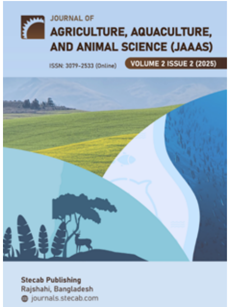

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Review Article

A Review of the Effects of Salicylic Acid Spray and Sulfur Fertilization on Strawberry Growth and Yield

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About Article

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ABSTRACT

Salicylic acid (SA) is a non-enzymatic phenolic compound that functions as an endogenous plant hormone. It plays a pivotal role in modulating plant responses under stress conditions by regulating metabolic activities, maintaining osmotic balance, promoting stomatal closure, and reducing transpiration and ethylene production. Additionally, SA enhances the activity of antioxidant systems, facilitates ion uptake, and increases the accumulation of insoluble sugars by inhibiting glucokinase activity. It also stimulates certain defense-related enzymes, strengthens plant resistance against fungal pathogens, and induces structural modifications in leaves and chloroplasts. These physiological changes collectively contribute to improved plant growth, higher yields, and better fruit quality. Sulfur (S), classified as a macronutrient, is essential for plant development due to its role in synthesizing sulfur-containing amino acids such as methionine, cysteine, and cystine, which together constitute approximately 90% of sulfur content in plant tissues. Sulfur is also required for the biosynthesis of coenzyme A, a critical component in the metabolism of amino acids, fatty acids, and intermediates of the citric acid cycle. Moreover, it is vital for chlorophyll formation and is a structural component of iron-sulfur (Fe-S) proteins within chloroplasts, including ferredoxin. In calcareous soils, where pH levels are typically ≥ 7.2, sulfur application effectively lowers soil pH, thereby enhancing the availability of micronutrients that are crucial for optimal plant growth and development.

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1. INTRODUCTION

The strawberry (Fragaria × ananassa Duch.) is a perennial herbaceous plant that is a member of the Rosaceae family's genus Fragaria (Soppelsa *et al.*, 2023). There are around 24 species of Fragaria known to exist worldwide, most of which are indigenous to China, which at the moment has the largest genetic reservoir of wild strawberry species (Yang *et al.*, 2020). In the middle of the 18th century, two American species—Fragaria virginiana from North America and Fragaria chiloensis from South America—naturally hybridized in European botanical gardens, giving rise to the contemporary cultivated strawberry. The hybrid species that is now commonly cultivated is the result of this hybridization. Strawberries' great degree of adaptability and extensive cultivation across a variety of climatic locations make them valuable both commercially and nutritionally (Soppelsa *et al.*, 2023). According to statistics released by the Food and Agriculture Organization (FAO) in 2022, there were around 397,603 hectares of strawberry cultivation worldwide, with 9,569,864 metric tons of output. With 3,354,803 tons, China was the world's top producer, followed by the US (1,261,890 tons) and Turkey (728,112 tons). Strawberry fruits are high in organic acids, vital vitamins, minerals, and natural sugars. Along with phenolic chemicals and antioxidants (Wang *et al.*, 2019), they also include digestive enzymes that make them easier to digest (Palei *et al.*, 2016). Numerous health advantages, such as anti-inflammatory, cardioprotective, antihypertensive, anti-obesity, and anticancer properties, are linked to these bioactive substances. Evidence also points to possible functions in promoting neurological health. Strawberries are one of the most often eaten little fruits in the world because of these qualities and their general appeal. Additionally, their adaptability facilitates a broad variety of commercial uses, especially in the manufacturing of baked products, ice cream, sweets, and preserves (Giampieri *et al.*, 2014). In plant systems, salicylic acid (SA) is becoming more widely acknowledged as an eco-friendly substitute for traditional chemical regulators. It is an endogenous phytohormone and a member of the class of non-enzymatic phenolic chemicals. SA has a molecular weight of 138.12 g/mol and the chemical formula $C_7H_6O_3$ (or $C_6H_4(OH)COOH$). It is produced in the plant mostly from the amino acid phenylalanine via metabolic processes including the chemical salicin and is part of a family of similar compounds known as salicylates. Salicylic acid belongs to the family of hydroxylated aromatic chemicals since it structurally consists of an aromatic ring that has been replaced with a hydroxyl group (Borsani *et al.*, 2001). Plant tissues contain salicylic acid in a variety of forms, such as free, methylated, glycosylated, glucose-esterified, or conjugated with amino acids. It performs a variety of physiological functions, particularly in the face of abiotic stressors as cold, drought, and salt (Sofy *et al.*, 2020). According to Naeem *et al.* (2020), SA helps to maintain osmotic equilibrium, control stomatal closure, improve ion absorption, increase antioxidant enzyme activities, and lower transpiration and ethylene generation rates. By modifying plant metabolic processes and stress response pathways, it also affects growth and developmental processes (Jiang & Asami, 2018). Salicylic acid effectively activates intricate signaling networks linked to plant responses to environmental stresses, even at low concentrations (Wani *et al.*, 2017). Additionally, SA facilitates important changes in the developmental dynamics of horticultural crops by controlling both internal and external stimuli (Kazan & Manners, 2012). By inhibiting glucokinase activity and increasing the activity of other defense-related enzymes, it also encourages the buildup of insoluble carbohydrates. This results in structural changes to the architecture of the leaves and chloroplasts, as well as enhanced resistance to fungal infections and other plant diseases (Yousif & Yousif, 2019).

2. LITERATURE REVIEW

2.1. Effect of foliar salicylic acid application on strawberry plant development

Salicylic acid (SA) foliar treatment has been shown in several studies to have a beneficial effect on strawberry plants' vegetative development. According to Yousif & Yousif (2019), the number of crowns, number of leaves, leaf area, and total chlorophyll content all significantly increased when SA was applied at doses of 0, 138.12, 276.24, and 552.48 mg L^{-1}. When compared to other treatments, including the control, the greatest benefits were seen at the concentration of 552.48 mg L^{-1}. In a similar vein, Haghshenas *et al.* (2020) discovered that, in comparison to untreated plants, foliar spraying with 207.18 mg L^{-1} of SA considerably enhanced leaf area and chlorophyll content. Compared to plants treated with 200 mg L^{-1} or left untreated, strawberry plants treated with 100 mg L^{-1} SA showed a significant increase in leaf number, leaf area, and total chlorophyll content, according to a different research by Al-Karawi *et al.* (2023). Moreover, Roozkhosh *et al.* (2024) showed that foliar application of SA at doses of 0, 138.12, and 207.18 mg L^{-1} significantly enhanced a variety of vegetative indices, such as total chlorophyll content, number of leaves, leaf area, and number of shoots. The reaction was at its best at 207.18 mg L^{-1}. Comparing treatments with 0, 276.24, and 828.72 mg L^{-1}, Ul Hasan *et al.* (2024) demonstrated that the application of SA at 552.48 mg L^{-1} substantially enhanced plant height, number of leaves, and leaf area per plant. In comparison to lesser concentrations and the control, Almutairi *et al.* (2024) observed that SA treatment at 500 mg L^{-1} produced better outcomes in terms of individual leaf area and total chlorophyll content. All things considered, the results of these investigations point to the critical function salicylic acid plays in promoting strawberry plants' vegetative development. SA's capacity to promote photosynthesis by boosting chlorophyll production and activating important photosynthetic enzymes may be the cause of this impact (Hayat *et al.*, 2014). Furthermore, SA helps to control the metabolism of carbohydrates by increasing the concentration of chlorophyll, which in turn improves the synthesis and storage of assimilates required for the growth of shoots and roots. Additionally, SA affects gas exchange and stomatal control, which optimizes the internal CO_2 concentration needed for effective photosynthesis (Rivas-San Vicente & Plasencia, 2011). Additionally, SA increases the production of antioxidant enzymes, which shield plants from abiotic stress, by promoting the synthesis of photosynthetic pigments (Khan *et al.*, 2003) and modifying gene expression (Janda *et al.*, 2020). Together, these physiological reactions enhance food intake, postpone senescence, and promote general vegetative vigor. According to Maruri-López *et al.* (2019), SA may also promote the growth of chloroplasts, which would help to further boost the accumulation of chlorophyll. Salicylic acid functions as a phytohormone that increases enzyme activity linked to photosynthesis and nutrient absorption, hence fostering plant growth and production (Al-Bayoumi *et al.*, 2000).

2.2. Impact of foliar salicylic acid application on strawberry plant flowering, fruit set, yield, and quantitative and qualitative features

Numerous studies have examined the effects of applying salicylic acid (SA) as a foliar spray on strawberry plants' reproductive and yield-related characteristics. The positive effects of SA on flowering dynamics, fruit development, yield amount, and fruit quality indices have been shown in several tests. In two growing seasons (2005–2007), Karlidag *et al.* (2009) discovered that foliar spraying strawberry plants with salicylic acid at concentrations of 0, 34.53, 69.06, and 138.12 mg L^{-1} resulted in a decrease in fruit acidity and a notable increase in total yield, early fruit set, total soluble solids (TSS) in fruits, and foliar nutrient content (N, P, K, Ca, and Mg). Comparing SA application at 276.24 mg L^{-1} to other treatments, Jamali *et al.* (2011) found that it substantially increased the number of flower buds, flowers per plant, fruits per plant, average fruit weight, total yield, and fruit nitrogen content. The highest dose tested (552.48 mg L^{-1}) resulted in a significant increase in fruit number per plant, average fruit weight, marketable yield, early harvest ratio, TSS, and leaf nutrient concentrations, as well as a decrease in acidity, as Youssef *et al.* (2017) showed. Using a range of SA concentrations (0–966.84 mg L^{-1}), these results held true across two growth seasons (2013–2015). Comparing a low-level SA treatment (13.81 mg L^{-1}) to both the control and a higher concentration (69.06 mg L^{-1}), Samadi *et al.* (2019) found that the latter considerably increased marketable yield. Foliar spraying at 552.48 mg L^{-1} considerably prolonged the blooming time, increased the number of flowers per plant, and enhanced overall output, according to Yousif & Yousif (2019). Similarly, treatment with 207.18 mg L^{-1} SA dramatically increased strawberry fruit's overall yield, phenolic content, protein content, vitamin C levels, and peroxidase enzyme activity, according to Haghshenas *et al.* (2020). According to Zhang *et al.* (2022), applying 276.24 mg L^{-1} of SA raised the level of TSS, anthocyanin, and vitamin C while lowering acidity. Under unheated greenhouse circumstances, Roozkhosh *et al.* (2024) demonstrated that SA treatment at 207.18 mg L^{-1} substantially increased fruit quantity, weight, and total production while simultaneously lowering fruit acidity. In comparison to other treatments (0, 250, and 1000 mg L^{-1}), Almutairi *et al.* (2024) found that SA foliar spray at 500 mg L^{-1} substantially increased TSS, anthocyanin, and total sugar content. Furthermore, 552.48 mg L^{-1} SA improved fruit weight, vitamin C, TSS, total and reducing sugars, catalase, and peroxidase activity, surpassing both lower and higher dosages used in their investigation (Ul Hasan *et al.*, 2024). All things considered, the results of these investigations lend credence to the idea that salicylic acid benefits strawberry fruit quality and reproductive development. SA's function in hormone modulation and photosynthetic efficiency enhancement is probably responsible for the increases in fruit output and quality. Salicylic acid may decrease the photoperiod needed for flowering initiation, allowing for faster and more prolific blooming (Luo *et al.*, 2022). Furthermore, SA affects the balance of phytohormones such cytokinins, auxins, and abscisic acid (ABA), which might alter flowering responses and nutrient distribution, according to Mady (2009). Key elements (N, P, K, Ca, and Mg) accumulate more readily in vegetative tissues when SA improves carbon absorption, photosynthetic activity, and nutrient uptake. These elements are then transferred to growing fruits (Karlidag *et al.*, 2009a, 2009b). Furthermore, SA delays senescence and improves nitrogen retention in plant tissues by suppressing ethylene production, according to Jamali *et al.* (2011). According to Singh and Singh (2008), applying SA enhances the growth of grana lamellae and chloroplast structures, which increases the synthesis of carbohydrates and chlorophyll. These metabolic alterations improve fruit fullness and production in general. Additionally, SA promotes lateral root growth and root system activity, which improves the absorption of nutrients and water (Hartwigsen & Evans, 2000; Dong *et al.*, 2002). Salicylic acid also affects important postharvest and quality-related characteristics. TSS content is increased by its role in the breakdown of organic acids into sugars and the slowing down of metabolic activities. Because SA decreases transpiration and respiration and delays the oxidation of ascorbic acid to dehydroascorbic acid, fruits retain more vitamin C. According to Sah *et al.* (2024), SA increases antioxidant activity via activating phenylalanine ammonia lyase (PAL), which promotes the formation of phenolic compounds. Furthermore, SA improves fruit colors and nutritional quality by promoting the manufacture of photosynthetic pigments including carotenoids and chlorophyll (Hayat & Ahmad, 2007; Huang *et al.*, 2004). Additionally, salicylic acid has a crucial function in controlling water relations, stomatal movement, ion absorption, and membrane permeability. It also affects how plants react to abiotic stimuli such heat, drought, and exposure to heavy metals (Meena *et al.*, 2001; Arfan *et al.*, 2007). Its importance as a growth regulator in strawberry agriculture is shown by these diverse physiological actions.

3. METHODOLOGY

3.1. Literature search strategy

This review was conducted following systematic approaches to ensure comprehensive coverage and unbiased synthesis of available research on the effects of salicylic acid (SA) spray and sulfur fertilization on strawberry (Fragaria × ananassa) growth and yield. Electronic databases including Web of Science, Scopus, PubMed, ScienceDirect, Google Scholar, and AGRIS were mined using a combination of keywords such as "salicylic acid," "sulfur fertilization," "strawberry," "growth," "yield," "fruit quality," and "plant physiology." Searches included literature published between 2000 and 2024 to capture recent advances and historical background.

3.2. Inclusion and exclusion criteria

3.2.1. Studies were included if they-

Investigated the effects of exogenous salicylic acid application (via spray/foliar treatments) and/or sulfur fertilization on strawberry plants, Reported on growth parameters, yield, fruit quality, or physiological responses, Utilized field, greenhouse, or controlled environment experimental designs and Were published in peer-reviewed journals or as conference proceedings in English.

3.2.2. Studies were excluded if they-

Focused solely on in vitro or non-crop model systems, Did not specifically address strawberries, Lacked relevant data on plant growth, yield, or fruit quality and Were review articles, opinion pieces, or editorial notes.

3.3. Study selection and data extraction

All search results were imported into a reference manager (e.g., EndNote or Zotero), and duplicates were removed. Titles and abstracts were screened for relevance. Full texts of potentially eligible articles were then assessed independently by two reviewers. Disagreements were resolved by discussion or consultation with a third reviewer.

3.4. Data synthesis

Extracted data were synthesized qualitatively due to the heterogeneity of experimental designs, treatment protocols, and measured outcomes among the studies. Where possible, trends and consistencies regarding the effects of SA spray and sulfur fertilization on strawberry growth and yield were identified and summarized. Contradictions and gaps in the literature were noted.

3.5. Quality assessment

The methodological quality of included studies was appraised using criteria adapted from established checklists (such as the Cochrane Collaboration's tool for experimental studies), with attention to aspects such as replication, control treatments, statistical analysis, and clarity in reporting of methods and results.

4. RESULTS AND DISCUSSION

4.1. Sulfur

For all living things, including plants, to grow and develop, sulfur (S) is a necessary macronutrient. It is essential to several physiological and metabolic functions. Sulfur is found in soils in a variety of forms, with organic matter accounting for around 95% of the total. Sulfate (SO_4^{2-}) is the main type of organic sulfur that plants may use when it breaks down. Certain plants may collect sulfur gasses from the atmosphere via their leaves in addition to soil sources. Sulfur is an essential structural component that plants need to synthesize a number of vital chemicals. It is a component of amino acids that include sulfur, including methionine, cysteine, and cystine, which together make up around 90% of the sulfur found in plant tissues. Additionally, sulfur helps to produce essential biomolecules such as phytochelatins, glutathione, biotin, and thiamine. Cellular redox balance, enzyme control, protein stability via disulfide bond formation, and general defense mechanisms against infections and environmental stressors are all impacted by these substances (Narayan *et al.*, 2022; Al-Maeni, 2024). Additionally, sulfur is essential for the manufacture of chlorophyll and for the activity of many different enzymes. According to Havlin *et al.* (2005) and Al-Maeni (2024), it is a crucial part of the ferredoxin and iron-sulfur (Fe–S) proteins found in the chloroplasts, which are necessary for electron transport and photosynthetic efficiency. The pH of calcareous soils, like those often found in Iraq, frequently rises beyond 7.5, resulting in alkaline conditions that restrict the availability of a number of vital elements, particularly micronutrients. Since elemental sulfur leads to soil acidity, its application is especially advantageous in these situations. When applied to soil, elemental sulfur undergoes microbial oxidation—primarily by Thiobacillus species—forming sulfuric acid (H_2SO_4), which subsequently reduces the pH in the root zone (Tabatabai, 1994; Havlin *et al.*, 2005). This pH reduction enhances the solubility and uptake of many nutrients required for optimal plant growth (Abu Thai & Mu'ayyad, 1988; Al-Mu'ayini, 2024). Furthermore, sulfur is indispensable for the biosynthesis of coenzyme A, which facilitates the oxidation and synthesis of amino acids and fatty acids, and participates in intermediary metabolism through the citric acid (Krebs) cycle. The uptake of sulfur is closely linked to nitrogen metabolism, as both elements are required in tandem for protein synthesis. The balance between nitrogen and sulfur in plant tissues is often used as a diagnostic tool for assessing sulfur status. According to Zhao *et al.* (2008), sulfur deficiency can be inferred when the nitrogen-to-sulfur (N:S) ratio exceeds 15:1. Optimal plant growth is typically supported when sulfur concentrations in dry matter exceed 0.2%, and the available sulfate content in soil solution ranges from 3 to 5 mg kg^{-1} (Narayan *et al.*, 2022; Al-Maeni, 2024).

4.2. Effect of sulfur fertilization on the vegetative growth of strawberry plants

Several studies have demonstrated the positive effects of sulfur fertilization on the vegetative growth and physiological performance of strawberry plants. Erdal *et al.* (2006) evaluated the impact of soil-applied sulfur in the form of mineral sulfide (containing 80% elemental sulfur) at application rates of 0, 500, and 1000 kg S ha^{-1} on 'Camarosa' strawberry plants. Their results indicated that the application of 500 kg S ha^{-1} significantly enhanced leaf chlorophyll content compared to the control and the highest application rate. Similarly, Santos (2013) investigated the effect of six sulfur application levels (0, 50, 100, 150, 200, and 250 kg S ha^{-1}) and reported that the highest level (250 kg S ha^{-1}) led to a marked increase in total chlorophyll content and elevated magnesium (Mg) and manganese (Mn) concentrations in the leaves. Silva *et al.* (2013) treated potted strawberry plants with sulfur at six different doses (0, 10, 20, 30, 40, and 50 mg S kg^{-1}) in a greenhouse trial. The treatment of 50 mg S kg^{-1} produced the highest concentrations of phosphate (P), calcium (Ca), and sulfur in fruit tissues as well as the largest dry biomass of vegetative tissues and fruits. The impact of sulfur on vegetative growth was evaluated by Afroz *et al.* (2016) at four different levels: 0, 15, 25, and 35 kg S ha^{-1}. When compared to other treatments, their results demonstrated that applying 25 kg S ha^{-1} considerably increased plant height and the number of leaves per plant. Together, these results imply that sulfur treatment enhances the chlorophyll content and total vegetative development of strawberry plants, which is in line with previous findings by Santos (2013) and Erdal *et al.* (2006). Sulfur's acidifying effect in the rhizosphere, particularly in calcareous or alkaline soils, may be responsible for the favorable results. This effect increases the availability and uptake of essential nutrients, especially nitrogen (N), phosphorus (P), iron (Fe), and zinc (Zn), which are critical for the synthesis of chlorophyll (Piri *et al.*, 2012). Significantly, as chloroplasts contain more than half of the plant's total nitrogen, nitrogen is essential to the construction of chlorophyll (Havlin *et al.*, 2005; Al-Maeni, 2024). Additionally, the manufacture of proteins and amino acids that sustain the development and operation of chloroplasts depends on nitrogen (Mohammed, 1985; Amar, 2003). Through its role in the production of δ-aminolevulinic acid and the transformation of Mg-protoporphyrin IX methyl ester into protochlorophyllide—two crucial processes in chlorophyll biosynthesis—iron, another micronutrient whose availability may be enhanced by sulfur application, aids in the synthesis of chlorophyll (Porra & Meisch, 1984). Additionally, sulfur has a direct role in the production of chlorophyll (Abu-Thahi & Moayad, 1988; Havlin *et al.*, 2005). Improved photosynthetic efficiency brought about by greater chlorophyll production is primarily responsible for the improvements in vegetative development features, such as larger leaf area, higher dry matter accumulation, and longer growth period. This is explained by how sulfur and related nutrients work in concert to support cellular growth, division, and energy production for plant development. Additionally, the production of chloroplast proteins is supported by the elevated sulfur content in plant tissues after sulfur fertilization, which increases the efficiency of photosynthesis and promotes improved plant growth and productivity (Piri *et al.*, 2012).

4.3. Effect of sulfur fertilization on flowering, fruit set, yield, and the quantitative and qualitative characteristics of strawberry plants

Numerous research have shown that sulfur fertilizer may greatly improve strawberry yield's quantitative and qualitative characteristics, as well as blooming and fruit set. According to Erdal *et al.* (2006), sulphur application at 500 kg S ha^{-1} to strawberry plants known as "Camarosa" resulted in a substantial increase in both the average fruit weight and total fruit output when compared to the control. Additionally, increased nutrient concentrations in the leaves were the result of the 1000 kg S ha^{-1} treatment. In a similar vein, Silva *et al.* (2013) discovered that administering 50 mg S kg^{-1} produced the greatest quantities of sulfur and calcium in the fruits in a greenhouse experiment that used six sulfur levels (0–50 mg S kg^{-1}). In comparison to the lesser sulfur treatments, Santos (2013) found that sulfur spraying at 250 kg S ha^{-1} significantly increased fruit weight, overall yield, and the proportion of marketable fruits. Afroz *et al.* (2016) investigated how field-grown strawberry plants responded to sulfur fertilizer at four different rates (0, 15, 25, and 35 kg S ha^{-1}). In addition to lowering the percentage of unmarketable fruits, their findings demonstrated that applying 25 kg S ha^{-1} greatly increased the number of flowers and fruits per plant, as well as the fruit's weight, diameter, and length. Interestingly, the 35 kg S ha^{-1} treatment produced the fruits with the greatest sulfur content. In a greenhouse, Santiago *et al.* (2018) treated "Albion" strawberry plants with sulfur at concentrations of 0 and 60 mg S dm^{-3}. At the greater application rate, they observed a significant rise in fruit weight and sulfur content. Additionally, Onofre *et al.* (2021) verified the advantages of sulfur fertilizer. They discovered that, in comparison to the control, applying 8.4 kg S ha^{-1} greatly increased overall production throughout the 2017–2018 season in both open-field and greenhouse growing methods. Three sulfur levels (0, 8.4, and 16.8 kg S ha^{-1}) across two growth seasons were included in their research. The findings from Erdal *et al.* (2006), Santos (2013), Santiago *et al.* (2018), and Onofre *et al.* (2021) taken together suggest that sulfur fertilizer improves strawberry fruit quality and production. These benefits are probably related to sulfur's capacity to lower the rhizosphere's soil pH, which improves nutrient bioavailability, particularly for micronutrients, and increases nutrient absorption and accumulation in the leaves. Consequently, this encourages physiological functions such fruit set, blooming, and photosynthesis (Al-Aa'reji, 2010). According to Havlin *et al.* (2005) and Al-Maeni (2024), the microbial oxidation of elemental sulfur by Thiobacillus spp. results in sulfuric acid, which acidifies the soil and lowers pH. This improves the solubility and absorption of nutrients, especially those that are essential for the development of the reproductive system. Processes like cell division and expansion, leaf area growth, and chlorophyll synthesis depend on greater photosynthetic activity and carbohydrate generation, which are facilitated by the higher nutritional content in plant tissues. In the end, these metabolic gains result in better reproductive characteristics, such as bigger and more numerous fruits, as well as better fruit quality. By increasing sugar content, decreasing acidity, and improving fruit structure, sulfur also contributes to fruit marketability, according to earlier research (Nijjar, 1985; Hurley *et al.*, 1986; Al-Aareji & Al-Douri, 2009a, 2009b; Al-Aareji & Bani, 2020; Tama & Hameed, 2021).

5. CONCLUSION

The results show that strawberry plants clearly and favorably respond to the treatment of sulfur and salicylic acid. When compared to the control, these treatments markedly improved the fruits' quantitative and qualitative qualities, overall yield, and vegetative development. However, a number of contributing variables, such as the strawberry cultivar, local climate, and soil fertility level, affected the ideal salicylic acid and sulfur treatment rates. As a result, these factors must be taken into account while choosing the right concentrations to achieve the highest levels of production and efficiency.

5.1. Future research needs

While significant progress has been made in understanding the effects of salicylic acid (SA) sprays and sulfur fertilization on strawberry growth and yield, several gaps and opportunities for further research remain:

- *Mechanistic insights:* Most existing studies focus on phenotypic outcomes such as yield and growth parameters. More research is required to elucidate the molecular and physiological mechanisms through which SA and sulfur, individually and in combination, influence plant hormones, defense responses, and metabolic pathways in strawberries.

• *Optimal dosages and application timing:* Future studies should systematically assess a range of SA and sulfur concentrations, as well as different timings and frequencies of application, to establish optimal protocols for various strawberry cultivars and growth stages.

• *Combined and synergistic effects:* Research on the interaction between SA spray and sulfur fertilization is limited. Studies should investigate potential synergistic or antagonistic effects, including whether co-application maximizes benefits or leads to diminishing returns.

• *Long-term and multi-location trials:* Most current research is based on single-season trials under controlled or specific local conditions. Multi-location and multi-year experiments are needed to validate the consistency and robustness of observed effects across diverse environmental conditions and soil types.

• *Impact on Fruit Quality and Shelf Life:* Although yield is a primary concern, the effects of SA and sulfur on strawberry fruit quality attributes (e.g., sugar content, acidity, firmness, flavor, antioxidant properties) and postharvest shelf life require more investigation.

• *Pest and disease resistance:* Both SA and sulfur have roles in plant defense, but more research is needed to quantify their combined impact on disease incidence and pest management in strawberry cultivation.

• *Soil health and microbiome interactions:* Sulfur fertilization affects soil properties and microbial communities, potentially influencing plant health indirectly. Future studies should explore how SA and sulfur together alter the soil microbiome and subsequent plant responses.

• *Environmental and economic assessments:* Life cycle assessments and cost-benefit analyses are required to determine the environmental sustainability and economic feasibility of integrating these treatments into commercial strawberry production systems.

• *Genotypic variation:* Response to SA and sulfur treatments may vary among strawberry cultivars. Screening a broad range of genotypes will help identify those with the greatest benefits from these interventions.

Addressing these research needs will facilitate the development of scientifically grounded, efficient, and sustainable practices for optimizing strawberry productivity and quality through salicylic acid and sulfur management.

REFERENCES

Abu-Thahi, Y. M., & A. Y. Moayad (1988). *Guide of Plant Nutrition.* Dar Al-Kutub for Printing and Publishing. Mosul Univ. Iraq.

Afroz, C. A., Shimul, M. A. H., Ikrum, M., Siddiky, M. A., & Razzaque, M. A. (2016). Effects of nitrogen, phosphorus, potassium, and sulphur on growth yield and nutrient content of strawberry (Fragaria ananassa). *Journal of Environmental Science and Natural Resources, 9*(1), 99-108.

Al-Aareji, J. M., & Bani, S. H. (2020, August). Rsponse of Dixired Peach Trees to Sulphur and Iron Application. In *IOP Conference Series: Earth and Environmental Science* (Vol. 553, No. 1, p. 012023). IOP Publishing.

Al-Aa'reji, J. M. (2010). Effect of organic fertilizer, urea, and sulfur on vegetative growth and concentration of some nutrient of young peach trees cv. *International Journal of Plant Research, 10*(2), 76-86. https://doi.org/10.5923/j.plant.20201002.01

Al-Aa' reji., J. M. A., & Al-Douri, E. F. S. (2009a). Effect of sulphur, nitrogen, and ascorbic acid on soil pH and concentration of available nutrients in the orchard soil of Anna and Vistabella apple cvs. *Tikrit Journal for Agricultural Sciences, 9*(1), 187–204 .

Al-Aa'reji., J. M. A., & Al-Douri, E. F. S. (2009b). Effect of sulphur, nitrogen, and ascorbic acid on vegetative growth and mineral content of young apple trees, cvs. Anna and Vistabella . 2-leaves chlorophyll and leaves and branches sugars. *Tikrit Journal for Agricultural Sciences, 9*(2), 183–199.

Al-Bayoumi, Abdel Aziz Al-Saeed, Yousry Al-Sayed Saleh, and Osama Handawi Sayed (2000). Fundamentals of Botany, Arab House for Publishing and Distribution, Egypt.

Al-Karawi, H. N., Salman, F. A., & Al-Deheimawi, A. J. (2023). The Effect of Foliar Application of Organic Matter and Salicylic Acid on The Growth and Yield in Strawberry (Fragaria ananassa). In *IOP Conference Series: Earth and Environmental Science, 910*(1), 012081. IOP Publishing.

Al-Maeni, A. M. T. (2024). *Soil Fertility and Fertilization Under Arid and Semi-arid Region Conditions.* Majdi Prin. Mosul. Iraq.

Almutairi, K. F., Alharbi, A. R., Abdelaziz, M. E., & Mosa, W. F. (2024). Salicylic Acid and Chitosan Effects on Fruit Quality When Applied to Fresh Strawberry or During Different Periods of Cold Storage. *BioResources, 19*(3).

Amar, S. (2003). *Fruit Physiology and Production.* Kalyani Publishers. New Delhi. India.

Arfan, M., Athar, H. R., & Ashraf, M. (2007). Does exogenous application of salicylic acid through the rooting medium modulate growth and photosynthetic capacity in two differently adapted spring wheat cultivars under salt stress?. *Journal of plant physiology, 164*(6), 685-694.

Borsani, O., Valpuesta, V., & Botella, M. A. (2001). Evidence for a role of salicylic acid in the oxidative damage generated by NaCl and osmotic stress in Arabidopsis seedlings. *Plant physiology, 126*(3), 1024-1030.

Dong, S., Cheng, L., Scagel, C. F., & Fuchigami, L. H. (2002). Nitrogen absorption, translocation and distribution from urea applied in autumn to leaves of young potted apple (Malus domestica) trees. *Tree physiology, 22*(18), 1305-1310.

Erdal, I., Kepenek, K., & Kizilgöz, I. (2006). Effect of elemental sulphur and sulphur-containing waste on the iron nutrition of strawberry plants grown in a calcareous soil. *Biological agriculture & horticulture, 23*(3), 263-272.

Food and Agriculture Organization (FAO). *FAOSTAT (Statistics) 2024*. https://www.fao.org/faostat/en/#data/QCL

Giampieri, F., Alvarez-Suarez, J. M., & Battino, M. (2014). Strawberry and human health: Effects beyond antioxidant activity. *Journal of agricultural and food chemistry, 62*(18), 3867-3876.

Haghshenas, M., Nazarideljou, M. J., & Shokoohian, A. (2020). Phytochemical and quality attributes of strawberry fruit under osmotic stress of nutrient solution and foliar application of putrescine and salicylic acid. *International Journal of Horticultural Science and Technology, 7*(3), 263-278.

Hartwigsen, J. A., & Evans, M. R. (2000). Humic acid seed and substrate treatments promote seedling root development. *HortScience, 35*(7), 1231-1233.

Havlin, L. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (2005). *Soil Fertility and Fertilizers* (7th ed.). Upper Saddle River, New Jersey 07458.

Hayat, S., & Ahmad, A. (2007). *Salycilic acid : a plant hormone* (ed.). Springer. Dortrecht, the Netherlands.

Hayat, S., Hayat, Q., Alyemeni, M. N., & Ahmad, A. (2014). Salicylic acid enhances the efficiency of nitrogen fixation and assimilation in Cicer arietinum plants grown under cadmium stress. *Journal of Plant Interactions, 9*(1), 35-42.

Huang, D. J., Chun-Der, L. I. N., Hsien-Jung, C. H. E. N., & Yaw-Huei, L. I. N. (2004). Antioxidant and antiproliferative activities of sweet potato (Ipomoea batatas [L.] LamTainong 57') constituents. *Botanical Bulletin of Academia Sinica, 45*, 179-186.

Hurley, A. K., Walser, R. H., Davis, T. D., & Barney, D. L. (1986). Net photosynthesis, chlorophyll, and foliar iron in apple trees after injection with ferrous sulfate. *HortScience, 21*(4), 1029-1031.

Jamali, B., Eshghi, S., & Tafazoli, E. (2011). Vegetative and reproductive growth of strawberry plants cv.'Pajaro' affected by salicylic acid and nickel. *Journal of Agricultural Science and Technology, 13*(6), 895-904.

Janda, T., Szalai, G., & Pál, M. (2020). Salicylic acid signalling in plants. *International Journal of Molecular Sciences, 21*(7), 2655.

Jiang, K., & Asami, T. (2018). Chemical regulators of plant hormones and their applications in basic research and agriculture. *Bioscience, biotechnology, and biochemistry, 82*(8), 1265-1300.

Karlidag, H., Yildirim, E., & Turan, M. (2009a). Exogenous applications of salicylic acid affect the quality and yield of strawberries grown under antifrost heated greenhouse conditions. *Journal of Plant Nutrition and Soil Science, 172*(2), 270-276.

Karlidag, H., Yildirim, E., & Turan, M. (2009b). Salicylic acid ameliorates the adverse effects of salt stress on strawberry. *Scientia Agricola, 66*, 180-187.

Kazan, K., & Manners, J. M. (2012). JAZ repressors and the orchestration of phytohormone crosstalk. *Trends in plant science, 17*(1), 22-31.

Khan, W., Prithiviraj, B., & Smith, D. L. (2003). Photosynthetic responses of corn and soybean to foliar application of salicylates. *Journal of plant physiology, 160*(5), 485-492.

Luo, Y., Liu, M., Cao, J., Cao, F., & Zhang, L. (2022). The role of salicylic acid in plant flower development. *Forestry Research, 2*, 14.

Mady, M. A. (2009). Effect of Foliar Application with Salicylic Acid and Vitamin E on Growth and Productivity of Tomato (Lycopersicon esculentum, Mill.) Plant. *Journal of Plant Production, 34*(6), 6715-6726.

Maruri-López, I., Aviles-Baltazar, N. Y., Buchala, A., & Serrano, M. (2019). Intra- and extracellular journey of the phytohormone salicylic acid. Frontiers in Plant Science, 423.

Meena, B. ; T. Marimuthu and R.Velazhan. (2001). Salycilic acid induce systmic arsistant in groundnut against late leaf spot caused by Cercosporidium personatum. *Journal of Mycology and Plant Pathology, 31*, 139-145.

Mohammed, A. K. (1985). *Plant Physiology* (2nd ed.). Dar Al-Kutub for Printing and Publishing. Mosul Univer.

Naeem, M., Basit, A., Ahmad, I., Mohamed, H. I., & Wasila, H. (2020). Effect of Salicylic Acid and Salinity Stress on the Performance of Tomato Plants. *Gesunde Pflanzen, 72*(4).

Narayan, O. P., Kumar, P., Yadav, B., Dua, M., & Johri, A. K. (2022). Sulfur nutrition and its role in plant growth and development. *Plant Signaling & Behavior*, 2030082.

Nijjar, G. G. (1985). *Nutrition of Fruit Trees* (pp. 52-137). Kylyani Publishers, New Delhi-Indian.

Onofre, R. B., Gadoury, D. M., & Peres, N. A. (2021). High efficacy and low risk of phytotoxicity of sulfur in the suppression of strawberry powdery mildew. *Plant Health Progress, 22*(2), 101-107.

Palei, S., Das, K., Sahoo, K., Dash, D. K., & Swain, S. (2016). Influence of plant growth regulators on strawberry Cv. Chandler under Odisha condition. *International Journal of Recent Scientific Research, 7*, 9945-9948.

Piri, I., Rahimi, A., Tavassoli, A., Rastegaripour, F., & Babaeian, M. (2012). Effect of sulphur fertilizer on sulphur uptake and forage yield of Brassica juncea in condition of different regimes of irrigation. *African journal of agricultural research, 7*(6), 958-963.

Porra, R. J., & Meisch, H. U. (1984). The biosynthesis of chlorophyll. *Trends in biochemical sciences, 9*(3), 99-104.

Rivas-San Vicente, M., & Plasencia, J. (2011). Salicylic acid beyond defence: its role in plant growth and development. *Journal of Experimental Botany, 62*(10), 3321-3338.

Roozkhosh, M., Khalil Tahmasebi, B., Soleimani, S., Meighani, H., Eshraghi-Nejad, M., Afshar Manesh, G. R., & Vahidi Nia, M. A. (2024). Salicylic acid can enhance quality characteristics, growth, and productivity of strawberry (Fragaria × ananassa cv. Camarosa) under drought stress conditions. *Plant Process and Function, 12*(58), 103-115.

Sah, A., Madhavi, M., Sivakumar, V., Subbaramamma, P., & Sekhar, V. (2024). Influence Of Pre Harvest Application Of Hexanal And Salicylic Acid At Different Storage Temperatures On Fruit Quality And Shelf Life Of Strawberry (Fragaria Ananassa) Cv. Winter Dawn. *Plant Archives (09725210), 24*(2).

Samadi, S., Habibi, G., & Vaziri, A. (2019). Effects of exogenous salicylic acid on antioxidative responses, phenolic metabolism, and photochemical activity of strawberry under salt stress. *Iranian Journal of Plant Physiology, 9*(2), 2685-2694.

Santiago, F. E. M., Silva, M. L. D. S., Ribeiro, F. D. O., Cipriano, P. E., & Guilherme, L. R. G. (2018). Influence of sulfur on selenium absorption in strawberry. *Acta Scientiarum. Agronomy, 40*.

Santos, B. M. (2013). Response of Strawberries to preplant sulfur fertilization in sandy soils. *International Journal of Fruit Science, 13*(3), 326-333.

Silva, M. L. S., de Cássia Piccolo, M., & Trevizam, A. R. (2013). Gypsum as a source of sulfur for strawberry crops. *Semina: Ciências Agrárias, 34*(4), 1683-1694.

Singh, A., & Singh, P. K. (2008). Salicylic acid induced biochemical changes in Cucumber cotyledons. *Indian Journal of Agricultural Biochemistry, 21*(1and2), 35-38.

Sofy, M. R., Seleiman, M. F., Alhammad, B. A., Alharbi, B. M., & Mohamed, H. I. (2020). Minimizing adverse effects of Pb on maize plants by combined treatment with jasmonic, salicylic acids, and proline. *Agronomy, 10*(5), 699.

Soppelsa, S., Gasser, M., & Zago, M. (2023). Optimizing Planting Density in Alpine Mountain Strawberry Cultivation in Martell Valley, Italy. *Agronomy, 13*(5), 1422.

Tabatabai, M. A.(1994). Soil Enzymes. P:775-833 in Weaver R.W. (Ed). Methods of Soil Analysis Part 2. Microbiological and Biochemical Properties 3rd ed. ASA, Madison, WI.

Tama, M. H., & Hameed, I. H. (2021). Effect of humic acid and sulfur on the biochemical traits of date palm (Phoenix dactylifera L.) Al-Sayer cultivar grown in saline soil. *International Journal of Agricultural & Statistical Sciences, 17*(1).

Ul Hasan, S. Z., Hassan, I., Khan, M. A., & Jilani, G. (2024). Effect of salicylic acid application on growth, production, fungal decay, and overall quality of strawberry. *Plant Protection, 8*(4), 729-739.

Wang, W., Wang, S., & Wang, M. (2019). Status and extension experience protected strawberry cultivation technology in Daxing District. *J. Veg., 4*, 67–70.

Wani, A. B., Chadar, H., Wani, A. H., Singh, S., & Upadhyay, N. (2017). Salicylic acid to decrease plant stress. *Environmental Chemistry Letters, 15*, 101-123.

Yang, J., Su, D., Wei, S., Chen, S., Luo, Z., Shen, X., & Cui, X. (2020). Current and future potential distribution of wild strawberry species in the biodiversity hotspot of Yunnan Province, China. *Agronomy, 10*(7), 959.

Yousif, D. Y. M., & Yousif, M. (2019). Evaluation of salicylic acid solution on the fungus Botrytis cinerea that caused strawberry gray mold. *Plant Archives, 19*(1), 229-238.

Youssef, S. M. S., Abu El-Azm, N. A. I., & Abd Elhady, S. A. E. (2017). Frequent foliar sprayings of salicylic acid with elevated concentrations enhance growth, yield, and fruit quality of strawberry (Fragaria x ananassa Duch. cv Festival) plants. *Egyptian Journal of Horticulture, 44*(1), 61-74.

Zhang, Y., Li, S., Deng, M., Gui, R., Liu, Y., Chen, X., & Tang, H. (2022). Blue light combined with salicylic acid treatment maintained the postharvest quality of strawberry fruit during refrigerated storage. *Food chemistry: X, 15*, 100384.

Zhao, F. J., Tausz, M., & De Kok, L. J. (2008). Role of sulfur for plant production in agricultural and natural ecosystems. *Sulfur metabolism in phototrophic organisms*, 417-435.