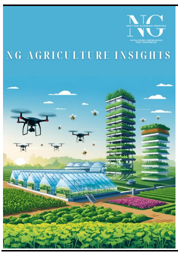

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Salicylic Acid: A Plant Defense Hormone

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ABSTRACT

Salicylic acid (SA) is a crucial plant hormone that acts as the master regulator of the innate immune system. Because plants lack specialized immune cells, they rely on SA to trigger localized programmed cell death and activate antimicrobial proteins to trap and neutralize invading pathogens and defend against insects by altering defensive metabolites and recruiting natural predators. Beyond insect and disease resistance, SA helps plants tolerate severe environmental stresses like drought and salinity. While SA offers immense potential for sustainable agriculture, researchers are developing advanced nano-formulations to overcome its natural phytotoxicity and ensure safe, controlled crop protection.

Keywords: Plant hormone, Immune system, Disease resistance, Insect defense, Environmental stress

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1. INTRODUCTION

Plants are continuously exposed to a wide range of threats throughout their life cycle. Insects such as caterpillars and aphids, along with harmful bacteria, fungi and viruses, constantly challenge their survival. Unlike animals, plants cannot escape from these attackers. Instead, they depend on a sophisticated internal defense system in which individual cells can recognize invading organisms, activate protective responses and limit the spread of damage. This built-in immune system is essential for plant survival and plays a major role in preventing severe losses in agricultural production (Fang *et al.*, 2025). A key player in this natural defense network is salicylic acid (SA), a small signalling molecule that coordinates plant immune responses (Oussou *et al.*, 2025). When a pathogen invades, SA functions as an internal warning signal, activating a series of defense mechanisms that help the plant resist infection (Fang *et al.*, 2025). One of these responses is the hypersensitive response, in which infected cells are deliberately sacrificed to confine the pathogen and prevent it from spreading further (Oussou *et al.*, 2025). Beyond this immediate protection, SA also initiates Systemic Acquired Resistance (SAR), a remarkable defense strategy that prepares healthy tissues throughout the plant to respond more rapidly and effectively to future attacks (Ding & Ding, 2020).

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2. SALICYLIC ACID

Salicylic acid (SA) is a ubiquitous β-hydroxy phenolic acid containing hydroxyl and carboxyl groups that confer polarity and solubility (Oussou *et al*., 2025). First isolated from willow (*Salix*) bark as salicin by Johann A. Buchner in 1828, SA has long been recognized for its medicinal properties. It accumulates in both photosynthetic and non-photosynthetic tissues, with basal levels varying among species, being higher in rice than in *Arabidopsis* (Lefevere *et al*., 2020; Zhang & Li, 2019). Plants synthesize salicylic acid (SA) from chorismate, the end product of the shikimate pathway, through two major pathways (Lefevere *et al*., 2020). The isochorismate (IC) pathway, predominant in *Arabidopsis*, converts chorismate to isochorismate in the chloroplast, followed by SA biosynthesis via PBS3 and EPS1 in the cytosol (Lefevere *et al*., 2020; Spoel & Dong, 2024). The phenylalanine ammonia-lyase (PAL) pathway, predominant in rice, converts chorismate to phenylalanine and subsequently to SA through trans-cinnamic acid and benzoic acid intermediates (Lefevere *et al*., 2020; Spoel & Dong, 2024).

3. PLANT DEFENSE SYSTEM

Plants possess a sophisticated defense system consisting of constitutive and induced defenses (Oussou *et al*., 2025). Constitutive defenses include pre-existing physical barriers such as trichomes and thorns (Fang *et al*., 2025). Upon pathogen invasion, plants activate induced physiological and biochemical defenses, which comprise two major immune branches (Oussou *et al*., 2025).

3.1 PAMP Triggered Immunity (PTI)

PTI is initiated when transmembrane pattern-recognition receptors (PRRs) on the plant cell surface detect highly conserved microbe or pathogen-associated molecular patterns (PAMPs), such as bacterial flagellin or fungal chitin (Oussou *et al*., 2025). This recognition rapidly triggers signalling cascades, including reactive oxygen species (ROS) production, to restrict pathogen colonization (Fang *et al*., 2025; Spoel & Dong, 2024).

3.2 Effector Triggered Immunity (ETI)

Successful pathogens secrete effector proteins that suppress Pattern-Triggered Immunity (PTI) (Spoel & Dong, 2024). In response, plants activate Effector-Triggered Immunity (ETI) through intracellular NLR receptors that recognize these effectors (Oussou *et al*., 2025). ETI often culminates in the hypersensitive response (HR), a localized programmed cell death that restricts pathogen spread.

4. HOW SALICYLIC ACID PROTECTS PLANTS FROM DISEASES

Salicylic acid (SA) is a key regulator of plant immunity, coordinating multi-layered defense responses against pathogens. At infection sites, endogenous SA rapidly accumulates, inducing the hypersensitive response (HR), a form of programmed cell death that restricts pathogen spread (Malamy *et al*., 1990). Simultaneously, SA activates the expression of pathogenesis-related (PR) genes, producing antimicrobial proteins such as chitinases and β-1,3-glucanases that degrade fungal cell walls and suppress pathogen growth (Raskin, 1992). Beyond local defense, SA mediates Systemic Acquired Resistance (SAR), where mobile signals from infected tissues stimulate SA biosynthesis in uninfected tissues (Ross, 1961; Gaffney *et al*., 1993). Systemic SA establishes SAR by priming the entire plant for enhanced defense, providing long-lasting and broad-spectrum resistance (Ding & Ding, 2020).

5. SALICYLIC ACID AND INSECT DEFENSE

Salicylic acid (SA) plays a pivotal role in plant defense against piercing-sucking insects, such as aphids and whiteflies. Infestation by these herbivores rapidly triggers SA biosynthesis and signaling networks, which fortify plant resistance (Fang *et al*., 2025; Filgueiras *et al*., 2019). To counteract insect attack, SA actively modulates the accumulation of various defensive metabolites, including phenolics, flavonoids, tannins and benzoxazinoids, which act as toxins or antifeedants that stunt larval growth and reduce leaf consumption (Setotaw *et al*., 2024; Wagay *et al*., 2026). SA induced changes in plant volatile organic compounds (VOCs) can directly alter pest host selection, either deterring settlement or confusing oviposition behaviors (Rodrigo *et al*., 2026). Beyond direct defenses, SA shapes intricate ecological interactions by coordinating tertiary defenses that recruit natural enemies. Upon herbivory, plants often convert SA into methyl salicylate, a highly volatile compound that functions as a critical airborne distress signal (Filgueiras *et al*., 2019), which strongly attracts an array of aboveground predators and parasitoids that naturally control pest populations (Filgueiras *et al*., 2019; Rodrigo *et al*., 2026).

6. BEYOND DEFENSE: PROTECTION AGAINST ENVIRONMENTAL STRESSES

Beyond its well-known role in immunity, salicylic acid (SA) is a versatile phytohormone that critically protects plants against a multitude of harsh environmental (abiotic) stresses (Spoel & Dong, 2024). Exogenous application and endogenous accumulation of SA significantly enhance plant tolerance to severe conditions such as drought, extreme temperatures (heat and cold), salinity, heavy metal toxicity and osmotic shock (Rodrigo *et al.*, 2026; Spoel & Dong, 2024). For instance, SA treatments improve drought tolerance by increasing water-use efficiency and stimulating the activity of protective antioxidant enzymes (Rodrigo *et al.*, 2026). Furthermore, environmental stressors frequently trigger the toxic overproduction of reactive oxygen species (ROS), leading to severe oxidative stress. SA serves as a potent shield against this cellular damage. It directly scavenges free radicals and upregulates robust antioxidant defense systems, including enzymes like peroxidases and superoxide dismutases, which neutralize ROS and restore cellular redox homeostasis (Rodrigo *et al.*, 2026).

7. APPLICATIONS OF SALICYLIC ACID IN AGRICULTURAL PRACTICES

Salicylic acid (SA) and its synthetic analogues are increasingly integrated into modern agricultural practices to enhance crop resilience and productivity.

7.1 Foliar Spray

Exogenous foliar application of SA is widely used to stimulate plant growth and defense. In crops like tomatoes, SA sprays significantly increase fruit yield, size and nutritional quality, such as vitamin C, protein and lycopene while mitigating the impacts of severe drought, heat and salinity (Gao *et al.*, 2024).

7.2 Seed Priming

Applying SA through seed treatments is highly effective for early-stage crop protection. SA seed priming alleviates the adverse effects of abiotic stressors, such as high soil salinity, by promoting successful and uniform germination rates (Rodrigo ***et al.*, 2026).**

7.3 Post-Harvest Treatment

Pre-harvest SA applications enhance fruit firmness and pericarp thickness, which directly improves fruit quality and storage potential (Gao *et al.*, 2024) and also significantly extends the longevity of cut flowers by inhibiting ethylene biosynthesis (Raskin, 1992).

7.4 Integrated Pest and Disease Management

Innovative slow-release SA-nanocomposites and volatile methyl salicylate dispensers are utilised to sustainably reduce pest settling and recruit natural predators in the field (Oussou *et al.*, 2025).

8. CONCLUSION

Although salicylic acid (SA) has emerged as a promising tool for sustainable crop protection, its large-scale agricultural application is constrained by several practical challenges. One of the major limitations is its potential to cause phytotoxicity when applied at inappropriate concentrations, coupled with its rapid metabolism within plant tissues, which can reduce its effectiveness. As a result, the successful use of exogenous SA depends on careful optimization of both dosage and application timing, as plant sensitivity to SA varies widely among crop species, cultivars and developmental stages. Advanced nano-formulations, including chitosan and silica-based SA nanocomposites, enable the controlled and sustained release of SA, ensuring prolonged activity while minimizing the risk of phytotoxicity caused by sudden increases in hormone. Their adoption is expected to support precision agriculture, reduce dependence on conventional synthetic pesticides and contribute to environmentally responsible crop protection, ultimately paving the way toward more resilient and sustainable agricultural production systems.

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