of the key hormones that activates the good drought tolerance in crops, because among other functions, it induces the stomata to close to decrease the loss of water transpiration (20). Big salinity stress can disrupt the hormonal balance (Altera growth and developmental processes negatively (42). Similarly, hormonal balance can change in contact with high temperature, which can interfere with important physical activities such as respiratory and photosynthesis (39). Together, these results highlight the most important effect of hormone networks that allow plants to understand and respond to sophisticated environmental signals and dangers operative and hormones in a complex and organized plant hormones series regulating the response of plants to stress. The effects of hormonal crosstalk may be synergistic or antagonistic, depending on the hormones and the nature of the stress (17). For example, the crosstalk of salicylic acid and jasmonic acid might be so important in the ability of the plant to defend itself against different pests and pathogeotsensm,2s (E = 830 nm and Ls = 10000).

As a promising alternative to the traditional agricultural practice, biotechnology can also be used to improve the plant tolerance through modulating hormonal signaling pathways. For instance, hormone biosynthesis genes or signal networks related to stress, the expression of which could be altered by gene editing (29). Furthermore, DNA marker assisted HR can be useful to screen the genotypes for elite allele for the tolerance symptoms and improve the conventional breeding process for consistent crop (50). On the other hand, foliar application of plant growth regulators can significantly enhance the crop stress tolerance, making it easier for the crop to survive in unfavorable environments (27).

Ultimately, the plant hormone is the master regulatory factor in the plant response to stress. They synchronize growth, development and physical adjustment in response to both biotic and abiotic cues. It is highly significant to have a comprehensive picture of the molecular genetic network that controls the hormonal signaling in the stress responses and this is essential to generate novel avenues aimed at ensuring the global food security by enhancing the adaptability of the crop plants worldwide under changing climatic conditions (4, 40).

The role of mineral elements in regulating growth, nutrient balance and defense responses against biotic and abiotic stressors

Plant minerals are fundamental to plant physiology and are involved in a variety of regulatory activities that are involved in fundamental biological processes such as growth, development, nutrient homeostasis and adaptive responses to biotic and abiotic stresses (1). Plants require large amounts of these important macronutrients, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur. Trace elements are essential to plants in smaller amounts, such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cl), boron (Bo) and molybdenum (17).

The plant environment in which minerals are provided and their concentrations can significantly affect physiological processes such as photosynthesis, respiration and the synthesis of important biomolecules such as proteins and nucleic acids (3).

Minerals are essential for the regulation of plant growth and development. For example, nitrogen, as a building block of amino acids, is essential for protein synthesis, enzyme activation and chlorophyll synthesis and is therefore essential for vegetative growth and photosynthesis (53). Phosphorus is required for cellular energy transfer, nucleic acid synthesis and the production of cell membrane phospholipids. Potassium regulates osmotic pressure and activates many important enzymes. It also regulates stomatal activity, thereby controlling gas exchange and water loss. Other elements such as calcium, magnesium and sulfur also play important roles in the structure and regulation of various developmental and metabolic processes (27). For example, cell wall stability and signaling depend on calcium, chlorophyll structure and enzyme activation depend on magnesium and protein (amino acid) and coenzyme synthesis depend on sulfur.

Deficiency in any of the essential minerals results in characteristic deficiency symptoms that reflect disruptions in important physiological processes and ultimately lead to growth inhibition and reduced productivity (40).

Plants maintain a delicate balance of nutrients in their tissues, which is affected by the other nutrients. The absorption, distribution and utilization of each nutrient are elaborate interactions (4). For example, excessive application of phosphorus fertilizers can lead to zinc deficiency by interfering with zinc absorption, while potassium deficiency can affect magnesium absorption by interfering with magnesium transporters. Notably, these mutual nutritional effects are affected by general environmental factors such as soil pH and microbial activity, which can alter nutrient availability. Therefore, understanding these complex interactions in the soil is essential to properly nourish the plant and optimize plant growth, thereby increasing crop yields (50). In addition to playing a major role in the development and supply of mineral nutrients, partners also regulate the plant's defenses against biotic and abiotic factors that threaten its survival (2). For example, calcium plays an important role in strengthening plant cell walls, which improves the plant's resistance to tissue-penetrating pathogens (9).

Several studies have shown that silicon can increase the resistance of plants through many mechanisms for a variety of fungi and insect pathogens, including strengthening plant tissue and triggering defense reactions (52). In addition to structural support, some mineral elements such as enzyme factors act, playing a fundamental role in activating antioxidants enzymes that protect plants from oxidative damage that occur from various inorganic tension (3, 16). For example, manganese, zinc and copper are important components of the (SODs), an enzyme that fees ROS and reduce oxidative damage. These micronutrients also have an active role in stress resistance and cell protection, as they can help, as they can help in ROS scavenging of routes (Fig. 2).

Finally, because biotic and abiotic factors can affect the sharp and internal distribution of minerals, the physical reaction of the plant will be more complex (42). For example, salt stress can reduce potassium and calcium due to ion competition, while drought can reduce the movement of nutrients in both soil and plants as a result of low water volume. In addition, some pathogens can be manipulated in mineral absorption to ease plant tissue infections and colonization (54). A remarkable example is tomato -yellow leaf curl virus (TYLCV), which replaces mineral content in infected tomato plants, affecting their resistance (34).

In light of these many roles to mineral elements, biotechnology wants to develop innovative strategies to improve uptake and efficient use of these elements in plants. These strategies include the use of soil microorganisms that promote plant growth (PGPR), which increases the availability of nutrients in the soil and increases the plant through different mechanisms. Nano technology is also employed to evenly apply the nutrients, to quantify them, to lower wastes and improve the utilization (51). Genetic manipulation can also enhance the expression of genes engaged in nutrients and transport in plants leading to more efficient resource use (29).

Mineral elements are often physiologically important to the plant, regulating growth and development, controlling the homeostasis of nutrients and participating in activing the defense response against biotic and abiotic agents. A more comprehensive understanding of the complex physiological role of mineral elements in plants is essential to enable the development of effective strategies to increase crop nutrition, productivity and food security in an expedited challenging environment (30).

Physiological adaptations and defensive compounds in plants as mechanisms to enhance tolerance to salinity and disease

In nature and in agriculture, plants face various types of environmental stresses like salt and plant diseases that need a sophisticated system of responses for the plants to survive and become productive (42, 55). These reactions involve a set of physiological adaptation and defensive compounds which act in a coordinated manner to enhance tolerance to adverse conditions and pathogens (1) (Fig. 2).

Association With Salinity The tolerance of plants to salinity is developed by a number of mechanisms, which are able to reduce the negative impact of soluble salts in the rhizosphere.

This may involve ion uptake regulation in which plants restrict the uptake of toxic Na and Cl and preferentially promote the uptake of essential nutrients such as K (3). Furthermore, certain plants sequester toxic ions into the cellular vacuoles (ion sequestration) as to reduce its cytoplasmic accumulation (16). Plants also accumulate compatible solutes like proline and glycine betaine for maintaining protein and enzyme bioactivity against salt stress (27). Also, salinity stress increases the production of anti-oxidants such as superoxide dismutase (SOD) and catalase (CAT) to overcome the oxidative stress which appears depends on the accumulation of ROS (43).

Plants use a sophisticated system in order to defend themselves against diseases consisting of both structural and biochemical defense responses (2). They also build a physical sieve in the form of lignified and silicated cell walls, thus making

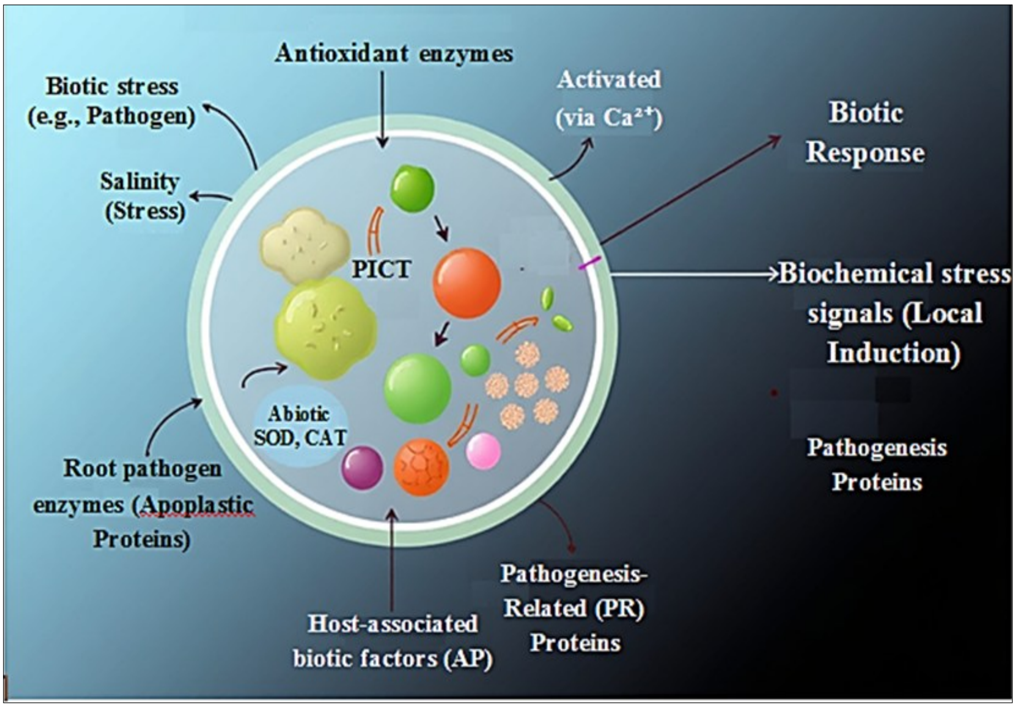

Fig. 2. Diagram of integrated defense responses in a plant cell under combined stress. The figure shows how concurrent biotic (e.g., pathogen) and abiotic (e.g., salinity) stresses trigger overlapping signaling pathways, leading to the activation of antioxidant enzymes (SOD, CAT), accumulation of compatible solutes (proline) and production of pathogenesis-related (PR) proteins, resulting in enhanced cellular tolerance.

invasion by pathogens more difficult (9). Biochemically, plants release an arsenal of antimicrobial metabolites, specifically phytoalexins, phenols, alkaloids etc. which hinder pathogen growth (45, 46). These chemical defenses cooperate with intricate hormonal signaling cascades including salicylic acid (SA), jasmonic acid (JA) and ethylene (ET), which regulate the expression of genes associated with defense (47).

It should be noted that such plant-pathogen interactions frequently lead to large changes in the physiology of the plant with changes in photosynthesis, respiration, and nutrient uptake (1). For instance, tomato yellow leaf curl virus (TYLCV) infection of tomato was reported to induce imbalance in hormonal level as well as in mineral nutrient, which leads to retarded growth and yield decline in the infected plants (8, 34, 35)

Some new studies have recorded to gain more detailed insights into the molecular basis of plant interaction with salt and disease stress, which lead to develop new useful strategies for improving crop resistance. This includes traditional breeding, in order to create resistant or salt-tolerant varieties (20, 29). Additionally, soil microorganisms such as the PGPR have also shown potential to augment plant resistance to salinity and diseases (14, 56).

In summary, the responses of plants to salt and pathogens are a complicated phenomenon that involves the alteration of physiology and defensive compounds. Finally, the responses of plants are complicated with respect to environmental stresses, such as salinity and disease and include activity/systems, including physical resistance and the induction of defense responses. Knowledge of molecular mechanism governing these reactions is essential to evolve durable strategies to enhance crop production under altered environmental conditions (4, 40).

Future research directions in plant physiology to understand stress mechanisms and develop strategies for improving tolerance

In view of the emerging issues of climate change and increasing environmental stress, plant physiology is in desperate need for in-depth studies that could untangle the complex stress regulation in plants and introduce novel paradigms for improving plant adaptation to stress (42). The focus of future research in the area covers everything from molecular biology and genomics to high tech agriculture. This paper reviews one of the most significant aspects of investigation, on the molecular mechanisms behind the stress tolerance system in plants. This also pertains to the phenomenon of identifying genes, protomies and metabolites and the skills of the plants were to withstand inorganic stress (i.e. drought, salinity, extreme) and biotic stress (i.e. pathogens and disease) (3, 57). This includes genomics, proteomics and metabolomics to understand changes in the expression of genes, the composition of proteins and the metabolites that are generated in response to a stressor (1).

Furthermore, gene manipulation approaches are also used to elucidate the function of candidate genes and to generate genetically improved plants with increased stress resistance (29). Another interesting field of investigation is the role of soil microorganisms on the improvement of plant tolerance to stress. Some of the soil microorganism species i.e., including plant-growth promoting rhizobacteria and symbiotic mycorrhizal fungi, have been recognized to enhance nutrient uptake and relieve biotic and abiotic stress conditions by the plants. Recent research seeks to elucidate the basis of stress tolerance in plants promoted by such microorganisms and, from this point of view, to apply them in agriculture for generating crops that are productive even under conditions of stress (14). Further, the recent applications of nanotechnology in plant physiology, to enhance the delivery of nutrients and other bioactive compounds to plants and enhance tolerance to stress are being evaluated (51). Nutrients and biopesticides can be enclosed in the nanoparticles, which prevent dissipation in the environment and allow for their controlled release in the plant.

Nutrient- and bio-pesticides can be loaded on to those nanoparticles to avoid these compounds' environmental breakdown and reduce their loss, as well as to control delivery into plants. It has been suggested that VLN might contribute to recovery from nutrient stress and oxidative stress in stressed plants (52). It is an exciting field read about and investigate, to help one try to understand how plant and pathogen interact with each other. This field investigates genes and proteins which the plants use for resisting pathogens and it has led to new techniques for controlling plant diseases (2). It's about how to prevent pathogens from infecting plants and how to speak for what that can teach us about how to prevent them in new ways. The potential of editing the plant genes and preventing infectious diseases is on its infancy some of these editions include the application of gene editing technology such as CRISPR-Cas9 technology (58).

Finally, the understanding of stress mechanisms of action and activities to improve plant tolerance are a front behind which interdisciplinary research takes place through the contribution to the approach to study issues in molecular biology, genetics, ecology and agro-technologies. The integration of above fields would enable scientists to evolve strategies for enhancing crop productivity and mitigating food security in response to rapidly changing environmental scenarios (4, 40).

To demonstrate more originality, future research must move beyond single-factor studies and embrace complexity. We propose a focus on:

1) Multi-omics approaches to unravel the complex gene and protein networks that regulate combined stress responses.
2) Development of nanotechnology-based sensors for real-time, in-field monitoring of plant physiological status.
3) Microbiome engineering design synthetic microbial communities that enhance plant resilience.
4) Agronomic innovations to improve crop quality, such as novel cultivation methods for beetroot that reduce nitrate content.

Furthermore, as more developed countries mandate the use of biowaste technologies to regenerate nutrients, research into closing the nutrient loop will become essential for a sustainable, circular agricultural economy.

Conclusion

This review confirms the central research hypothesis: that the physiological responses to biotic and abiotic stresses are deeply interconnected and that sustainable food security hinges on shifting from isolated research to integrated, holistic strategies.

We have synthesized evidence showing that the combined impact of multiple stressors is not merely additive but is the result of complex, synergistic and antagonistic interactions at the molecular level. Moving beyond disciplinary silos to embrace an approach that unites genetics, precision agriculture and soil science is not an option but a necessity. By doing so, we can turn the challenges posed by a changing environment into opportunities for innovation, fostering a new generation of resilient agricultural solutions that ensure a healthy and sustainable food future.

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Authors' contributions

The review was conceptualized by FKKA. The search for literature, analysis, drafting and critical revision of the manuscript was done by all authors. All authors read and approved by final manuscript.

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