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Some environmental aspects of salicylic acid

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Abstract. Salicylic acid is an environmentally safe growth regulator with multifunctional properties, which has great prospects in agricultural practice, as it was effective at low concentrations and has natural catabolic pathways. The aim of the study is to determine the participation of salicylic acid in the interactions of plant organisms with other biotic components of ecosystems and to reveal the prospects for its use in crop production and for the development of environmentally safe agricultural technologies. To achieve this goal, scientific sources were searched, analysed, systematised and compared using leading scientific databases and methods of logical generalisation. It was established that plants, leading a sessile lifestyle, are constantly exposed to biotic stresses, primarily phytopathogens and herbivorous organisms. In response, they have formed a defence system that includes passive barriers and active immune responses at the cellular and molecular levels. At the centre of these processes are phytohormones, among which salicylic acid is of key importance. It has been found that salicylic acid is one of the main signalling molecules that coordinates the expression of genes associated with plant defence, induces the synthesis of secondary metabolites, contributes to the strengthening of cell walls and activates the mechanisms of systemic acquired resistance. Particular attention was paid to the interaction of salicylic acid with other phytohormones, in particular jasmonic acid, ethylene, abscisic acid and auxin, which together form a complex signalling network that provides an integrated and effective immune response. A separate section was devoted to the participation of salicylic acid in symbiotic interactions between plants and beneficial microorganisms, such as mycorrhizal fungi and rhizobia, which enhance the host's resistance to pathogens. The practical aspect of using salicylic acid in agriculture as an environmentally safe means of enhancing the immunity of cultivated plants through exogenous application or stimulation of endogenous synthesis was also considered. The conclusions

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drawn are important both for understanding the fundamental principles of plant immunity and for the practical application of biotechnology in protecting plants from pests and diseases

Keywords: growth regulators; biotic stress factors; abiotic stress factors; phytopathogens; phytohormones

INTRODUCTION

The increased impact of stress factors on plant organisms caused by global climate change and growing anthropogenic pressure necessitates the search for new growth regulators with stress-protective properties that are safe for the environment. One such compound is salicylic acid (SA), a phenolic phytohormone involved in various morpho-physiological reactions in plants, including responses to stress.

As noted by Z. Iqbal *et al*. (2021) and P. Kumar *et al*. (2025), plants, as a sedentary component of the biosphere, are constantly exposed to numerous biotic stress factors, the most common of which are phytopathogens and herbivorous organisms. In response to these threats, plants have developed a complex system of defence mechanisms, including both passive barriers and active immune responses. S. Mishra *et al*. (2024) found that phytohormones, in particular SA, which is a central signalling molecule in the formation of the immune response of plants to biotic stressors, play an important role in regulating these processes. According to Q. Han *et al*. (2022), these processes are based on the coordination of SA transcriptional activity of genes associated with pathogenesis, activation of secondary metabolite production, and promotion of systemic acquired resistance (SAR). C. Kaya *et al*. (2023) concluded that SA participates in complex hormonal interactions with other regulators, such as jasmonic acid (JA), ethylene (ET), auxin, and abscisic acid (ABA), which ensures the integration of signaling pathways within the overall defense strategy.

According to O. Tsvilynyuk & L. Telehii (2020), the use of phytohormones was a promising technology for intensifying and greening agricultural production. SA was of particular interest in this context because it activates anti-stress activity in plants in response to various adverse environmental factors. Yu.E. Kolupaev *et al*. (2021) summarised that the activation of SA biosynthesis pathways and its accumulation are observed in plants under the influence of various stress factors, such as extreme temperatures, dehydration, salinisation and the influence of heavy metals. The main protective responses induced by SA include increased gene expression and antioxidant enzyme activity, increased content of low-molecular-weight antioxidants, and accumulation of multifunctional protective compounds, including proline and sugars. Under the influence of SA, the synthesis of a number of heat shock proteins, dehydrins and alternative oxidase is activated. At the plant organism level, an important response is the induction of SA closure of stomata. Despite the rich phenomenological material on the action of SA, its functional interaction with other signalling mediators and stress phytohormones in the formation of adaptive responses in plants remains understudied.

Research into the functional role of SA in plant immunity not only deepens understanding of plant molecular biology, but also has significant applied potential for the development of bio-oriented crop protection products in agriculture, since the use of natural growth regulators to increase plant resistance to stressors will reduce the use of pesticides. According to Y.M. Koo *et al*. (2020), another compelling argument in favour of studying SA and its application in plant growing is the low cost of SA production.

At the same time, as noted by Y. Kavulych *et al*. (2023), there were certain difficulties in developing preparations based on SA and its application. First of all, this concerns the selection of growth regulator concentrations, since even for representatives of the same family, the range of optimal concentrations can vary widely. It is also sometimes difficult to predict the result of SA application, as it depends on a number of factors, including the phase of plant ontogenesis and their varietal characteristics, the stage of application of the preparation, weather conditions and the influence of other external factors. As evidenced by a number of review publications on this issue, the use of SA in field experiments remains insufficiently studied (Saleem *et al*., 2021; Sambyal & Singh, 2021).

In view of this, the aim of the study was to systematise current scientific data on the role of SA in protecting plants from biotic stressors, as well as to assess the possibilities of its use in crop production to increase the resilience of agricultural crops. During the writing of the article, a set of general scientific and special research methods characteristic of review works in the field of biology was used. The main method was the analysis of scientific literature from open international databases (PubMed, Scopus, Web of Science, Google Scholar), which made it possible to cover relevant publications (Gong *et al*., 2023; Fang *et al*., 2025) devoted to the role of SA in plant immunity to biotic stresses. The data were systematised and classified according to the main areas: the participation of SA in the formation of the immune response, interaction with other phytohormones, the role in systemic acquired resistance, and participation in symbiotic relationships. A comparative analysis method was also used, which allowed comparing different signalling pathways involving SA in plants of different species. In addition, the work used a method of logical generalisation, on the basis of which conclusions were formulated regarding the importance of SA in the formation of resistance to pathogens and the possibilities of its application in agricultural technologies.

SALICYLIC ACID AS A MEDIATOR OF PLANT DEFENCE RESPONSES TO BIOTIC STRESSES

Stress factors of a biotic nature are often the cause of plant diseases and reduced crop yields. Phytohormones are important elements in stimulating complex defence mechanisms against these harmful influences and are involved in the processes of perception, adaptation and the formation of plant resistance. According to P. Ding & Y. Ding (2020), salicylic acid (SA) occupies a special place among them. The participation of SA as an intermediary in the formation of defence mechanisms against biotic stressors has been studied in detail. In particular, M. Naz *et al*. (2024) showed that treatment with (D, L)-3-aminobutyric acid, which is an inducer of SA signal transduction, increases the resistance of pepper plants to late blight and other fungal pathogens. Y. Hu *et al*. (2024) also established the positive effect of an enzyme that forms SA derivatives on the resistance of tea plants to fungal infection. As summarised by L. Bauters *et al*. (2021), in many agricultural crops (spinach, soybeans, tomatoes, etc.), as well as *Arabidopsis*, SA is involved in plant responses to biotic stressors. In a recent review article based on an analysis of a large number of scientific publications, S. Mishra *et al*. (2024) concluded that SA is a key signalling molecule in the formation of the immune response of plants to various biotic stressors and can increase plant resistance to a wide range of pathogens, including viruses, bacterial and fungal infections.

A. Ali *et al*. (2024) found that in realising their protective potential, SA molecules can function either independently and/or in interaction with other phytohormones, such as jasmonic acid (JA) and ethylene (ET), which are also involved in the fight against necrotrophs. According to S. Hou & K. Tsuda (2022), JA and ET can synergistically or antagonistically interact with SA, altering the levels of each hormone or modulating their signalling pathways. In addition to JA and ET, other phytohormones, commonly referred to as “stress hormones,” are also involved in the formation of pathogen resistance and can interact with SA. For example, abscisic acid (ABA) causes stomata closure, stimulates callus formation and secondary metabolite synthesis, which limits the penetration of bacteria and insects (Torii, 2022; Wei *et al*., 2025).

Auxin, although associated with cell division and growth processes, also regulates plant interactions with phytopathogens. Increased SA levels can alter auxin accumulation and the expression of related genes, enhancing plant defence responses (Kunkel & Johnson, 2021). Brassinosteroids (BR) also increase plant protection against a number of pathogens, including *Fusarium culmorum*, tobacco mosaic virus, and *Magnaporthe grisea*. Y. An *et al*. (2024) showed in their studies that the combination of BR with pyraclostrobin significantly enhanced the resistance of *Arabidopsis* to *Botrytis cinerea* and *Hyaloperonospora arabidopsidis*. BRs can also increase endogenous SA levels by activating SA-dependent immune responses (Park *et al*., 2023). Describing the interaction of SA with other small molecules with phytohormonal activity, Y. Arif *et al*. (2020) identify several possible mechanisms: regulation of SA biosynthesis of other phytohormones, regulation of SA hormonal signal transduction pathways, regulation of SA expression of hormone-sensitive genes, and competition between SA and other phytohormones that interact with it.

Together, these studies confirm that salicylic acid is a key phytohormone in plant defence responses to biotic stresses, including pathogens and herbivores. It activates immune mechanisms and can interact with other phytohormones – jasmonic acid, ethylene, abscisic acid, auxin and brassinosteroids. These interactions can be synergistic or antagonistic, including the regulation of signalling pathways and the expression of resistance genes. Thus, SA functions as a central mediator in a complex hormonal network that ensures the adaptation of plants to biotic threats.

THE ROLE OF SALICYLIC ACID IN THE FORMATION OF SYSTEMIC ACQUIRED RESISTANCE IN PLANTS

Plant immunity is a complex multi-level system that includes several stages of protection. According to F. Zhu *et al*. (2024), for a phytopathogen to access the endogenous contents of the host cell and complete its life cycle, it must first overcome passive defence mechanisms, which include structural barriers such as the cuticle, cell wall and antimicrobial compounds produced by plant cells. Cell membranes also play an important role in preventing pathogen penetration, the composition and ratio of whose components vary depending on environmental conditions (Kobyletska, 2020).

F. Zhu *et al*. (2024) distinguish between passive and active defence mechanisms possessed by plants, including elements of the immune system that are activated in response to phytopathogen penetration. These processes include specific and non-specific reactions of the plant immune system. J.D.G. Jones *et al*. (2024) include basal barriers (the presence of a cuticle, cell wall and waxy coating), as well as receptor-mediated pathogen recognition, the activation of which triggers signalling cascades: the release of active forms of oxygen, increased synthesis of phytoalexins and expression of PR proteins. The authors attribute the expression of R-genes (resistance genes) to the specific reactions of the plant immune system. whose products are usually receptors capable of recognising specific phytopathogen effectors and activating a powerful protective response, often associated with a hypersensitivity reaction – programmed cell death in the area of pathogen penetration. This process stops and limits the further spread of the pathogen. Specific responses are significantly more powerful components of immunity and are more persistent than non-specific ones. In the process of infection of the host plant X by a phytopathogen. X. Fang *et al*. (2025) identify several sequential processes, in particular, the primary stage is the identification of the pathogen by plant cell recognition receptors and the induction of pattern-triggered immunity (PTI) to initiate the first defensive responses. Most phytopathogens release effectors to inhibit PTI, which further stimulates a series of signalling cascades, such as biosynthesis and signalling of SA, formation of systemic acquired resistance (SAR) and activation of the synthesis of secondary compounds with high biological activity (Bauters *et al*., 2021).

A study by N. Rakhmatova *et al*. (2023) showed that the concentration of salicylic acid in biotechnological cotton genotypes changes under the influence of abiotic stresses (salinisation, drought, temperature fluctuations). Such fluctuations indicate that salicylic acid plays an important role in triggering protective mechanisms, contributing to the formation of systemic acquired resistance of plants to adverse environmental conditions. Q. Guo *et al*. (2023) note that any sufficiently strong biotic or abiotic stress activates the same defence mechanisms in plants, resulting in a non-specific short-term increase in plant resistance to repeated exposure to the stressor. A wide range of such resistance is called SAR, which provides stable resistance of plant organisms to non-specific pathogens. A typical form of SAR can be activated by virulent, avirulent and non-pathogenic microorganisms, or artificially using compounds that are components of intermediate reactions of the immune response. Such metabolites include SA, its derivative methyl salicylate, 2,6-dichlorisonicotinic acid, systemin, etc.

R. Zavaliev & X. Dong (2024) note that the duration of SAR formation is species-specific and sometimes variety-specific, and also depends on the type of elicitor. During this period, SA and proteins that provide plant resistance to pathogens (PR, pathogenesis-related proteins) accumulate. These processes are based on the expression of corresponding PR genes, which belong to at least nine classes. In addition, the authors found that treatment of plants with SA also activates the synthesis of PR proteins. An increase in intracellular SA levels induces the accumulation of active forms of oxygen and changes in the redox potential of the cell, possibly through the influence on the expression of genes associated with the antioxidant system (Fig. 1).

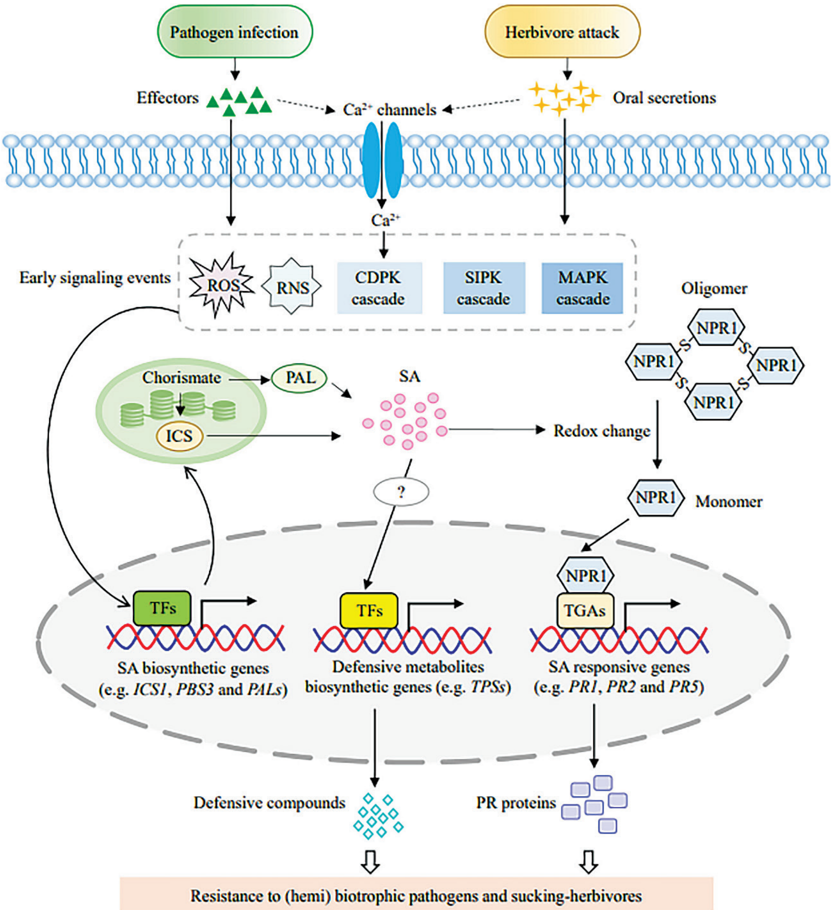

Figure 1. SA-mediated defence mechanisms against phytopathogens and herbivorous organisms
Note: ROS – reactive oxygen species; RNS – reactive nitrogen species; CDPK – calcium-dependent protein kinase; SIPK – SA-induced protein kinase; MAPK – mitogen-activated protein kinase; TF – transcription factors; PR – proteins related to pathogenesis
Source: X. Fang *et al*. (2025)

According to the diagram (Fig. 1), the primary signals involved in plant contact with pest effectors are the activation of early signalling processes, in particular the release of reactive oxygen species (ROS) and reactive nitrogen species (RNS), an increase in intracellular Ca^{2+} levels, and the activation of several protein kinase cascades (CDPK, SIPK, MAPK). These early responses trigger transcription factors that stimulate the expression of genes responsible for SA biosynthesis. As a result, SA accumulates in the cell. The increase in SA levels disrupts redox homeostasis, leading to the transition of the NPR1 protein from an oligomeric to a monomeric form. Monomeric NPR1 moves to the nucleus and interacts with the TGA factor, promoting the activation of SA-sensitive genes (PR1, PR2, PR5). SA also initiates the production of secondary metabolites with bactericidal activity, probably through the activation of certain transcription factors (TF) that directly bind to the promoters of the genes of these metabolites. The detailed mechanisms of this process still need to be clarified. These protective metabolites and PR proteins contribute to improving plant resistance to biotrophic pathogens and herbivorous animals.

However, the participation of SA in plant defence reactions is not limited to this. T. Van Butselaar & G. Van den Ackerveken (2020) note that the regulation of SA-sensitive gene transcription processes and PR protein synthesis, immune responses triggered by SA also contribute to increasing plant resistance to pathogens by stimulating the biosynthesis of callose and lignin, which strengthen cell walls, and activating the synthesis of secondary metabolites with bactericidal action. At the same time, SA plays a significant role in increasing plant resistance to both phytopathogens and herbivorous animals. The works of scientists B. Ali (2021) and Y.B. Setotaw *et al.* (2024) reveal the positive effect of SA on the regulation of secondary metabolite accumulation in plants during feeding by herbivorous insects. However, the exact mechanism of SA involvement in the biosynthesis of these compounds is still poorly understood. In-depth study of this SA-mediated process will contribute to the development of biopesticides and reduce the use of synthetic compounds.

Q. Gong *et al*. (2023) also found that SA is important for the aerial defence of plants. Methyl salicylate, a volatile form of SA, acts as a mobile signal to activate SAR over long distances and triggers protective responses in neighbouring plants when they are attacked by pests or phytopathogens. Studies of the process and nature of signal transmission between aphid-infested and uninfested plants have shown that the concentration of methyl salicylate is significantly higher in plants attacked by aphids. In neighbouring plants, this compound is converted back to SA and activates protective responses against pests and viruses carried by these insects.

Thus, SA plays a key role in the formation of the plant's SAR to biotic factors, acting as a signalling molecule that coordinates a wide range of protective responses. The plant's response to infection or damage by herbivorous insects begins with the activation of early signalling events, including the formation of ROS/RNS, increased Ca^{2+} levels and the activation of protein kinases. These signals trigger transcriptional programmes that stimulate SA biosynthesis. The accumulation of SA in cells initiates the transition of NPR1 to a monomeric form, allowing it to activate the expression of PR genes responsible for the production of defence proteins. In addition, SA promotes the accumulation of secondary metabolites with bactericidal activity and the synthesis of callose and lignin, which strengthen cell walls. The volatile form of SA, methyl salicylate, serves as a mobile signal for the activation of SAR in distant parts of the plant and in neighbouring organisms. Thus, SA functions not only as a local but also as a systemic regulator of resistance, providing effective protection against a wide range of pathogens and phytophages.

THE ROLE OF SALICYLIC ACID IN THE INTERACTIONS OF PLANT ORGANISMS WITH MICROORGANISMS AND PESTS

Plants form mutually beneficial, mutualistic symbioses with various microorganisms, including endophytes, arbuscular mycorrhizal fungi (AMF) and nitrogen-fixing rhizobia, which are actively studied in the field of symbiont biology. These microorganisms improve mineral nutrition and plant growth, receiving in return carbohydrates and other metabolites produced as a result of the host's photosynthetic activity. In addition to this effect, they also increase plant resistance to a wide range of abiotic and biotic stresses. Studies show that symbiotic microorganisms can modulate phytohormone metabolism in the host plant. Salicylic acid (SA) is of irreplaceable importance in this context as a key regulator of defence mechanisms. It has been established that this compound plays an important role not only in responses to pathogen damage, but also in establishing symbiotic relationships between plants and microorganisms (Benjamin *et al*., 2022). Thus, symbiotic microorganisms not only optimise plant growth and development, but also activate the host's defence systems through phytohormonal signals, among which SA plays a special role.

Exogenous application of SA or induction of its synthesis affects plants, phytopathogens, herbivorous animals, and natural enemies at several trophic levels. S.C. Filgueiras *et al*. (2019) identify three main areas of use of SA in agriculture to combat pests and pathogens: (1) exogenous application of compounds that induce SA synthesis for direct plant protection; (2) genetic modification of plants to alter the expression of defence genes; (3) exogenous application of volatile compounds associated with SAs (e.g., methyl salicylate) to attract natural antagonists that limit the spread of insect pests.

According to D. Tripathi *et al*. (2019), the use of exogenous application of compounds that induce SA formation to stimulate plant defence metabolic pathways, induce resistance and enhance SA signalling has opened the way to consider new management strategies to combat agricultural pests and pathogens. Exogenous application can take many forms, including a wide range of elicitors and synthetic analogues of SA, which can lead to increased plant resistance to pathogen load. The effect of exogenous elicitors may also be enhanced over time from generation to generation, as epigenetic effects of exogenous elicitors have been identified, thus potentially leading to the inheritance of defence mechanisms with fewer applications.

According to C.C. Filgueiras *et al*. (2016), genetic modification of plants to alter the expression of defence genes should be aimed at creating organisms in which immune responses are not activated in the absence of pathogen exposure, as they require significant energy resources. At the same time, under conditions of infection, these plants would be capable of powerful defence responses. Overexpression and constitutive expression of specific genes involved in plant defence responses can create enhanced and broad-spectrum resistance to pathogens. Although these approaches may be effective in situations of intense pathogen pressure, they also have certain drawbacks, in particular the constant allocation of plant resources to defence through genetically modified constitutive expression is likely to have negative consequences for yield. J. Ali *et al*. (2023) believe that the exogenous application of volatile compounds such as methyl salicylate, associated with SA, has great potential because it has a repellent effect on pests and pathogens, in particular reducing pest productivity by altering their behaviour, egg laying and colonisation of new plants. However, deciphering the mechanisms of action of these compounds on phytophages requires further study, taking into account their variety- and species-specific characteristics.

Thus, SA is an indispensable component in the regulation of both symbiotic interactions between plants and beneficial microorganisms and protective responses to phytopathogens and phytophages. It participates in signalling processes that ensure both increased resistance to biotic stressors and the formation of favourable relationships with symbionts. Exogenous application of SA and its volatile derivatives, in particular methyl salicylate, is a promising approach to increasing plant resistance and attracting natural enemies of pests. The rational use of SA or its inducers, including the selective activation of PR genes, can be an effective alternative to chemical plant protection in modern agricultural production.

AGROTECHNICAL FEATURES OF SALICYLIC ACID APPLICATION

As a natural phytohormone that influences a number of physiological processes in plants, SA has great potential in crop production for improving plant growth, yield and resistance to various types of stress. The ability of SA to regulate seed germination, stomatal movement and enzyme activity makes it an important tool in agricultural practice (Souri & Tohidloo, 2019). According to Y. Castro-Torres *et al*. (2015), the use of SA and its derivatives reduces the risk of developing numerous chronic diseases in humans, including heart attack, stroke, arthritis, diabetes, some types of cancer, and Alzheimer's disease. Given the positive impact of SA on both the physiological state of plants and human health, SA and salicylates can be used as an effective means of plant protection with very little side effects on the environment and humans. The use of SA as a multifunctional plant growth regulator and environmentally safe plant protection agent raises several issues. First of all, it is important to determine the effective concentrations of SA for specific plant species and/or purposes. In particular, a high dose of SA (>2 mM) increases disease resistance on the one hand, but on the other hand has a negative effect on plant growth and productivity, which is caused by an undesirable balance between the cost and benefit of the limited energy that the plant can use (Koo *et al*., 2020). In humans, a concentration of SA above 2.5 mM in blood plasma leads to acute intoxication (Choi *et al*., 2019). However, the use of high concentrations of SA (~2 mM) as a plant growth regulator may be appropriate, especially if producers need to reduce the growth rate of certain plant species with a protective effect against phytopathogens (Koo *et al*., 2020). Secondly, the method of application of SA, of which there are several, is important. In particular, M. Alotaibi *et al*. (2023) studied the effect of irrigation (spraying) with SA solution and found a positive effect of such treatment on growth parameters and the content of photosynthetic pigments in plants. A. Alam *et al.* (2022) studied the effect of soaking seeds in a SA solution before sowing on plant growth, development and productivity and consider this method to be the most effective and cost-effective, especially in drought conditions. C.M. Vinay *et al*. (2025) added SA to hydroponic solutions and found that under such conditions, a greater amount of secondary metabolites accumulates in plants, which is an advantage over soil cultivation. However, it is clear that from a practical point of view, not all of the methods described can be used equally successfully in field conditions, especially for cereal crops grown on large areas. The addition of salicylates to hydroponic crops is only suitable for use in greenhouses (Alotaibi *et al*., 2023).

A number of authors, including S. Pedrini *et al*. (2021), A. Alam *et al*. (2022), and M.R. Karimi *et al*. (2025), note that soaking seeds before sowing is a promising way to increase the resistance and yield of agricultural crops. Compared to other methods, this method has several advantages. It requires less active solution than spraying, is relatively inexpensive, and the dose applied can be better controlled than in the case of surface treatment of plants. In particular, this method was used by the authors in a series of studies on the effectiveness of SA application (Berková *et al*., 2023). Researchers M.K. Souri & G. Tohidloo (2019) also found that the reduction in tomato seedling growth caused by salinisation with 100 mM NaCl was offset by the application of SA, as it induced a decrease in Na concentration in the leaves under stress conditions. It was concluded that the most effective method of applying SA under salinity conditions was preliminary foliar treatment with SA, followed by preliminary root treatment. Foliar spraying with SA showed the lowest efficacy in this study. It was also found that foliar spraying with SA was very effective in mitigating the negative effects of water stress on wheat plants (Parveen *et al*., 2021).

Thirdly, the timing of treatment with SA or its derivatives is important. Furthermore, field studies conducted by K. Matysiak *et al*. (2020) showed that it was not the concentration but the timing of acetylsalicylic acid application that was more important for wheat growth. Although no significant difference was found between the effects of earlier and later application on plant height and chlorophyll content, most of the structural and qualitative parameters of the yield, in particular the number of seeds in the ear, grain density, its hardness, protein, gluten and starch content, were better after the application of acetylsalicylate at later stages of plant ontogenesis, in particular during the flag leaf formation phase compared to the tillering phase. An equally important aspect of SA application is the physiological state of plants. The use of SA and its derivatives for weakened plants that are already functioning under stressful conditions may prove to be an additional stressor. Another problem is the fact that due to the genotypic differences of plants, which determine their specific phytohormonal background, the concentration (dose) and optimal time of application may depend on the individual characteristics of a particular species and variety (Li *et al*., 2022).

Therefore, research on SA and its derivatives should be expanded, in particular, field studies should be used, which, unlike studies in controlled laboratory conditions, involve interaction with other environmental factors. Further work on the practical use of SA for various agricultural plants will contribute to the development of a cost-effective and environmentally friendly system for managing growth, development and yield in changing environmental conditions.

CONCLUSIONS

Based on the analysis of literary sources, the following conclusions can be drawn. Salicylic acid (SA) is one of the key signalling molecules that plays a central role in regulating plant defence responses against biotic stress factors, including phytopathogens and herbivorous organisms. The protective action of salicylic acid is realised both through the activation of resistance gene expression and PR protein synthesis, and through the stimulation of the biosynthesis of secondary metabolites that have antimicrobial and repellent effects. A particularly important property of SA is its ability to induce SAR, a complex form of long-term protection that provides non-specific resistance of plants to re-infection by a wide range of pathogens. This function allows the plant to mobilise protective resources even in uninfected tissues, increasing the overall effectiveness of the immune response. A close interaction of SA other phytohormones – jasmonic acid (JA), ethylene (ET), abscisic acid (ABA), auxin, and brassinosteroids (BR) – has been established, which form a complex and highly coordinated signalling network that ensures the coordinated work of numerous physiological and biochemical processes during the formation of an integrated immune response. In addition to its direct protective function, SA is involved in symbiotic interactions between plants and beneficial microorganisms (mycorrhizal fungi, rhizobia), which further increases plant resistance to pathogens and improves their nutrition. Such mutually beneficial relationships not only enhance plant resistance to stress, but also improve nutrient uptake, which overall contributes to increased yields. The practical use of SA through exogenous application or stimulation of its endogenous synthesis is a promising and environmentally safe tool for boosting the immunity of cultivated plants and reducing dependence on chemical pesticides, which is relevant in the context of sustainable agriculture, environmental protection and food security.

Further research into the mechanisms of action of SA is important for the development of bio-oriented agricultural technologies and the improvement of integrated plant protection methods in the context of sustainable agriculture. Therefore, SA can be considered one of the most promising objects for research and practical application in modern agrobiotechnology, the use of which will increase plant resistance to stress factors of various nature and reduce the use of herbicides.

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Деякі екологічні аспекти впливу саліцилової кислоти

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Анотація. Саліцилова кислота є екологічно безпечним регулятором росту з поліфункціональними властивостями, яка має великі перспективи у практиці ведення сільського господарства, оскільки використовується у низьких концентраціях і має природні шляхи катаболізму. Метою роботи було з'ясувати участь саліцилової кислоти у взаємодіях рослинних організмів з іншими біотичними компонентами екосистем та розкрити перспективи її використання у рослинництві та для розробки екологічно безпечних агротехнологій. Для досягнення мети було проведено пошук, аналіз, систематизацію та порівняння наукових джерел із використанням провідних наукових баз даних та методів логічного узагальнення. Встановлено, що рослини, ведучи прикріплений спосіб життя, постійно зазнають впливу біотичних стресів, насамперед фітопатогенів і травоїдних організмів. У відповідь вони сформували систему захисту, що включає пасивні бар'єри та активні імунні реакції на клітинному й молекулярному рівнях. У центрі цих процесів знаходяться фітогормони, серед яких саліцилова кислота має ключове значення. Було з'ясовано, що саліцилова кислота є однією з основних сигнальних молекул, що координує експресію генів, пов'язаних із захистом рослин, індукує синтез вторинних метаболітів, сприяє зміцненню клітинних стінок та активує механізми системної набутої стійкості. Особлива увага приділена взаємодії саліцилової кислоти з іншими фітогормонами, зокрема жасмоновою кислотою, етиленом, абсцизовою кислотою та ауксином, що разом утворюють складну сигнальну мережу, яка забезпечує інтегровану і ефективну імунну відповідь. Окремий розділ присвячено участі саліцилової кислоти у симбіотичних взаємодіях рослин з корисними мікроорганізмами, такими як мікоризні гриби та ризобії, що посилюють стійкість господаря до патогенів. Було також розглянуто практичний аспект використання саліцилової кислоти у сільському господарстві як екологічно безпечного засобу підвищення імунітету культурних рослин шляхом екзогенного застосування чи стимуляції ендогенного синтезу. Отримані узагальнення є важливими як для розуміння фундаментальних основ імунітету рослин, так і для практичного впровадження біотехнологій у захисті рослин від шкідників і хвороб

Ключові слова: регулятори росту; біотичні стресові чинники; абіотичні стресові чинники; фітопатогени; фітогормони