Review Article

Current knowledge of enhancing power of Salicylic acid for biotic and abiotic stress tolerance in field crops

ABSTRACT

The salicylic acid is involved in the control of plant development in addition to being a well-known signal molecule that mediates plant immunity. On the flip side of side, its effect on plant development has not yet been thoroughly defined, despite its well-established involvement in plant immunity. The corpus of evidence demonstrating salicylic acid's vital roles in regulating cell division and expansion—two processes that eventually establish the structure of a plant. The present understanding of the action and molecular processes by which salicylic acid controls plant development via a variety of channels is summed up in this review. Here, it is emphasized how salicylic acid influences cell division and expansion to regulate growth control. The relationships between salicylic acid and other hormones as well as their significance in determining plant development were also covered. Future crop improvement will greatly benefit from a deeper understanding of the process underpinning salicylic acid-mediated growth.

Keywords: Salicylic acid; plant immunity; cell division; hormones.

1. INTRODUCTION

Ortho-hydroxybenzoic acid, or salicylic acid (SA)—derived from the Latin word *Salix*, which means willow tree —is another name for this phenolic derivative that is widely found in the plant kingdom and is recognized for its ability to regulate several physiological and biochemical processes, including plant signaling or defense mechanism, thermogenesis, and response to differentabiotic and biotic stress [1,2].

Salicylic acid may be extracted from plants in both free and conjugated form, and it is a member of a broad class of plant phenolics from a chemical perspective. The conjugated form specifically starts with the aromatic ring being hydroxylated, methylated, and/or glucosylated [3,4].Johan Büchner first extracted salicin, one of the naturally occurring salicylic acid derivatives, from the willow tree's

(*Salix*sp.) bark in 1828 [5,6]. The concentration of this natural compound in plants varies significantly with the seasons with values of 3 mg/g of fresh biomass in *S. laponum* plants[7]. The highest content of salicylic acid is found in spring and summer and the lowest content in autumn and winter. Subsequently, it was found that nearly all willow trees, including *Salix daphnoides*,*Salixpurpurea*, *Salix alba*, and *Salix fragilis* were particularly rich in it [7]. The Italian chemist Raffaele Piria obtained salicylic acid in the bloom and buds of the European plant *Spiraea ulmaria*, later renamed *Filipendula ulmaria* (L.) Maxim. Piria was the first scientist to find this natural substance in species other than *Salix* sp. in late 1838. The identification of this molecule as non-specific to the *Salix* genus has allowed for further research into its production, biochemical properties, and physiological roles in plants [8].

Two metabolic pathways are known to create salicylic acid via the shikimate pathway in terms of its production. The first route—also referred to as the phenylalanine route—occurs in the cytoplasm of the cell. Trans-cinnamic acid (t-CA), which is oxidised to benzoic acid (BA) is produced by the enzyme phenylalanine ammonia lyase (PAL) from phenylalanine (Phe). Salicylic acid is subsequently formed via the hydroxylation of the aromatic ring of benzoic acid (BA), which is catalyzed by the enzyme benzoic-acid-2-hydroxylase (BA2H). Hydrogen peroxide (H_2O_2) must be present for BA2H to convert benzoic acid (BA) into salicylic acid [9- 11].The initial evidence for the first pathway came from Ellis and Amrchein, who noted that salicylic acid was produced when *Gaultheria procumbens* plants were fed 14C-cinnamic acid or 14C-benzoic acid [12].Nevertheless, new findings suggest that salicylic acid is more likely to originate directly from benzoyl glucose, a conjugated form of benzoic acid (BA) [11,13].

The second step, known as the isochorismate (IC) pathway, takes place within the chloroplast [14-16]. Isochorismate pyruvate lyase (IPL) and Isochorismate synthase (ICS) are the two enzymes that catalyze the conversion of chorismate in plants into isochorismate and ultimately salicylic acid.It is well recognized from a physiological perspective that salicylic acid is essential for controlling plant development and growth, defense against different abiotic and biotic stress, and immunological responses [4,17- 21]. From that point on, there was an exponential rise in the number of articles focusing on salicylic acid as a plant growth regulator, signaling molecule, and plant elicitor that protects plants from different abiotic and biotic stress [20- 27].

By concentrating on these elements, the current study offers a thorough compilation of information on the roles that salicylic acid plays in plant growth and development (fig 1). The objective is to create a clear picture of salicylic acid and help guide future research on this subject.

2. BOOSTING POWER OF SA ON GROWTH AND DEVELOPMENT OF PLANT

Salicylic acid might play disputed functions in the growth and development of plants,depending on its concentration, the growing environment of the plant, and its developmental stage[28]. High concentrations of salicylic acid often have a detrimental effect on the growth and development of plants (depending on the type of plant; nonetheless, >1 mM salicylic acid is considered a high concentration). However, using the right amounts of salicylic acid had positive benefits on it. Salicylic acid stimulated growth in various plant species under both normal and varied abiotic stress conditions[29].

Exogenous salicylic acid application diverselyimpacts plant growth, such as germination of seed, budding, blooming, fruit setting, and ripening. Salicylic acid-induced blooming in finger millet plants [30].Seed germination of maizeand barley was inhibited when infused with more than 3 mM of salicylic acid [31]. However, ingesting maize seeds in 0.3 mM to 0.9 mM salicylic acid resulted in increased shoot length, germination rate, and germination percentage[32]. The strongest germination-stimulating impact was notably shown by 0.43 mM salicylic acid; however, at higher doses, its effectwas diminished. So, various salicylic acid concentrations in various plants may either promote or inhibit plant growth.

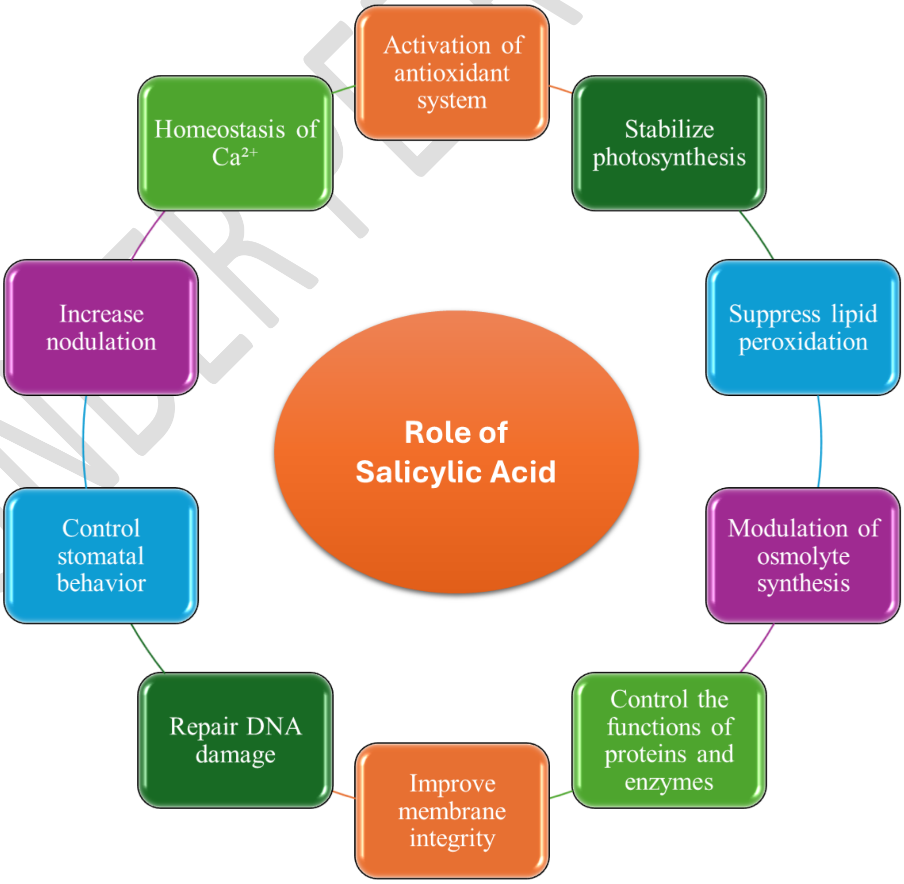

Fig. 1. Role of Salicylic acid on growth and development of field crops

3. BOOSTING POWER OF SA ON BIOTIC STRESS TOLERANCE

Salicylic acid is a plant hormone associated with defense that is essential for resistance against several microbial diseases, including fungi, bacteria, viruses, and oomycetes[33]. It is widely known that endogenous salicylic acid levels in plants are positively correlated with resistance mechanisms to both biotrophic and hemibiotrophic diseases [34]. Furthermore, the application of exogenous salicylic acid results in the induction of both local and systemic acquired resistance in a variety of plant species against a range of pathogens, such as*Alternaria alternata*, *Fusarium oxysporum*, *Colletotrichum gloeosporides*,*Magnaporthe grisea*,*Xanthomonas* spp., various viruses, and so forth [35- 37](Table 1). Notably, the growth of the powdery mildew disease in cucumber plants was almost entirely inhibited by the exogenous application of salicylic acid. Due to its intricacy, salicylic acid's functions in plant defense against necrotrophic diseases are yet unclear. There have been a few reports of exogenous salicylic acid treatment-induced higher sensitivity among various plant-necrotrophic pathogen interactions. Salicylic acid treatment in broad beans reduced red light-induced resistance to the necrotrophic fungus *Botrytis cinerea*, but it did not increase black light-induced vulnerability[38]. Application of tomato SA-induced increased susceptibility in a dose-dependent manner against *B. cinerea*.It is also controversially suggested that salicylic acid increases the resistance of Arabidopsis and tomato plants to *B. cinerea* [39,40].

Table 1.Enhancement of disease resistance mechanism by foliar spray of SA in different plants

Host	Pathogen	Salicylic acid concentration	Effect	Reference
Oryza sativa (Rice)	*Xanthomonas oryzae*	1 mM	Reduction of leaf blight lesion	[41]
		1 mM	Reduction of severity of disease (30%)	[42]
	Magnaporthe grisea	8 mM	Reduction of severity of disease (70%)	[43]
	Oebalus pugnax	16 mM	Reduce the number of bugs (35%)	[44]
Cicer arietinum (Chickpea)	*Fusarium oxysporum*	14.5 mM (stem)	Reduction of severity of disease (20%)	[45]
		0.58 mM (soil)	Reduction of severity of disease (20 %)	
Vigna mungo (Black gram)	*Mungbean yellow mosaicIndian virus (MYMIV)*	0.1 mM	Reduction of severity of disease (71%)	[36]

4. BOOSTING POWER OF SA ON ABIOTIC STRESS TOLERANCE

Plant productivity is threatened by climate change and continuous cropping due to several abiotic stressors, including salt, ozone, UV light, temperature, drought, and heavy metals [46]. It's interesting to note that salicylic acid regulates tolerance to a variety of abiotic stimuli in addition to resistance to biotic challenges[47] (Table 2). The following are the mechanisms of salicylic acid-induced abiotic stress tolerance: (1) osmolytes accumulation, which may support the maintenance of osmotic homeostasis; (2) regulation of the absorption of minerals; (3) increased activity of scavenging reactive oxygen species; (4) increased production of secondary metabolites, comprising nitrogen (alkaloids, non-protein amino acids, and cyanogenic glucosides,) and sulphur-containing compounds (allinin, glutathione, thionins, phytoalexins, defensins, and glucosinolates) and (5) control of additional hormone pathways [47,48].

A group of pathogenesis-related (*PR*) genes, including *PR1*, *PR2*, and *PR5*, are expressed when exogenous salicylic acid treatment is applied[49]. Transgenic overexpression of several *PR* genes improved tolerance to various abiotic stressors as well as resistance to various infections [50- 52]. Increased resistance to heavy metals was shown by transgenic tobacco that overexpressed pepper *PR-1*[51]. In *Arabidopsis* plants, overexpression of pepper *PR-1* increased resistance to salt and drought stress [50]. Further research is necessary to understand the underlying molecular processes by which these PR proteins improve resistance to abiotic stress.

Table 2.Improvement of abiotic stress resistance by exogenous application of SAin different plants

Host	Abiotic stress	Salicylic acid concentration	Effect	Reference
Triticum aestivum (Wheat)	Freezing	0.01, 0.1, and 1 mM	Cell mortality and the loss of PS II quantum yield brought on by freezing stress were dramatically reduced by 0.01 and 0.1 mM salicylic acid.	[53]
Zea mays (Maize)	Cadmium (Cd)	0.5 mM	Root DW and shoot FW are raised by around 121% and 262%, respectively.	[54]
Hordeum vulgare (Barley)	Cadmium (Cd)	0.5 mM	Root DW and shoot FW are raised by around 127% and 133%, respectively.	[55]
	Osmotic stress	30, 60, and 120 nM	Approximately 50% less osmotic stress-induced membrane damage occurred.	[56]

5. SALICYLIC ACID AND PLANT MICROBES

The plant science community has recently shown increased interest in studies examining the relationship between plant health and microbiome[57, 58].The impact of salicylic acid on the microbiome of the model plant Arabidopsis thaliana was examined using either exogenous salicylic acid application or mutants with changed endogenous salicylic acid levels [59]. The results showed that the application of salicylic acid significantly increased the amount of certain bacterial isolates from the Synthetic Community (SynCom) experiment and decreased the amount of *Mitsuaria* sp. 370 (β-Proteobacteria). Furthermore, in *cpr5* mutants that constitutively manufacture salicylic acid, the population density of twelve Proteobacteria and nine Actinobacteria groups was decreased and raised, respectively. This implies that salicylic acid may significantly change the microbiome of the soil orrhizosphere. The stimulation of the systemic immune response has been the primary focus of salicylic acid's effects on plants so far after soil drench application; however, not much is known regarding the compound's effects on endophytic microbiomes or plant roots.Therefore, further research on the impact of salicylic acid on a variety of soil or endophytic microbiomes will provide insight into howsalicylic acid affects many aspects of plant physiology, such as immunity, growth, development, and so on.

6. SALICYLIC ACID WITH OTHER PLANT GROWTH REGULATORS (PGRs)

Salicylic acid controls many plant responses through interactions with other plant growth regulators or plant hormones in both favourable and unfavourable environments. Under both ideal and stressful conditions, the relationship between salicylic acid and other hormones, including cytokinin, auxin, gibberellins, abscisic acid, brassinosteroids, and ethylenehas been investigated. In stressful situations, the interaction between salicylic acid and hormones may have an antagonistic or synergistic effect. Tamás et al. (2015) [60]recently examined how salicylic acid controlled the reduction of Cd-induced auxin-mediated ROS (reactive oxygen species) generation in barley roots, hence mitigating Cd stress. The authors hypothesize that salicylic acid plays a part in the IAA (indole-3-acetic acid)signaling system since salicylic acid treatment reduces the stress responses that IAA generates in plants. Agtuca et al. (2014)[61] documented thatsalicylic acid and IAA had opposing roles in maize roots. IAA applied exogenously promoted lateral development by inhibiting primary root growth, while salicylic acid increased the total biomass of roots [61].

Plants may experience oxidative stress and increased ethylene production when exposed to several environmental conditions, such as heavy metals (HM) [47]. Peaked expression of ethylene-related biosynthetic genes or expression of ethylene-responsive genes is the cause of the enhanced ethylene synthesis.The exogenousspray of salicylic acid helped wheat under Cd stressby raising GSH levels, which led to metal detoxification and scavenged ROS (reactive oxygen species) produced by HM (heavy metal)-triggered ethylene synthesis. Under Cd stress, salicylic acid supplementation led to elevated ABA (Abscisic acid) levels in wheat seedlings, which were linked to the biosynthesis of ABA [62]. Additionally, during HM stress, endogenous ABA regulated SA-mediated changes in the concentration of dehydrin proteins, indicating the protective function of salicylic acid in wheat plants [62].

Crosstalk between salicylic acid and jasmonates is essential for controlling plant development in the presence of abiotic stressors [63]. The signaling pathways for jasmonic acid and salicylic acid often function antagonistically. The antagonistic action between salicylic acid and jasmonic acid cell signaling is mediated by the Mitogen-Activated Protein Kinase (MAPK) signaling pathway [64]. Nonantagonistic interactions between salicylic acid and jasmonic acid have also been recorded, although further research is necessary to determine the precise mechanism [63]. Cu stresscaused the production of salicylic acid in maize plants, which in turn caused jasmonic acid priming and jasmonic acid-induced volatile organic molecules.

7. CONCLUSION

Salicylic acid and its derivatives show promise as eco-friendly plant protectors due to their positive impacts on plant and human health. Determining the optimal concentrations, from micromolar to low millimolar levels, is crucial to provide disease resistance without hindering plant growth. Higher 2 mM concentrations may serve as effective growth regulators to slow development for disease control. Exploring natural salicylic acid derivatives, like amorfrutins, with improved efficiency could lead to better plant protection techniques. Further research is needed to understand the practical implementation of salicylic acid across crop species and develop sustainable, cost-effective crop management systems utilizing these versatile compounds.

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