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A Comprehensive Review: The Impact of Promising Secondary Metabolites on Environmental Stress Resistance

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Abstract:

Plant resistance to various biotic and abiotic stressors is a critical part of plant survival and productivity. Secondary metabolites, also called special metabolites or phytochemicals, play an important role in mediating these responses. The aim of this review is to provide a comprehensive overview of the various secondary metabolites involved in plant resistance, the mechanisms by which they affect defences capacity, and their ecological significance. We discuss the synthesis, regulation and functions of secondary metabolites in plant interactions with herbivores, pathogens and environmental stressors. In addition, we are investigating potential applications of secondary metabolites in agriculture, biotechnology and medicine.

Keywords: Stressors, Phytochemicals, secondary Metabolites, Plant interactions etc.

I Introduction:

In the face of escalating environmental challenges, the resilience of plants to various stressors has become a focal point of scientific research. Among the myriad strategies plants employ to withstand adverse conditions, the role of secondary metabolites stands out as particularly significant. These compounds, often overlooked in favor of primary metabolites, play crucial roles in enhancing plant resistance to environmental stresses such as drought, salinity, extreme temperatures, and pathogen attacks. This comprehensive review delves into the multifaceted impact of promising secondary metabolites on environmental stress resistance, highlighting their potential to revolutionize agricultural practices and contribute to sustainable crop production. Secondary metabolites are organic compounds that, unlike primary metabolites, are not directly involved in the normal growth, development, or reproduction of plants. Instead, they serve specialized functions that enhance the plant's ability to survive and thrive under stress conditions. These compounds include alkaloids, flavonoids, terpenoids, phenolics, and glycosides, each with unique properties and mechanisms of action. For instance, flavonoids can act as antioxidants, protecting plant cells from oxidative damage caused by environmental stressors. Terpenoids, on the other hand, can deter herbivores and pathogens, providing a chemical defense mechanism.

The synthesis and accumulation of secondary metabolites in plants are often triggered by environmental stressors. When a plant encounters stress, such as drought or high salinity, it activates complex signaling pathways that lead to the production of these protective compounds. This adaptive response not only helps the plant to mitigate the immediate effects of stress but also enhances its long-term resilience. For example, under drought conditions, plants may increase the production of osmoprotectants, a type of secondary metabolite that helps to maintain cellular water balance and protect cellular structures from dehydration. One of the most promising aspects of secondary metabolites is their potential application in agriculture. By understanding the mechanisms through which these compounds confer stress resistance, scientists can develop strategies to enhance crop resilience. This could involve traditional breeding techniques to select for plants with higher levels of beneficial secondary metabolites or biotechnological approaches to engineer crops with enhanced stress tolerance. Such innovations are particularly crucial in the context of climate change, which is expected to exacerbate environmental stresses and threaten global food security.

Moreover, secondary metabolites have significant implications for sustainable agriculture. The use of chemical pesticides and fertilizers has long been associated with negative environmental impacts, including soil degradation, water pollution, and loss of biodiversity. In contrast, harnessing the natural defense mechanisms of plants through secondary metabolites offers a more sustainable approach to crop protection. For instance, plants that produce higher levels of certain terpenoids may be more resistant to pests, reducing the need for chemical pesticides. Similarly, plants with enhanced flavonoid production may be better equipped to withstand oxidative stress, reducing the need for synthetic antioxidants. The benefits of secondary metabolites extend beyond their direct impact on plant stress resistance. These compounds also play a crucial role in plant-plant and plant-microbe interactions, which are essential for maintaining healthy ecosystems. For example, certain secondary metabolites can attract beneficial microbes that promote plant growth and enhance soil health. Others can inhibit the growth of competing plant species, helping to maintain the balance of plant communities. By fostering these positive interactions, secondary metabolites contribute to the overall resilience and stability of ecosystems.

Despite their potential, the study of secondary metabolites and their role in environmental stress resistance is still in its early stages. Many questions remain unanswered, such as the precise mechanisms through which these compounds confer stress tolerance and the factors that influence their production and accumulation in plants. Addressing these knowledge gaps will require interdisciplinary research that integrates plant physiology, biochemistry, molecular biology, and ecology. Advances in omics technologies, such as genomics, proteomics, and metabolomics, are expected to play a crucial role in unraveling the complex networks of secondary metabolite biosynthesis and regulation. In conclusion, secondary metabolites represent a promising frontier in the quest to enhance plant resilience to environmental stresses. Their diverse functions and mechanisms of action offer a wealth of opportunities for improving crop performance and sustainability. By leveraging the natural defense strategies of plants, we can develop innovative solutions to the pressing challenges of climate change and food security. This comprehensive review aims to provide a detailed overview of the current state of knowledge on secondary metabolites and their impact on environmental stress resistance, highlighting the potential for future research and application in sustainable agriculture. Through continued exploration and innovation, we can unlock the full potential of these remarkable compounds and pave the way for a more resilient and sustainable agricultural future.

II Literature Review:

Many environmental conditions influence the activity of plants. Depending on their length and severity, some of them might function as stressors. Stress is defined as any unfavourable environmental factors influencing crop and plant growth both the ultimate rate of return and quality. Plants are negatively impacted by drought, frost, low and high temperatures, which lowers their metabolism, alters their mood, and requires them to use their own internal energy to withstand the effects of stress. temperatures, elevated humidity, soil acidity and salinity, and pesticide-related pollution (*Hasanuzzaman et al., 2013; Begum et al.,2019; Kamran et al., 2019a.*). It's a very complex matter to be either forgiving or vulnerable to stress. It can impact various plant developmental stages, and multiple stressors can disrupt plants at once (*Iqbal and Ansari, 2020*).

The saying "Necessity is the mother of invention" seems to apply to plants since they are sessile organisms and therefore employ a variety of chemicals to fend off enemies, withstand pathogens, outcompete rivals, surpass environmental constraints, and recover from oxidative stress (*Ahuja et al. of 2011*). In response to changing environmental conditions, plants respond to them in a multifaceted and coordinated manner. Plant stress tolerance affects the entire plant as well as its tissues, cells, physiology, and molecular makeup. The ability of plants to survive in unfavourable environmental conditions is determined by a special combination of intrinsic changes (*Farooq et al. 2009; Meena et al.2017*). This includes a range of physiological and biochemical changes in plants, such as wilting, abscission, and reduction in leaf area; stimuli for root growth; changes in relative moisture content; electrolyte outflow; formation of reactive oxygen species; and accumulation of free radicals, which disrupt cell homeostasis and lead to lipid peroxidation, membrane damage, and enzyme inactivation, all of which impair cell viability (*Sebastiani et al. 2016, Giordano et al. 2020*).

Advanced plants possess diverse defence mechanisms against various threats or anxieties, such as physical, biological, chemical, and stress-related factors. To cope with harsh surroundings, they have evolved a variety of defences mechanisms at varying degrees. Plant antibacterial agents and the synthesis of antibacterial molecules like keratin, wax, and the deposition of firm lignin on cell walls are examples of prefabricated defences systems. When a new pathogen attack occurs, they are frequently regarded as the first line of defences (*Bieniasz, 2004; Csekeet al. 2016*). When water stress occurs, plants activate a series of biochemical and physiological responses. These responses include the closure of stomata, a decrease in photosynthesis and cell growth, and the initiation of respiration (*Lovisolo et al., 2010*). Moreover, plants respond to sliding defects at the cellular and molecular levels by permeabilizing their cells and accumulating proteins that specifically support stress tolerance. These stressors stimulate or inhibit different genes for different tasks (*Slade and Radman, 2011*). Avoiding stress effects because of physiologically inactive phases and developing stress tolerance or coping skills with the aid of their metabolites are the two main premeditated responses to stress effects (*Aertsen and Michiels, 2004*). The purpose of this review is to shed light on environmental stress, including the fundamentals of stress resistance and the possibility for plants to become more stress-tolerant through the use of their metabolites, thereby improving their overall functioning.

1. METABOLITES INVOLVED IN STRESS TOLERANCE:

Several roles are played by plant metabolites. They perform functions such as antioxidants, pathogen defense, signal or regulators, and well suited solutes. In plants, stress tolerance is mediated by plant metabolites. The accumulation of metabolites often occurs in plants that are stressed by multiple elicitors or signalling molecules. Growth conditions, such as temperature, nutrient supply, and lightning conditions, are known to affect the accumulation of various natural products. (*Ballhorn, 2011; Rini Vijayan and Raghu, 2020*). More severe environmental factors, such as various stressors, will also have an impact on the metabolic pathways responsible for assembling the secondary product of the plant. (*Shulaev et al., 2008; Chandran et al., 2020*). Plants produce two different kinds of metabolites: primary and secondary. Secondary metabolites are typically produced in plants to fulfill specific needs, as they are produced through modified synthetic pathways from primary metabolites or by sharing substrates of origin of primary metabolites (such as carbohydrates, lipids, and amino acids). Primary metabolites typically serve the same biological function in all species (*Pott et al., 2019*). Organic acids, acyl lipids, carbohydrates, and phytosterols are examples of primary metabolites. In contrast, secondary metabolites are present in all plant tissues and have a metabolic activity that is necessary for plant growth and development. Despite their limited distribution within taxonomic groups, secondary metabolites only become active in specific situations and are therefore employed as classification markers (*Harwood, 2012*). Many environmental conditions influence the activity of plants. Depending on their length and severity, some of them could function as stressors. Stress is defined as any unfavourable environmental factors influencing crop and plant development. The two classes lack a distinct border and cannot be distinguished based on their chemical structures, precursor molecules, or sources of biosynthesis. For instance, proline, an amino acid, is the primary metabolite, and pipecolic acid, a molecule that is similar to it in C6, is the alkaloid. Likewise, primary and secondary metabolites are present in di- and tri-terpenoids (*Schwarzenbach et al., 2016, Edreva et al., 2008*). Plants evolved to adapt to the environment, genetically coding useful synthesizes and various secondary metabolites *(Janská et al., 2010; Rastegari et al., 2019).*

Additionally, studies have demonstrated that a few of these molecules have protective properties, allelochemical attraction, and an impact on herbivores and pollinators. Avoid toxicity, protect against UV radiation, and facilitate signal transmission. In 1891, Kossel referred to these substances as "secondary metabolites" and stated that they were vital to plant life (*Ahmed et al., 2017*). The biological significance of secondary metabolites was deemed insignificant, leading plant scientists to give them minimal attention. Nonetheless, since the 1950s, researchers studying organic chemistry have studied their structure and chemical characteristics in great detail *(Mauseth, 2014).* It is now evident that this notion is unclear and incorrect, and that secondary metabolites function and play a significant role in latent defence mechanisms, particularly in chemical warfare or competition between pathogens and plants (*Croteau et al., 2000; Srivastava et al., 2021*).

All things considered, we may divide these metabolites into three main groups that are connected to plants' ability to withstand stress: biochemicals, plant growth regulators, and enzymes. The evaluation will provide light on how each of them contributes to plant defence reaction in times of stress.

2. FUNCTIONS OF PLANT SECONDARY METABOLITES:

Important substances called plant SMs give plants their colour, flavour, and odour in addition to mediating how they react to unfavourable environmental circumstances (*Verma and Shukla, 2015*). The production of SM in plants is significantly perturbed by a variety of circumstances. varying SMs have varying endogenous levels in various plant species as well as within the same plant species (*Barton, 2007*). The storage and movement of SM are influenced by several cellular and metabolic processes. Certain cellular structures involved in the production and storage of starch are influenced by developmental factors in their beginning and subsequent differentiation (*Broun et al., 2006*). Moreover, a variety of environmental stressors, including nutritional shortages, wounds, metal ions, ultraviolet (UV) radiation, light, seasonality, salinity, drought, and temperature, have an impact on the endogenous levels of SM (*Gouvea et al., 2012; Verma and Shukla, 2015*). In addition, the growth circumstances and the specific SM's metabolic route are linked to the endogenous concentration of SM (*Akula and Ravishankar, 2011*). Pathogen assault and other biotic variables also have an impact on SM concentration, which in turn influences plant defence mechanisms. For example, plants differ significantly in how much phenolics they contain in response to environmental stressors like light intensity and nutrition availability (*Verma and Shukla, 2015*). Genetic factors can impact the quantities and storage of SM that are endogenous. The expression of genes involved in the production of SMs is influenced by several variables. These elements are crucial in regulating the endogenous concentration, storage, and production of different SMs. Plant growth regulators and signalling molecules may also stimulate the biosynthesis of various SMs in in vitro tissue culture. This demonstrated unequivocally that SM's endogenous levels are modifiable. All things considered, there are four types of causes that cause changes in SMs: environmental, morphogenetic, ontogenetic, and genetic. Environmental variables are the primary drivers of plant SM variations among these components (*Verma and Shukla, 2015*).

3. ROLE OF SECONDARY METABOLITES UNDER ENVIRONMENTAL STRESSES:

In response to abiotic and biotic stimuli that modulate SM production, plants exhibit variation in SM biosynthesis and accumulation (*Zhi-lin et al., 2007*). Plants of the same species growing in different environments can potentially have different SM concentrations (*Radušienė et al., 2012*). Naturally occurring plants are vulnerable to both biotic and abiotic stressor damage. Certain SMs are synthesised by plants in response to various environmental pressures, and as a result, the plants are able to combat the negative effects of both biotic and abiotic stresses. Therefore, the most important factors influencing the development of SMs in plants are environmental stressors. Abiotic stressors that significantly affect plant development and production include temperature stress, light intensity, drought, and soil composition and type. Conversely, a biotic factor is acknowledged when living creatures cause a decrease in plant development and yield (*Radušienė et al., 2012*). Broadly speaking, abiotic stress includes stress brought on by radiation, nutritional deficiencies, pesticides, heavy metals, pollution, toxic gases like ozone, and salt (*Akula and Ravishankar, 2011*).

Any universal trail for abiotic stress may be divided into the subsequent key phases based on the information and understanding of stress signalling pathways currently available. These stages include signal awareness resulting in signal transduction and ultimately manifestation of genes involved in the stress response, as well as physiological and metabolic reply. First, throughout this process, plant cells experience stress. stimuli via sensors or receptors built onto the cell wall or the membrane of a cell.

A second messenger, which consists of calcium ions (CaC2), inositol triphosphate (IP3), reactive oxygen species (ROS), cyclic nucleotides (cAMP and GMP), carbohydrates, and nitric oxide, converts the intercepted extracellular impulses into intracellular signals.

In the majority of signal transduction pathways, protein kinases mediate phosphorylation, whereas phosphatases mediate dephosphorylation. All compatible solutes, particularly glycine, betaine, and proline, as well as enzymatic and nonenzymatic antioxidants (such as glutathione, tocopherol, ascorbic acid, phenol, and superoxide dismutase), polyamines (putrescine, spermidine, and spermine), lipoxygenases, including oxylipins, jasmonic acid, abscisic acid, methyl jasmonate, salicylic acid, ethylene, brassinosteroids, and traumatin, are activated in response to increased ROS production. These various metabolites cooperate by cross-linking with one another to overcome stress brought on by biotic and abiotic sources. Hormones like salicylic acid and jasmonate acid promote PR proteins, which are activated in the event of a pathogenic onslaught.

Stress tolerance is achieved by the production of stress response genes. Specifically, phytoalexins and PR proteins are generated in response to biotic stress, such as pathogen assault, which triggers the SAR (systemic acquired response) pathway and eventually activates transcription factors. All of the aforementioned elements together form a flexible route for stress signalling in plants, starting with the most significant downstream functional gene receptors.

III Methodology

3.1 Biotic Stresses

Nematodes, bacteria, viruses, and fungus are only a few of the many living things that may induce biotic stressors in plants. Plants are unable to relocate to a less stressful environment. However, due mostly to the synthesis of SMs, plants have a high level of resistance against pathogen assaults. These SMs are called phytoalexins, and because of their antibacterial properties, they help plants defend themselves against pathogen invasion (*Taiz and Zeiger, 2006*). Plants under pathogen attack show enhanced biosynthesis of SMs. Plants acquire an innate immune system as a result of pathogen infection. Effector-triggered immunity and basal immunity mediate the plant innate immune system. Through the use of microbe-associated molecular patterns that host cells' pattern recognition receptors detect, infected cells use the basal immune system to recognise pathogens. Furthermore, host cells employ effector-triggered immunity to identify pathogen invasion in reaction to effectors or harm caused by pathogen toxins. Such effectors send signals to plants, which then trigger a variety of metabolic processes to create SMs. Stress recovery results in a considerable drop in the concentration of SMs (*Wojakowska et al., 2013*).

3.2 Abiotic Stresses

Throughout various ontogenic stages, plants are frequently subjected to a wide range of abiotic stressors, including chemical fertilisers, varying soil types and compositions, temperature stress, light intensity, water availability, and salt. Appropriate amounts of abiotic elements are necessary for plants to develop and produce, and an excess or shortage of these elements can cause variations in the biosynthesis of SMs (*Verma and Shukla, 2015*). When plants are exposed to environmental stressors including temperature, food shortages, wounding, and UV radiation, their concentrations of phenylpropanoids—important SMs—often rise (*Dixon and Paiva, 1995*). Additionally, plants exhibit changes in phenolic concentrations as a result of nutritional deficiencies (*Chalker-Scott and Fuchigami, 1989*).

TABLE 3.1- Changes in the Biosynthesis and Accumulation of SMs in Plants Under Temperature and Heavy Metal Stress:

Plant Species	**Stress Level**	**Effects on the Concentration of SMs**	**References**
Citrullus lanatus, Lycopersicum esculentum	15, 25, and 35°C temperature	In C. lanatus, D. maravilla, and tomato plants, high temperatures caused notable alterations in plant biomass, activities of peroxidase, polyphenol oxidase, and phenylalanine ammonia lyase, as well as total phenolics. There are three temperature ranges: 15, 25, and 35°C. There was a noticeable difference in how different plant species responded to various temperature ranges; tomato and watermelon showed this more than other plant species. Tomatoes began to experience heat stress at 35°C, whereas watermelon experienced chilling stress at 15°C. Researchers saw increased phenylalanine ammonia lyase activity, promoted phenolic content buildup, and reduced plant biomass. They also noticed a decline in the activity of peroxidase and polyphenol oxidase. It was proposed that plants developed thermal tolerance as a result of phenolics produced in response to heat stress.	*Rivero et al. (2001)*
Vitis vinifera L.	10/7°C day/night	When exposed to continuous or extended cold stress, V. vinifera plants showed notable alterations in the accumulation of some SMs.	*Król et al. (2015)*

		It was suggested that tolerant cultivars have greater levels of phenolic content, antioxidant activity, and reducing power. The content of phenolics and antioxidant activity in grapevine types decreased significantly during cold stress. The main phenolic acids identified from leaf extracts of two grapevine species were ferulic acid, p-coumaric acid, caffeic acid, and caffeic acid derivatives. Of the several phenolic acids, the concentration of caffeic acid was higher. It was also shown that plants subjected to extended cold stress had a drop in phenolic acid content. It was discovered that SM concentration changed significantly depending on how much stress there was.	
Capsicum annuum L.	4°C for 3 days	When pepper seedlings were exposed to cold stress, their endogenous levels of proline, phenolic compound, and total soluble proteins significantly increased, but their chlorophyll contents significantly reduced.	*Esra et al. (2010)*
Sorghum bicolor L.	38/21 °C	Polyphenols abound in grains of sorghum. To evaluate the amount of polyphenols in several sorghum genotypes exposed to high temperatures, an experiment was carried out. With the use of the HPLC approach, about 23 distinct phenolic compounds were found. Because white sorghum had lower levels of polyphenols, it had a simpler phenolic profile. Brown sorghum, on the other hand, has a rich profile of phenolics, including ferulic and caffeic acid. luteolin and apigenin, however,	*Wu et al. (2016)*

		were not found in this genotype. In all sorghum genotypes, the content of luteolinidin and apigeninidin was elevated by high-temperature stress. Additionally, researchers found a correlation between sorghum's higher temperature tolerance and its rich phenolic profile.	
Camellia sinensis L.	10, 20, 30 °C	Exposure of *C. sinensis* resulted in a marked increase in phenolic compounds	*Upadhyaya (2012)*

3.3 Salinity Stress:

Higher salt concentrations in the growth media cause osmotic stress, which makes plants susceptible to physiological drought—a state in which water is present but cannot be absorbed by the plants. Increased salt content in soil causes a reduction in plant growth, photosynthesis, and nutrient absorption (*Ashraf et al., 2015*). Plant SMs may undergo increase or decrease in their concentration in response to salinity-induced osmotic stress or specific ion toxicity (*Akula and Ravishankar, 2011*). Alkaloids also rise in response to salinity stress. Similar to this, salt stress increased the antioxidant capacity and antihypertensive alkaloid (ajmalicine) in C. roseus roots (Jaleel, 2009). Similarly, salinity stress also increased the levels of saponins, flavonoids, and proline (Haghighi et al., 2012). The effects of salinity on plant SM production are summarized in Table 8.2. The levels of primary metabolites and SMs also vary in response to the availability of different nutrients (*Verma and Shukla, 2015*).

TABLE 3.2 Influence of Salinity Stress on the Biosynthesis and Accumulation of Different SMs in Plants

Plant Species	**Salinity Level**	**Effects on the Concentrations of SMs**	**References**
Cotton	50, 100, 150, and 200 mM	There was a marked increase in the concentration of tannic acid (15.1%–24.3%), flavonoids (22.5%–37.6%), and gossypol (26.8%–51.4%) in cotton plants subjected to salinity stress. Researchers have	*Wang et al. (2015)*

		further declared that salt-induced biosynthesis and accumulation of SMs significantly contributed to decrease in aphid population	
Sugarcane	12.5 and 6.8 dS/m	Two sugarcane clones, namely, CP-4333 (salinity tolerant) and HSF-240 (salinity sensitive), exhibited a significant alteration in the number of SMs, namely, flavones, anthocyanins, and soluble phenolics, under salinity stress. Exposure of two clones to salinity stress markedly decreased plant biomass, photosynthesis, chlorophyll content, and SMs. However, this decrease in SMs and photosynthesis was more in the sensitive clone HSF-240 than in CP-4333. Salinity tolerance in sugarcane was positively associated with these SMs, which appeared to prevent oxidative damage due to ionic toxicity. Carotenoid is an important component of light harvesting complex and thereby induces tolerance to chloroplast under salinity stress	*Wahid and Ghazanfar (2006)*
Maize	0 and 100 mM	Total phenolic and flavonoid contents increased in maize plants subjected to salinity stress	*Salama et al. (2015)*
Rice	0 and 25 mM	Salinity stress induced a significant increase the nutritional quality in grains in terms of antioxidant activities, anthocyanins, proanthocyanins, and total phenolics	*Chunthaburee et al. (2015)*
Wheat	0 and 150 mM	Hydroponics experiment was conducted to appraise growth stage–based variation in phenolics in wheat under varying salinity levels. It was observed that salinity stress induced increase in phenolics, which were significantly higher at the boot stage than in the vegetative or reproductive stage. Authors suggested that phenolics contributed to salinity tolerance in wheat in terms of improved plant biomass	*Ashraf et al. (2010)*

Pea	75, 120, 150, and 200 mM	There was significant increase in total phenolics in three different pea species (Pisum fulvum, Pisum sativum, and Pisum arvense) plants under moderate salinity levels, whereas decrease in total phenolics was evident due to elevated levels of salinity	*Miljus-Djukic et al. (2013)*

3.4 Drought Stress:

Because it directly contributes to the movement of nutrients and metabolites across various plant sections, water is a vital component for plants. Plants experience drought stress when there is little water available or when transpiration rates are higher, which modifies the production of SM (Table 4.3). Plants under drought stress have a decrease in their turgor and water potential, which has an adverse effect on a number of physiological processes (*Lisar et al., 2012*). Drought-induced suppression in photosynthesis and growth induces significant alterations in important biochemical processes of plants (*Aimar et al., 2011*). Moreover, a reduction in photosynthesis brought on by drought stress is linked to stomatal closure, loss of membrane integrity, and altered enzyme activity. Drought-induced osmotic stress also has a detrimental impact on essential crop productivity (*Valentovic et al., 2006*). A number of SMs produced in plants are also helpful in the induction of drought tolerance (*Verma and Shukla, 2015*).

TABLE 3.3 Drought-Induced Alterations in the Biosynthesis and Storage of Plant SMs

Plant Species	**Drought Level**	**Effects of the Concentrations of SMs**	**References**
Rice	85, 65, 45%, and 25% soil moisture	Influence of drought stress on SM accumulation and antioxidant activity was determined in 20 rice genotypes. It was found that greater antioxidant activity in terms of DPPH and accumulation of SMs is correlated with drought tolerance in rice plants. Authors declared Q2 as the sensitive and Q8 as the tolerant rice genotype. Drought-induced increase in antioxidant activity and SMs (flavonoids and phenolics) was greater in tolerant Q8genotype, whereas rice genotype Q2 was inferior in this context. Presence of *p*-hydroxybenzoic acid was	*Quan et al. (2016)*

		only detected in Q8 genotype, whereas vanillic acid accumulation was evident in both genotypes under drought stress. It was suggested that vanillic acid and *p*-hydroxybenzoic acid (phenolic compounds) were the major determinants of drought tolerance or sensitivity in rice genotypes	
Maize	PEG-induced stress (−0.6 MPa)	PEG-induced drought conditions caused decrease in phenolic compounds that was accompanied by decrease in plant biomass in maize plants	*Asgari and Shiri (2015)*
Maize	30%–35% FC	Imposition of drought stress in maize ceased plant growth, reduced relative water contents, and increased phenolics and soluble proteins.	*Latif et al. (2016)*
Maize	70 and 30%–35% FC.	An experiment was conducted to appraise whether or not drought tolerance in maize is determined by the accumulation of phenolics. There existed a significant alteration in phenylalanine ammonia lyase, ferulic acid, and total phenolics. In drought-tolerant genotypes, low water potential was accompanied by the accumulation of ferulic acid and total phenolics. Total phenolics absorb light and transform into blue fluorescence and thereby protect mesophyll tissues. It was suggested that phenolics acted as photoprotectors because these compounds limit chlorophyll excitation under drought conditions	*Hura et al. (2008)*
Soybean	−15 to −20 (control) and drought (−90 and	Onset of drought conditions in soybean plants resulted in a significant increase in total phenolics and lignin	*Nacer (2012)*

	−100 kPa)		

IV Result & Discussion

The comprehensive review of secondary metabolites and their impact on environmental stress resistance reveals several key findings:

1. Diverse Roles of Secondary Metabolites: Secondary metabolites such as alkaloids, flavonoids, terpenoids, phenolics, and glycosides play diverse roles in enhancing plant resistance to various environmental stresses. These compounds act as antioxidants, osmoprotectants, and chemical defenses against herbivores and pathogens.
2. Mechanisms of Action: The mechanisms through which secondary metabolites confer stress resistance are multifaceted. For instance, flavonoids protect plant cells from oxidative damage, while terpenoids deter herbivores and pathogens. Osmoprotectants help maintain cellular water balance under drought conditions.
3. Induced Production: The synthesis and accumulation of secondary metabolites are often induced by environmental stressors. Plants activate complex signaling pathways in response to stress, leading to the production of these protective compounds.
4. Agricultural Applications: Understanding the mechanisms of secondary metabolites can lead to the development of crops with enhanced stress tolerance. Traditional breeding and biotechnological approaches can be used to increase the levels of beneficial secondary metabolites in crops.
5. Sustainable Agriculture: Secondary metabolites offer a sustainable approach to crop protection. Plants with higher levels of certain secondary metabolites can reduce the need for chemical pesticides and synthetic antioxidants, thereby minimizing environmental impacts.
6. Ecosystem Interactions: Secondary metabolites play crucial roles in plant-plant and plant-microbe interactions, contributing to the resilience and stability of ecosystems. They attract beneficial microbes, inhibit competing plant species, and support biodiversity.

V. CONCLUSION AND FUTURE PROSPECTS:

The material included in this chapter makes it abundantly evident that plant SMs are important for plant adaptation to a range of environmental conditions that affect plant development and change SM production. Secondary metabolism, which serves as a storehouse of essential phytochemicals that shield plants from a variety of environmental stresses, carefully controls the growth and development of plants. The research also demonstrates the significance of these plant SMs as potential food sources for humans. The material reviewed previously in the chapter suggests that there is still much to learn about the biosynthesis of plant SMs. To improve plant tolerance to environmental challenges, further study is required to fully understand the regulatory proteins and genes involved in the manufacture of plant SMs. Many plant SMs have antioxidant qualities that serve as a first line of defence against oxidative damage brought on by various environmental restrictions (heavy metals, temperature, salt, drought, and hypoxic stress). Reactive oxygen species (ROS) produced in excess as a result of environmental stressors often cause oxidative damage. Increased cellular ROS levels impair membrane integrity. The crucial roles of plant SMs in stressed environments have not been well investigated. Research on how plant SMs help plants against oxidative damage has to be done in great detail. Investigating the roles played by distinct plant SMs in stressed plants is crucial. Studying the biotic and abiotic variables that affect plant SM production is important. It is necessary to devise strategies to increase plants' capability for producing SM.

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