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Biostimulants: The First Line of Defense Against Plant Diseases—A Review

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Abstract

Biostimulants are natural substances or microorganisms that stimulate plant physiological processes. Unlike fertilizers, they do not supply nutrients directly but enhance nutrient uptake, stress tolerance, and plant immunity. Key benefits include: enhanced root growth and efficiency, improved tolerance to salinity, drought, heat and cold, increased photosynthesis and chlorophyll content, activation of systemic acquired resistance SAR and PR proteins against pathogens, and improved soil properties with reduced chemical inputs. Main types include: Microbial biostimulants such as *Trichoderma* fungi that parasitize pathogens and produce chitinase enzymes, and PGPR bacteria like *Bacillus* and *Lysinibacillus* that fix nitrogen, solubilize phosphorus, produce antibiotics and siderophores. Non-microbial biostimulants include seaweed extracts, amino acids, humic and fulvic acids for soil and root improvement, and salicylic acid for immunity activation and delaying senescence. In conclusion, biostimulants act through direct antagonism of pathogens and by strengthening plant defense systems. They offer a sustainable solution to reduce pesticides and fertilizers, especially under abiotic stress conditions.

Keywords

Biostimulants,
Microbial Biostimulants,
Non-Microbial Bio Stimulants,
PGPR,
Humic acid,
Fulvic acid.



Introduction

Biostimulants are substances or microorganisms used to stimulate natural processes within plants, thereby improving nutrient uptake and enhancing their ability to tolerate environmental stresses. Their effects include promoting nutrient acquisition, increasing stress tolerance, and stimulating plant growth. Most biostimulants are derived from organic sources and include beneficial fungi and bacteria, amino acids, plant-derived compounds, and other bioactive substances.

Unlike fertilizers, which directly supply plants with essential nutrients through soil application or foliar spraying, biostimulants primarily act by stimulating physiological and biochemical processes that improve plant performance. They promote root development, enabling plants to access greater amounts of nutrients and water, improve nutrient transport and utilization within plant tissues, and enhance the plant's natural defense mechanisms, thereby increasing its ability to resist and suppress phytopathogens (Calvo et al., 2014; Colla et al., 2020).

Biostimulants may also influence the rate of photosynthesis, thereby improve energy production and promote plant growth. In addition, they can stimulate beneficial soil microorganisms and improve soil properties by supporting microbial activity and soil aggregation. Consequently, the application of biostimulants may contribute to reducing the dependence on conventional fertilizers while improving plant health and productivity.

Biostimulants comprise a wide range of bioactive substances and beneficial microorganisms, including *Trichoderma* spp.,

plant growth-promoting bacteria such as *Bacillus* spp., seaweed extracts, amino acids, humic and fulvic acids, and salicylic acid (Ertani et al., 2013). These substances and microorganisms can affect plants through multiple mechanisms, including stimulation of plant growth, enhancement of nutrient-use efficiency, modulation of physiological and biochemical processes, and activation of plant defense responses.

In this article, we review the major groups of biostimulants and discuss their effects on plant pathogens, as well as their roles in soil health and in regulating biological, physiological, and biochemical activities within plants.

Benefits of Biostimulants

Biostimulants provide a wide range of beneficial effects on plant growth, development, stress tolerance, and natural defense mechanisms. Their major benefits include:

1. Stimulation of root growth:

Biostimulants promote root development and increase root biomass and size, enabling plants to explore a larger volume of soil and consequently improving their ability to acquire and utilize water and essential nutrients.

2. Improved tolerance to climate change and adverse weather conditions:

Biostimulants help plants cope with the effects of climate change and extreme weather events by increasing their resilience to environmental stresses. This may also reduce the dependence on plant protection products by improving overall plant

health and strengthening the plant's natural capacity to withstand biotic and abiotic stresses.

3. Enhancement of the plant's natural defense system:

Biostimulants enhance the plant's innate defense mechanisms and can stimulate defense-related physiological and biochemical responses. This contributes to the development of more sustainable food production systems by reducing agricultural losses and decreasing dependence on synthetic agricultural inputs.

4. Improvement of photosynthetic efficiency:

Biostimulants can enhance photosynthetic performance by increasing chlorophyll content and improving the physiological activity of leaves. Consequently, leaves may exhibit a deeper green coloration, reflecting improved chlorophyll accumulation and photosynthetic capacity.

5. Enhanced tolerance to salinity and drought:

Amino acids and seaweed extracts can improve plant tolerance to salinity and drought by enhancing cellular water retention, maintaining membrane stability, and supporting osmotic adjustment under water-deficit and saline conditions.

6. Increased tolerance to high and low temperatures and frost:

Biostimulants can enhance plant tolerance to temperature extremes, including heat, cold, and frost. They may reduce oxidative damage in leaf tissues by enhancing antioxidant defense systems and maintaining

cellular integrity. In addition, salicylic acid can act as a signaling molecule that activates or enhances plant defense responses, thereby contributing to improved resistance to environmental stresses and pathogens (Bulgari et al., 2015; Zhang et al., 2021).

Types of Biostimulants

Biostimulants can be broadly classified into microbial biostimulants, which include beneficial fungi and bacteria, and non-microbial biostimulants.

1. Microbial Biostimulants

Microbial biostimulants include beneficial fungi, such as *Trichoderma* spp., and beneficial bacteria, particularly plant growth-promoting rhizobacteria (PGPR).

Trichoderma spp. can improve nutrient availability in the soil, produce beneficial enzymes, stimulate plant growth, and enhance plant tolerance to biotic and abiotic stresses. In addition, beneficial rhizobacteria promote plant growth by increasing the availability of nutrients in forms that can be readily absorbed by plants, stimulating the production of plant growth-promoting hormones, and suppressing phytopathogens through the production of antimicrobial compounds, including antibiotics.

2. Non-Microbial Biostimulants

Non-microbial biostimulants include several groups of substances, among which are amino acids, plant extracts, seaweed extracts, and humic substances.

Amino acids:

Amino acids support plant growth by providing the basic building blocks required for the synthesis of proteins and other essential cellular compounds. They can also contribute to the regulation of plant metabolism and enhance plant responses to environmental stresses.

Plant extracts:

Plant extracts can promote root development, improve nutrient uptake and utilization, stimulate plant defense mechanisms, and increase plant resilience to drought and extreme temperatures.

Seaweed extracts:

Seaweed extracts are among the most widely used types of biostimulants. They are commonly obtained from brown marine algae, particularly *Ascophyllum nodosum* and *Ecklonia maxima*. These extracts contain a complex mixture of biologically active compounds, including plant hormones such as cytokinins, auxins, and gibberellins, as well as amino acids, polysaccharides, micronutrients, antioxidants, and vitamins. These compounds can contribute to improved water retention, nutrient uptake, and plant growth. Seaweed extracts may also contain micronutrients such as Fe, Zn, Mn, Cu, and B, which contribute to various physiological and metabolic processes in plants (Attia et al., 2024).

Humic Substances

Humic substances are complex organic compounds formed during the decomposition and transformation of plant and animal residues in soils over long periods. They are important components of soil organic matter and play significant roles in improving soil properties, nutrient availability, and plant metabolism. The major groups include:

1. Humic acid (HA):

Humic acid is generally dark brown to black in color and is insoluble in acidic media but soluble under alkaline conditions. It can improve several physical, chemical, and biological properties of soil and contribute to long-term improvements in soil quality, nutrient availability, and plant growth (Khan et al,2013).

2. Fulvic acid (FA):

Fulvic acid is generally yellow to brown in color and remains soluble across a wide range of pH conditions. Its relatively low molecular weight and high content of functional groups facilitate its interaction with plant tissues and mineral nutrients. Fulvic acid can act as a natural carrier or complexing agent for nutrients, thereby enhancing nutrient availability and uptake. It also contributes to improving soil structure and influencing plant metabolic processes (Nardi et al., 2002).

Examples of Microbial Biostimulants**The Biocontrol Fungus *Trichoderma* spp.**

Fungi belonging to the genus *Trichoderma* have been recognized since the 1920s for their ability to act as biological control agents against plant pathogens. These fungi employ several major mechanisms that act directly against pathogens, including mycoparasitism, antagonism, and competition for nutrients and space. In addition, *Trichoderma* spp. can affect plants by inducing systemic resistance, thereby promoting plant growth and improving nutrient uptake. Studies have demonstrated that these fungi produce a diverse array of antifungal enzymes, particularly chitinases and β -1,3-glucanases, which act synergistically with other enzymes to suppress plant-pathogenic fungi (Harman, 2006).

The genus *Trichoderma* comprises a large number of species and strains that are widely distributed in the environment. These fungi are commonly isolated from forests and agricultural soils and can grow readily under laboratory conditions. *Trichoderma* species produce green-colored spores, and some species generate a characteristic coconut-like odor due to the production of volatile organic compounds. *Trichoderma* is one of the most common fungal genera in soil and possesses a high capacity for colonization and proliferation on different substrates and hosts. It is widely used to promote crop growth and for the production of enzymes and antibiotics for industrial and molecular applications. In addition, *Trichoderma* spp. are used as commercial biopesticides and for the management of diseases caused by fungi, bacteria, and nematodes through soil, seed, and plant treatments. They have also been employed in the bioremediation of heavy-metal contamination and in the degradation of pesticide residues, among several other applications (Pandey et al., 2022).

Numerous studies have demonstrated that *Trichoderma* species possess most of the mechanisms associated with biological control, including competition for resources such as space and nutrients production of secondary metabolites, including antibiotics and cell-wall-degrading enzymes (Vinale et al., 2013), mycoparasitism of plant-pathogenic fungi (Vinale et al., 2008), and stimulation of plant defense responses, including systemic acquired resistance (SAR), induced systemic resistance (ISR), and the hypersensitive response (HR). Among these mechanisms, competition, mycoparasitism, and the production of antifungal compounds are considered particularly important (Verma et al., 2007).

Mycoparasitism involves recognition and attachment to the pathogen's cell wall, followed by its degradation and disruption through the action of several enzymes, particularly chitinolytic and glucanolytic enzymes (Monte, 2001). As a consequence of this antagonistic interaction, however, several *Trichoderma* species have also been identified as causal agents of green mold disease in white button mushroom crops in different countries (Wang et al., 2016).

The fungus *Trichoderma aggressivum* f. *europaeum* can be considered a biological control agent as well as a plant growth-promoting microorganism. One of its most effective characteristics is its strong competitive ability against the inhibitory effects of various bacteria and fungi, which may explain its rapid growth and prolific sporulation (Savoie et al., 2001). Accordingly, Ordaz-Ochoa et al. (2017) reported the inhibition of mycelial growth of different *Armillaria* spp. isolates in dual-culture assays by *T. aggressivum*.

More recently, Sánchez-Montesinos et al. (2019) demonstrated the ability of *T. aggressivum* to promote the growth of melon plants under saline soil conditions. The researchers also reported the suppression of wilt disease caused by the plant pathogen *Pythium ultimum* in melon seedlings following treatment with *T. aggressivum* f. *europaeum*, resulting in a 63% reduction in disease severity.

Rodríguez et al. (2021) isolated and identified *T. aggressivum* as a mycoparasite of *Hemileia vastatrix*, the causal agent of coffee leaf rust, and described this interaction for the first time in tropical regions. Sánchez-Montesinos et al. (2020) reported that

volatile compounds produced by *T. aggressivum* promoted the growth of *Arabidopsis* plants, increasing shoot fresh weight by 37.1% and chlorophyll content by 82.5%.

Similarly, Sánchez et al. (2021) demonstrated that *T. aggressivum* exhibited antagonistic activity against several plant pathogens. The fungus completely inhibited the growth of the phytopathogenic fungi *Botrytis cinerea*, *Sclerotinia sclerotiorum*, and *Mycosphaerella melonis*, with 100% inhibition observed in detached-leaf assays. It also inhibited the germination of sclerotia of *S. sclerotiorum*. Nevertheless, relatively little is known about the potential role of *T. aggressivum* in the management of different plant pathogens under both in vitro and in vivo conditions.

Plant Growth-Promoting Rhizobacteria (PGPR)

The region surrounding plant roots is known as the rhizosphere. The term was first introduced by Hiltner in 1904 to describe the soil region surrounding plant roots that is inhabited by microorganisms and plays an important role in plant health (Hartmann et al., 2008). The rhizosphere is a nutrient-rich environment for microorganisms, particularly due to the accumulation of amino acids, sugars, and other compounds released through plant root exudates. This abundance of readily available nutrients explains the higher microbial population densities in the rhizosphere compared with bulk soil located away from the root system (Gray and Smith, 2005).

In a study investigating the effects of root exudates from banana plants, Yuan et al. (2015) demonstrated an association between root exudation and the occurrence of

microorganisms, particularly plant growth-promoting rhizobacteria (PGPR). Root exudates provide microorganisms with various nutrient sources, including proteins, organic acids, amino acids, and sugars, and can also act as chemical signals that attract and recruit beneficial microorganisms to the rhizosphere.

The term plant growth-promoting rhizobacteria (PGPR) was first introduced by Kloepper and Schroth (1978) to describe bacteria that colonize the rhizosphere and have the ability to promote plant growth either directly or indirectly. Vessey (2003) subsequently provided a broader definition of PGPR, describing them as a group of microorganisms that inhabit the rhizosphere and promote plant growth through direct mechanisms, such as biological nitrogen fixation, solubilization of nutrients, and production of plant growth-promoting hormones, or through indirect mechanisms, such as suppression of plant pathogens and induction of systemic resistance.

Yang et al. (2009) reported that PGPR can also enhance plant tolerance to abiotic stresses by contributing to improved soil structure and increasing soil water-holding capacity.

PGPR employ diverse and complex mechanisms to suppress plant diseases. These mechanisms can be classified into direct and indirect mechanisms. Direct mechanisms include the production of antibiotics, siderophores, and hydrolytic enzymes, competition for nutrients and colonization sites, and interference with bacterial quorum sensing. Indirect mechanisms include modification of root exudation patterns, stimulation of plant hormone production or signaling, including

auxins, cytokinin's, gibberellins, and 1-aminocyclopropane-1-carboxylic acid (**ACC**)-related pathways, as well as induction of systemic resistance in plants.

The induction of systemic resistance by PGPR is associated with the activation of several defense-related enzymes, including phenylalanine ammonia-lyase (PAL), peroxidase (POX), polyphenol oxidase (PPO), and chitinases, which contribute to the strengthening of plant defense responses against pathogens (Dutta et al., 2022).

The Biocontrol Bacteria *Bacillus* spp.

Species of the genus *Bacillus* represent a widely distributed and diverse group of bacteria that inhabit a broad range of environments. They can be isolated from various sources, including soil, water, plant roots, animals, and humans (Altinok et al., 2013). These species may have either beneficial or detrimental effects on their hosts. Most soil- and plant-associated bacteria, particularly members of the genus *Bacillus*, are commonly characterized as plant growth-promoting rhizobacteria (PGPR). These bacteria are well known for their ability to produce a wide range of bioactive compounds, fix atmospheric nitrogen, produce phosphatases, facilitate iron (Fe) acquisition, and stimulate the production of plant hormones, ultimately inducing induced systemic resistance (ISR) in plants (Kavamura et al., 2021).

Treatment of plants with certain *Bacillus* species can function as a form of biofertilization. Their ability to competitively colonize plant roots contributes to improved seedling establishment, enhanced germination, and increased plant biomass (Xu et al., 2020). Some *Bacillus* species compete for essential

resources, including carbon and iron, while also producing antibiotics and hydrolytic enzymes that suppress plant pathogens, reduce disease pressure, and improve overall plant health. These secondary metabolites play an important role in enhancing bacterial survival, adaptation, and competitiveness within their surrounding environments (Brito et al., 2018; Choyam et al., 2021).

In 2015, *Bacillus paralicheniformis* was separated from *Bacillus licheniformis* based on phylogenetic and phylogenomic studies (Jeong et al., 2018). *Bacillus licheniformis* and *Bacillus paralicheniformis* are closely related, spore-forming, saprophytic bacteria capable of facultative anaerobic growth. Although closely related, they are distinct from *Bacillus subtilis* strains. Determining the evolutionary origins and taxonomic relationships of *B. licheniformis* and *B. paralicheniformis* was challenging before the availability of complete genome sequences. Advances in whole-genome sequencing technologies have enabled more accurate classification of these strains and improved understanding of their evolutionary relationships (Zeng et al., 2021). Recent studies have demonstrated that some *B. paralicheniformis* strains can promote plant growth and suppress plant pathogens (Pylro et al., 2019).

Bacillus paralicheniformis has also been isolated from deep-sea environments and represents a potential source of enzymes capable of degrading petroleum-derived plastic polymers, such as polystyrene. Such enzymes may have considerable value in the bioremediation of plastic pollution through the degradation of petroleum-derived materials, making this bacterium a promising candidate for biotechnological applications

aimed at reducing plastic pollution (Kumar et al., 2021).

Several *Bacillus* species, including *B. subtilis*, *B. velezensis*, *B. paralicheniformis*, and *B. amyloliquefaciens*, are capable of producing fengycins, a group of non-ribosomally synthesized antifungal lipopeptides. These compounds can inhibit the growth of phytopathogenic fungi, making them important biological control agents for the management of plant diseases (Du et al., 2019).

The strain *Bacillus paralicheniformis* TRQ65 was isolated from the rhizosphere of durum wheat (*Triticum turgidum* subsp. *durum*). Individual inoculation of wheat seedlings with *B. paralicheniformis* TRQ65 resulted in significant increases in plant biomass. Furthermore, the strain inhibited the mycelial growth of the plant-pathogenic fungus *Bipolaris sorokiniana*, the causal agent of wheat spot blotch (Valenzuela-Ruiz et al., 2019).

Similarly, the strain *Bacillus paralicheniformis* MDJK30, isolated from the rhizosphere of peony plants in Shandong, China, demonstrated antagonistic activity against *Fusarium solani*, a pathogen associated with root rot disease of peony (Wang et al., 2017).

Lysinibacillus fusiformis

Lysinibacillus fusiformis is a Gram-positive, rod-shaped, mesophilic bacterium characterized by its ability to tolerate unfavorable environmental conditions, including high temperatures, exposure to certain chemical compounds, and ultraviolet radiation. This resilience is largely associated with its ability to produce highly resistant **endospores**, which enable the bacterium to

survive for extended periods under adverse conditions (Jabeur et al., 2020).

Lysinibacillus fusiformis has been isolated from a variety of environments, including water, soil, and plants (Zhang and Zhou, 2022), as well as from earthworms (Rostami et al., 2021). In Iraq, this bacterial species was isolated and characterized by Mohamed et al. (2024), who demonstrated its ability to promote wheat growth and increase crop productivity.

The bacterium was previously known as *Bacillus fusiformis*. In 2007, *L. fusiformis* was reclassified from the genus *Bacillus* based on differences in its peptidoglycan cell-wall composition, which contains lysine, aspartic acid, alanine, and glutamic acid, distinguishing it from the typical species of the genus *Bacillus* (Ahmed et al., 2007).

In recent years, increasing attention has been directed toward *L. fusiformis* in the context of sustainable and environmentally friendly agriculture because of its plant growth-promoting properties. The bacterium has demonstrated beneficial effects on several plant species, including citrus and apple trees, through mechanisms such as biological nitrogen fixation, production of indole-3-acetic acid (IAA), phosphate solubilization, and siderophore production (Trivedi et al., 2011; Passera et al., 2020).

Lysinibacillus fusiformis has also demonstrated biocontrol activity against several plant pathogens, including the fungi *Aspergillus niger*, *Botrytis cinerea*, *Phomopsis viticola*, and *Rhizoctonia solani* (Passera et al., 2021).

Rostami et al. (2021) reported that application of *L. fusiformis* to tomato

seedlings reduced several parameters associated with infection by the root-knot nematode *Meloidogyne javanica*. These parameters included the number of root galls, egg masses, eggs, and second-stage juveniles (J2) in the soil, in addition to reducing the reproductive factor of the root-knot nematode.

Studies have also demonstrated that certain species of the genus *Lysinibacillus* can produce secondary metabolites that play important roles in the suppression of plant diseases. Some species have been reported to produce Cry-like crystalline proteins with toxic effects against second-stage juveniles (J2) of nematodes, possibly through disruption of cellular membrane function (Berry, 2012).

Non-Microbial Biostimulants

Bio Health Biostimulant

Bio Health is a compound fertilizer formulated from potassium humate, potassium oxide, fulvic acid, seaweed extracts, and mycorrhizal strains. It stimulates the growth and activity of beneficial microorganisms in the rhizosphere, enhances seed germination and seedling development, and improves the water-holding capacity of the soil. The product can be applied alone or in combination with compound fertilizers, and it can be delivered through irrigation systems, including drip and flood irrigation.

Owing to its content of symbiotic mycorrhizal fungi, Bio Health contributes to the development of an extensive root network, thereby enhancing the uptake of nutrients and water from the soil. This improved root system may also increase plant tolerance to

root rot diseases and adverse environmental conditions.

The presence of potassium humate enhances various physiological and enzymatic activities, while seaweed extracts may stimulate plant growth through naturally occurring phytohormones, particularly auxins and gibberellins. In addition, the biostimulant components provide further support for the proliferation and activity of beneficial bacteria in the rhizosphere (Ren et al., 2022).

Because its effects extend beyond simple nutrient supply, Bio Health Myco can be considered an integrated approach for improving plant vigor, enhancing water-use efficiency, accelerating germination, and improving flowering and fruit development.

Accordingly, this type of biostimulant can be viewed as a potential "soil engineer", contributing to the restoration of beneficial interactions between plant roots and soil in a sustainable and effective manner. Such effects may help transform degraded soils into biologically active environments enriched with beneficial microorganisms (Lee et al., 2013).

Hernandez and Morales (2021) reported that the successful application of biological agents as biofertilizers depends on several factors, including the effectiveness of the biological agent, its compatibility with the host plant, its competitive ability against other microorganisms, its capacity to establish a sufficiently high population density in the rhizosphere, and its tolerance to different environmental conditions.

Toledo et al. (2023) demonstrated that seaweed extracts possess inhibitory activity against the phytopathogenic fungi *Fusarium*

oxysporum, *Botrytis cinerea*, and *Alternaria alternata*, which are associated with postharvest fruit rot of pear. Similarly, Abed and Ibade (2022) reported that seaweed extracts applied alone were effective in reducing the incidence of gray spot disease of pepper caused by *Alternaria alternata*. In addition, seaweed extract application increased nutrient accumulation in plants and improved crop yield in both quantitative and qualitative terms.

These findings highlight the potential of seaweed extracts as an important component of integrated plant disease management. Their bioactive constituents can stimulate several plant defense mechanisms, including oxidative responses, hormone-mediated signaling pathways, and the expression of stress-related genes, thereby enhancing the plant's ability to respond to biotic and abiotic stresses (Bahmani et al., 2025).

Humic Acid

Humic acid is a naturally occurring organic compound obtained from deposits rich in highly decomposed and fossilized organic matter that have accumulated over thousands of years. It is extracted and widely used to improve soil quality and fertility. Humic acid provides numerous physiological and biological benefits to plants, as well as physical, chemical, and biological benefits to soil. It can stimulate enzymatic activity and energy-related compounds within plant tissues, thereby promoting cellular metabolic processes and cell division. In addition, humic acid enhances root growth and development, strengthens the root system, and may improve fruit quality. It can also contribute to osmotic adjustment within plant tissues, thereby increasing plant tolerance to environmental stress (Phelps, 2000).

Salicylic Acid

Salicylic acid (SA) is an important plant hormone and biostimulants that plays a central role in activating plant defense systems and enhancing resistance to a wide range of plant pathogens. It is well recognized for its pivotal role in protecting agricultural crops through natural and environmentally friendly defense mechanisms (Siegrist and Uzunova, 1997).

What is Salicylic Acid?

Salicylic acid is a naturally occurring phenolic compound belonging to the group of phenolic acids. Plants naturally synthesize SA in relatively small amounts, where it functions as an important signaling molecule in responses to both biotic and abiotic stresses. When plants are attacked by microbial pathogens, SA acts as an internal warning signal that activates a range of defense-related responses.

Mode of Action of Salicylic Acid in Plants

Salicylic acid exerts several important physiological and biochemical effects in plants, including:

1. **Induction of systemic acquired resistance (SAR):**
SA plays a central role in the activation of systemic acquired resistance, which enables plant tissues distant from the initial infection site to develop enhanced resistance against subsequent pathogen attack.
2. **Induction of pathogenesis-related proteins:**
SA stimulates the expression and accumulation of **pathogenesis-related (PR) proteins**, several of which possess antifungal and antibacterial

activities and contribute to the suppression of plant pathogens.

3. **Reduction of oxidative damage:**
Salicylic acid contributes to the regulation of reactive oxygen species (ROS) and antioxidant defense systems, thereby reducing oxidative damage associated with environmental stresses such as high temperature, salinity, and drought.
4. **Regulation of stomatal opening and closure:**
SA participates in the regulation of stomatal behavior and can contribute to maintaining plant water status under water-deficit conditions.
5. **Promotion of flowering and delayed senescence:**
At appropriate concentrations, SA can influence flowering and delay leaf and fruit senescence. It can also interact with ethylene-related signaling pathways, potentially contributing to prolonged postharvest quality and storage life in some crops.
6. **Disease resistance:**
Exogenous application of SA can enhance plant resistance to several diseases, including powdery mildew, foliar blight, and various fungal diseases and rots, by activating multiple components of the plant defense system.
7. **Strengthening of cell walls:**
SA can enhance structural defenses by promoting the reinforcement of plant cell walls, thereby reducing pathogen penetration and limiting the establishment and development of fungal and bacterial pathogens.

Historical Background of Salicylic Acid

Salicylic acid was first synthesized by the Italian chemist **Raffaele Piria** in 1838. Its chemical name is **2-hydroxybenzoic acid**, and it is structurally distinct from **acetylsalicylic acid**, which is the active pharmaceutical compound commonly known as aspirin. Salicylic acid has attracted considerable attention in plant science because of its role as a natural signaling molecule involved in the activation of **systemic acquired resistance (SAR)** in plants (Benjamin et al., 2022; Quaglia et al., 2022).

The role of salicylic acid in plant defense became particularly evident through studies of plants infected with **tobacco mosaic virus (TMV)**. Early research demonstrated that SA levels increased in tissues associated with pathogen resistance and that SA was involved in the activation of genes encoding **pathogenesis-related (PR) proteins**. These findings established SA as a key signaling molecule in plant defense responses (Ali et al., 2024; Spoel and Dong, 2024).

Roychowdhury et al. (2024) reported that salicylic acid can be applied to plants through different routes. When applied to the soil, SA can be taken up by roots and transported through the vascular system, where it may contribute to the activation of systemic defense responses. Alternatively, foliar application can induce localized defense responses in treated tissues and may subsequently influence systemic signaling. These effects are associated with increased activities of several defense-related enzymes, particularly oxidative enzymes involved in plant defense responses.

Conflicts of Interest:

The authors declare that there is no conflict of interest regarding the publication of this research, this research was conducted independently, without any financial, commercial or personal relationships that could be interested as representing a potential conflict of interest affecting the study design, methodology, interpretation or analysis of its results.

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