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Study on the Role of Selenium in Enhancing Stress Resistance and Quality Improvement of Strawberries

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Abstract Strawberries are widely favored for their high nutritional value and economic benefits, but their yield and quality are often constrained by various environmental stresses. This study explores the mechanisms by which selenium alleviates salt stress, heavy metal pollution, and drought stress in strawberries, including enhancing antioxidant enzyme activity, optimizing water use efficiency, and maintaining cell membrane stability to improve stress tolerance. The results demonstrate that selenium application promotes strawberry growth and development under extreme conditions, enhances fruit quality, and boosts market competitiveness. Moreover, selenium biofortification effectively increases the content of functional compounds such as flavonoids and polyphenols in strawberry fruits, significantly improving sugar-acid balance and flavor characteristics. However, further research is needed to optimize selenium application, focusing on dosage, safety, and synergistic interactions with other nutrients for practical agricultural promotion. This study provides critical insights for the development of selenium-enriched strawberry varieties and sustainable agricultural practices.
Keywords Strawberries; Selenium; Biofortification; Stress tolerance; Fruit quality; Sustainable agriculture

1 Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is a perennial herbaceous plant in the genus *Fragaria* of the family Rosaceae. Known for its vibrant color, sweet taste, and high nutritional value, it is often referred to as the "Queen of Fruits" (Lei et al., 2006). Strawberries are rich in vitamin C, antioxidants, minerals, and dietary fiber, making them highly favored by consumers and a crop of significant economic value (Yuan and Sun, 2021). With a short production cycle and high economic returns, strawberries are one of the most widely cultivated small berries globally. In recent years, the growing demand for high-quality strawberries has been driven by rising living standards and an increasing focus on healthy diets. China has become the largest producer and consumer of strawberries worldwide. According to the National Bureau of Statistics (2022), China's strawberry cultivation area has increased by 78.51% over the past decade, while production has grown by 79.25% (https://data.stats.gov.cn/easyquery.htm?cn=C01). However, meeting the ever-expanding market demand while improving both yield and quality remains a critical challenge in agricultural production and scientific research.

Selenium (Se) is an essential trace element whose biological significance has gradually been unveiled since its discovery in 1817. Selenium plays a critical role in human health, contributing to immune response, antioxidant functions, and hormonal regulation. Research has shown that selenium plays a multifaceted and critical role in the human body. It is involved in immune response, antioxidant defense, and hormonal regulation, and it also helps prevent cardiovascular diseases, delay aging, and combat cancer (Wang et al., 2023; Zhang et al., 2023). Selenium deficiency can impair the antioxidant system, affecting the health of various organs (Duborskáe et al., 2022). In plants, selenium is a beneficial element primarily found in two forms: inorganic selenium and organic selenium. Common forms of organic selenium include selenocysteine (SeCys) and selenomethionine (SeMet), which enter plants through amino acid transporters and participate in various metabolic activities (Svennerstam et al., 2008; Kikkert and Berkelaar, 2013). Plants can convert absorbed inorganic selenium into organic selenium and store it in chloroplasts or cytoplasm, earning them the title of "Selenium Production Workshops" (Hasanuzzaman et al., 2020; Gui et al., 2022). This conversion process not only supports plant growth but also produces selenium-enriched products, providing essential contributions to the selenium cycle within ecosystems (Xie et al., 2020; Chen et al., 2023; Yang et al., 2024).

The role of selenium in plants has garnered extensive research interest, particularly regarding its potential to enhance stress tolerance and improve crop quality. Selenium can scavenge excess free radicals in plants, increasing resistance to adverse conditions such as salinity, heavy metal contamination, and drought, while also optimizing the nutritional composition and flavor characteristics of fruits (Hasanuzzaman et al., 2020; Huang et al., 2018). In strawberries, the biofortification potential of selenium and its role in enhancing stress tolerance have become research hotspots in recent years (Iqbal et al., 2022; Yuan et al., 2024). However, the comprehensive mechanisms underlying selenium's dual role in improving strawberry stress tolerance and quality remain insufficiently studied.

This study systematically analyzes the integrated mechanisms of selenium (Se) in enhancing strawberry stress tolerance and quality. It explores selenium's specific roles in alleviating multiple stress conditions in strawberries and evaluates its potential applications in agricultural production. The study findings will further clarify the critical role of selenium in strawberry production, provide a scientific foundation for the development of selenium-enriched strawberry varieties, and serve as an important reference for promoting sustainable agricultural practices and the cultivation of high-quality crops.

2 Mechanisms of Selenium in Enhancing Stress Tolerance in Strawberries

Selenium, as a functional trace element, demonstrates significant potential in enhancing strawberries stress tolerance. By regulating physiological, biochemical, and molecular mechanisms, selenium markedly improves strawberries resilience to adverse environmental conditions such as salinity, heavy metal contamination, and drought, while simultaneously enhancing overall growth and quality traits (Figure 1) (Heijari et al., 2006; Zahedi et al., 2019; Gui et al., 2022; Yuan et al., 2024). Selenium promotes photosynthetic efficiency, increases antioxidant enzyme activity, reduces the accumulation of reactive oxygen species (ROS), and optimizes water use efficiency (WUE), thereby comprehensively boosting plant stress tolerance (Santiago et al., 2018; Lai et al., 2022). These mechanisms provide a basis and potential agricultural application value for the use of selenium in strawberries and other economically important crops.

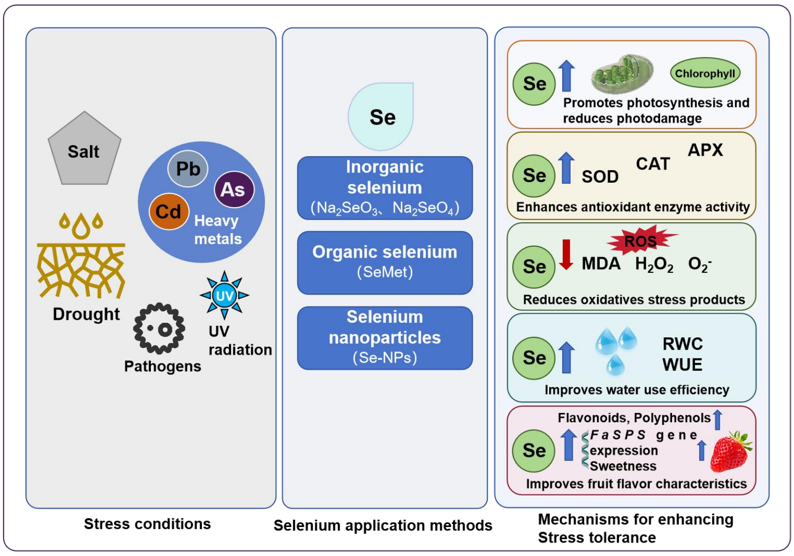

Figure 1 Effects of Se supplementation in strawberry under stress conditions

2.1 Protective effects of selenium under salt stress

Selenium (Se) and its nanoparticles (Se-NPs) have demonstrated significant efficacy in alleviating the adverse effects of salt stress on strawberries. Studies indicate that Se and Se-NPs promote strawberry growth under high salinity conditions by enhancing oxidative stress tolerance, improving mineral nutrient uptake, mitigating the inhibitory effects of salt on photosynthesis, and maintaining cell membrane integrity (Nedjimi, 2024). For instance, Zahedi et al. (2019) observed that foliar application of Se-NPs not only improved growth parameters in strawberries but also increased the levels of osmotic regulators such as total soluble carbohydrates and free proline. This treatment enhanced the activity of antioxidant enzymes and reduced lipid peroxidation and hydrogen peroxide (H_2O_2) accumulation, significantly improving salt stress tolerance. Moreover, low concentrations of Se-NPs (10 μM) were found to mitigate the loss of calcium and potassium, boost catalase activity, increase phenolic compound content, and improve photosynthesis and antioxidant capacity (Soleymanzadeh et al., 2020).

Further research by Pourebrahimi et al. (2023) demonstrated that the combined application of sodium selenate (Na_2SeO_4) and hydrogen sulfide (NaHS) significantly enhanced selenium concentration, antioxidant system activity, and flavor quality in strawberry fruits. These findings suggest that appropriate doses of Se-NPs or selenium compounds can not only alleviate the negative impacts of salt stress on strawberries but also improve fruit quality by enhancing antioxidant capacity and photosynthetic efficiency.

2.2 Mechanisms of selenium in alleviating heavy metal stress

Heavy metal pollution is one of the major abiotic stresses limiting strawberry productivity. Studies have shown that exogenous selenium supplementation can alleviate the toxicity of heavy metals such as cadmium (Cd) and lead (Pb) in strawberries by restricting metal ion uptake at the root level, reducing the translocation of metals to aboveground tissues, and enhancing antioxidant responses (Hasanuzzaman et al., 2022). Zhang et al. (2011) found that foliar application of sodium selenite (Na_2SeO_3) not only reduced the absorption of Cd and Pb but also maintained cell membrane stability by lowering the content of malondialdehyde (MDA), a lipid peroxidation product. Similarly, Zhang et al. (2020) demonstrated that low concentrations of Na_2SeO_3 significantly enhanced the activities of antioxidant enzymes such as superoxide dismutase (SOD), ascorbate peroxidase (APX), and catalase (CAT), reducing Cd accumulation and thereby improving the growth performance and fruit quality of strawberries.

Moreover, selenium effectively alleviates oxidative damage and photosynthetic inhibition caused by Cd stress (Song et al., 2024). A meta-analysis by Tian et al. (2024) further revealed that the effectiveness of selenium in mitigating heavy metal stress is closely related to its application concentration, plant species, and soil conditions. Through its multifaceted regulatory mechanisms, selenium significantly reduces the toxic effects of heavy metals on strawberries, providing new possibilities for sustainable strawberry production in polluted soil environments.

2.3 Role of selenium in alleviating drought stress

Drought is another critical factor limiting strawberry yield and quality, and selenium has shown significant potential in enhancing plant drought tolerance. Studies have demonstrated that Se and Se-NPs can mitigate the adverse effects of drought on strawberries by enhancing antioxidant enzyme activity, improving WUE, and stabilizing cell membranes (Ahmad et al., 2016; Dar et al., 2021). For instance, Zahedi et al. (2020) investigated the potential of SiO_2-NPs, Se-NPs, and Se/SiO_2-NPs in mitigating the negative impacts of drought on strawberry growth and yield. The results showed that exogenous application of Se/SiO_2-NPs significantly increased carbohydrate and proline content as well as the activity of the antioxidant system, thereby enhancing drought tolerance and fruit quality in strawberries.

Furthermore, Wang et al. (2022) found that treatment with selenomethionine (Se-Met) not only improved photosynthesis and water status in strawberries but also significantly increased soluble solids, sugar-to-acid ratio, and vitamin C content in the fruits. Liu et al. (2024) further reported that the combined application of Se-NPs and copper nanoparticles (Cu-NPs) markedly improved photosynthetic pigment content and chlorophyll fluorescence parameters under drought conditions, while also optimizing fruit quality. These findings indicate that selenium has considerable potential in alleviating drought stress in strawberries, providing essential insights for enhancing the adaptability and yield of strawberries in arid environments.

3 Effects of Selenium on Strawberry Quality

3.1 Enhancing the nutritional value of strawberries

Selenium biofortification has proven highly effective in enhancing the nutritional value of strawberries. Studies have shown that exogenous selenium supplementation can significantly increase the levels of minerals, vitamins, and antioxidants in strawberry fruits. For example, Huang et al. (2023) reported that a selenium treatment concentration of 0.006% significantly increased the vitamin C content in strawberries, contributing to enhanced antioxidant capacity. Additionally, selenium application did not negatively impact the growth or yield of strawberries but instead promoted mineral accumulation in the fruits (Mimmo et al., 2017).

Metabolomic analyses further revealed that selenium-enriched strawberries showed an increase in flavonoids and polyphenolic compounds. These secondary metabolites not only benefit human health but also enhance the antioxidant properties of the fruit (Mimmo et al., 2017). These results indicate that selenium, as a biofortifying element, improves the nutritional profile of strawberries while offering potential health benefits, providing valuable insights for the development of selenium-enriched strawberry varieties.

3.2 Improving flavor and texture of strawberries

Selenium has also demonstrated a positive role in improving the flavor and texture of strawberry fruits. By regulating sugar and acid metabolism, selenium application can optimize the flavor characteristics of the fruit. For instance, Lin et al. (2024) found that Na_2SeO_3 treatment significantly increased the activities of sucrose phosphate synthase (SPS) and acid invertase, leading to higher sucrose, fructose, and glucose levels in the fruit, thereby enhancing its sweetness. Simultaneously, the treatment inhibited citrate synthase activity, reducing the fruit's acidity and further improving its taste.

Similarly, research by Huang et al. (2023) demonstrated that combined application of selenium and zinc promoted the accumulation of soluble sugars in strawberries, significantly enhancing the fruit's taste. By balancing sugar and acid metabolism, selenium not only improves the nutritional composition of strawberries but also enhances their flavor and consumer appeal, boosting their market competitiveness.

3.3 Extending postharvest shelf life

Selenium treatments have shown remarkable potential in extending the postharvest shelf life of strawberries, making them highly applicable in postharvest management. It was reported that selenium-treated strawberries exhibited significantly reduced incidence and severity of gray mold, while maintaining better peel color and overall appearance (Lin et al., 2023). The results showed that the 12 mg/L selenium treatment significantly reduced the weight loss and decay rate of strawberries, while maintaining fruit skin brightness, increasing selenium content, and effectively delaying the onset and progression of gray mold (Figure 2). This effect is primarily attributed to the selenium treatment's ability to reduce oxidative stress in the fruit, decrease the production of reactive oxygen species (H_2O_2 and O_2^-), and thereby protect the integrity of the cell membranes.

Additionally, Zhu et al. (2021) highlighted that treatment with highly efficient and stable Se-NPs effectively inhibited the growth of pathogenic fungi, such as those causing wilting and red leaf disease, while increasing selenium accumulation in the fruit. This approach not only extended the shelf life of strawberries but also preserved their nutritional value and flavor, offering a practical solution for improving the postharvest quality of strawberries.

4 Applications of Selenium Biofortification in Strawberry Cultivation

4.1 Current status of selenium-enriched strawberry varieties

The development of selenium-enriched strawberry varieties has gained increasing attention in recent years, aiming to enhance the selenium content in strawberry fruits through biofortification techniques while maintaining or improving their nutritional value and quality. Studies have shown that exogenous selenium supplementation does not significantly negatively affect strawberry growth and yield but instead promotes selenium accumulation in the fruits (Mimmo et al., 2017). By applying selenium via foliar spray or soil amendment, researchers have successfully achieved effective selenium accumulation in strawberries, laying a solid technical foundation for developing selenium-enriched varieties.

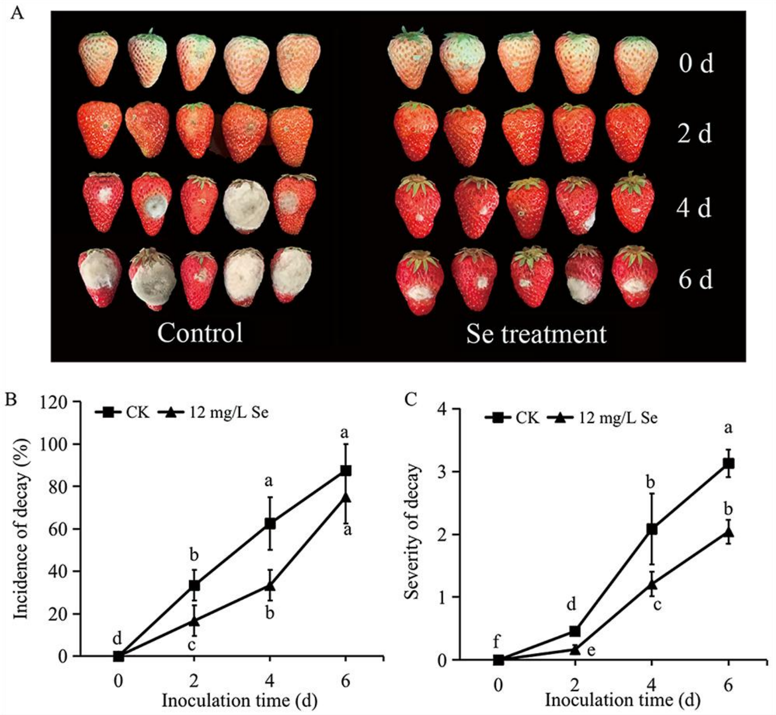

Figure 2 The effects of Se treatment on the defense of strawberries against *B. cinerea*. (A), the symptoms of Se-treated or untreated strawberry fruit infected with *B. cinerea*; (B), the incidence of gray mold decay; (C), the severity of decay. All data were expressed as the mean values ± standard deviation. The letters indicate the statistically significant difference at $p \leq 0.05$ based on the ANOVA analysis with LSD test (Adopted from Lin et al., 2023)

In practice, the effectiveness of selenium enrichment in strawberries varies depending on the form of selenium and the application method. Huang et al. (2023) reported that combined application of selenium and zinc in substrate and soil cultivation significantly increased selenium content in the fruit, with low selenium concentrations (0.006%) yielding more stable results. Selenium not only enhanced the fruit's nutritional value but also improved its antioxidant capacity, providing strong scientific support for the promotion and commercialization of selenium-enriched strawberries.

4.2 Synergistic effects of selenium with other nutrients

The synergistic effects between selenium and other nutrients play a pivotal role in improving strawberry growth and quality. For example, combined application of selenium and zinc not only increased the content of these trace elements in the fruit but also significantly improved its taste and flavor (Huang et al., 2023). Additionally, the combination of selenium and NaHS was shown to mitigate the adverse effects of salt stress on strawberries, with both elements enhancing antioxidant capacity and improving the antioxidant quality and flavor characteristics of the fruit (Pourebrahimi et al., 2023).

The mechanisms behind these synergistic effects may involve the co-regulation of antioxidant enzyme activity and secondary metabolite synthesis within plants. Lin et al. (2024) reported that the combined application of selenium and zinc significantly improved the sweetness and balance of fruit by regulating sugar-acid metabolism, thereby enhancing the overall quality of strawberries. These findings provide a theoretical basis for optimizing multi-element application techniques in strawberry cultivation.

4.3 Promotion and application of selenium in strawberry cultivation

Selenium biofortification technology has seen initial applications in strawberry cultivation, but its large-scale promotion faces several challenges. Existing research indicates that different selenium forms and application concentrations have significantly varied effects on strawberry growth, stress tolerance, and quality (Huang et al., 2023; Lin et al., 2023). Therefore, optimizing selenium application methods-such as foliar spraying, soil amendment, and combined application with other elements-has become a key focus of current research.

Moreover, to ensure the feasibility and economic viability of selenium biofortification in practical agriculture, more field trials are needed to validate laboratory findings. Tailoring selenium application strategies to regional agricultural characteristics can further drive the widespread application of selenium in strawberry cultivation. This approach not only enhances the quality and market value of strawberries but also addresses consumer demand for high-quality selenium-enriched foods.

5 Recent Advances in Selenium Research on Stress Tolerance in Strawberries

5.1 Application of nano-selenium technology in strawberry stress tolerance research

Nano-selenium technology, with its high stability and bioactivity, has shown great potential in enhancing strawberry stress tolerance. Studies have demonstrated that Se-NPs effectively mitigate growth constraints in strawberries under adverse conditions such as salt stress, drought, and diseases by enhancing antioxidant system activity and photosynthetic efficiency (Zahedi et al., 2019; Pourebrahimi et al., 2023). For example, Zahedi et al. (2020) found that Se-NPs reduced oxidative damage in strawberries under salt stress by enhancing antioxidant enzyme activity and osmotic regulation, while also improving fruit quality. Furthermore, Se-NPs significantly increased the content of antioxidants, such as total phenolics and anthocyanins, thereby enhancing the antioxidant capacity and nutritional value of strawberries.

The potential of Se-NPs in disease prevention has also been validated. Zhu et al. (2021) investigated spherical Se-NPs synthesized biologically and found that they significantly suppressed the growth of pathogenic fungi in strawberries, reducing disease incidence and increasing selenium content in the fruits. These findings suggest that nano-selenium technology provides an efficient approach to enhancing stress tolerance in strawberries and offers theoretical support for developing disease-resistant and selenium-enriched varieties.

5.2 Interactions between selenium and plant hormones

The interaction between selenium and plant hormones plays a crucial role in improving strawberry stress tolerance. Selenium regulates the synthesis and signaling pathways of plant hormones, enhancing the physiological response of strawberries to salt stress, heavy metal contamination, and drought (Hasanuzzaman et al., 2020). For instance, under salt stress, exogenous selenium treatment promoted the accumulation of indole-3-acetic acid (IAA) and abscisic acid (ABA) in strawberries, helping to regulate water use efficiency and osmotic adjustment (Zahedi et al., 2019).

Selenium’s interaction with hormones such as ethylene, cytokinins, and jasmonic acid has also shown significant effects. Research indicates that selenium reduces stress-induced leaf senescence by inhibiting excessive ethylene production and promotes strawberry growth and differentiation by increasing cytokinin levels (Lin et al., 2024). These findings provide important insights into the molecular mechanisms of selenium-plant hormone synergy and offer theoretical guidance for optimizing selenium applications in agriculture.

5.3 Molecular regulation of selenium in strawberry stress tolerance

Selenium enhances strawberry stress tolerance not only through physiological improvements but also by regulating molecular mechanisms. Selenium has been shown to enhance antioxidant capacity by modulating the expression of antioxidant enzyme genes. For example, Zhang et al. (2020) reported that Na_2SeO_3 treatment significantly upregulated the expression of SOD, CAT, and APX genes in strawberry leaves, thereby alleviating oxidative damage caused by heavy metal stress.

Selenium’s regulatory effects on secondary metabolic pathways in strawberries have also garnered attention. Metabolomic and transcriptomic analyses reveal that selenium modulates the expression of key enzyme genes involved in the synthesis of polyphenols and flavonoids, thereby enhancing the antioxidant capacity and nutritional value of strawberry fruits (Mimmo et al., 2017; Lin et al., 2024). These molecular studies deepen our understanding of selenium’s mechanisms in enhancing stress tolerance and provide valuable insights for developing more resilient and high-quality strawberry varieties.

6 Case Studies

6.1 Application of the synergistic effects of Se and SiO_2 nanoparticles in enhancing strawberry stress tolerance

Drought stress is a critical factor limiting strawberry growth and yield, and traditional methods struggle to rapidly improve crop drought resistance. In recent years, nanotechnology has gained attention for its efficiency, with selenium (Se) and silicon dioxide (SiO_2) nanoparticles (NPs) showing potential in enhancing crop stress tolerance (Zahedi et al., 2020; Liu et al., 2024). However, the synergistic effects of Se and SiO_2 have yet to be thoroughly investigated.

Zahedi et al. (2020) evaluated the recovery effects of Se, SiO_2, and Se/SiO_2-NPs on strawberry plants under drought stress. The results demonstrated that Se/SiO_2-NPs (100 mg/L) exhibited significant effects in protecting photosynthetic pigments, enhancing the activity of antioxidant enzymes (e.g., peroxidase and superoxide dismutase), and mitigating oxidative stress by reducing H_2O_2 and MDA levels. Additionally, this treatment significantly increased antioxidant components in strawberry fruits, such as total phenolics, anthocyanins, and vitamin C, thereby improving fruit quality and nutritional value (Figure 3).

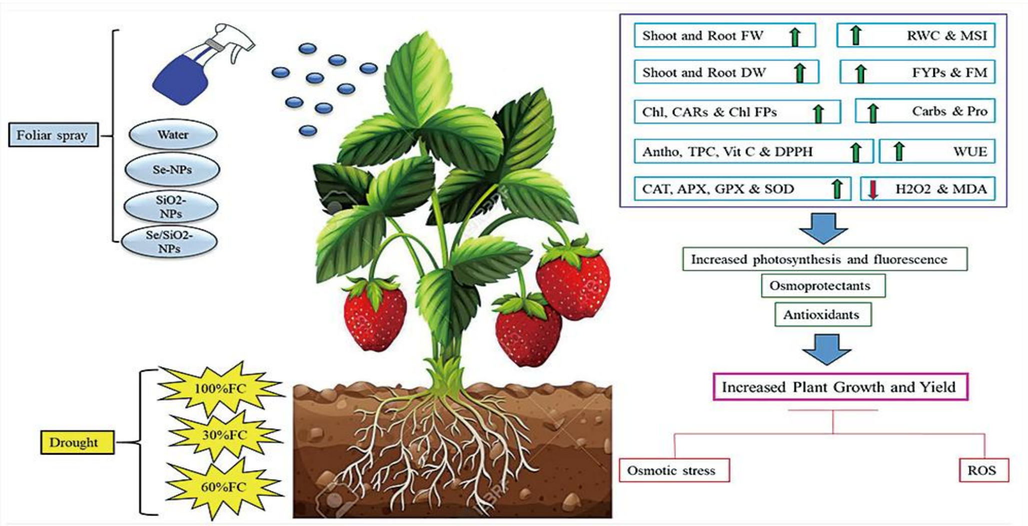

Figure 3 Schematic diagram illustrating the proposed mechanisms of selenium (Se), silicon dioxide (SiO_2) and Se/SiO_2 NPs-induced drought stress tolerance in strawberry plants. Application of Se-, SiO_2- and Se/SiO_2-NPs to drought-stressed strawberry plants could improve growth performance and yield parameters by (i) protecting photosynthetic pigments and chlorophyll fluorescence to improve photosynthetic capacity, (ii) increasing proline and total carbohydrates for greater osmoprotection, (iii) activating antioxidant systems for maintenance of efficient reactive oxygen species (ROS) homeostasis, (iv) enhancing water use efficiency (WUE) level for improvement of root biomass and maintenance of proper osmotic status of the cells, and (v) accumulation of fruit biochemical compounds to increase fruit quality (Adopted from Zahedi et al., 2020)

Compared to the individual use of selenium or silicon dioxide nanoparticles, Se/SiO_2 nanoparticles exhibit a stronger synergistic effect, particularly excelling in improving WUE and membrane stability index (MSI) under drought conditions. By increasing the levels of soluble carbohydrates and proline in leaves, these nanoparticles also enhance osmoprotection. The study suggests that such nanoparticle treatments could serve as a potential solution for managing drought stress in crops; however, further research is needed to validate their feasibility for large-scale agricultural applications.

6.2 The role of selenium in improving strawberry quality

Strawberries are highly favored by consumers for their unique flavor and rich nutritional value. However, environmental stress and insufficient cultivation management often affect the yield and quality of strawberry fruits. Selenium, as an essential trace element, has been proven to play a significant role in enhancing plant stress resistance and increasing the content of secondary metabolites (Huang et al., 2018; Zahedi et al., 2019; Lin et al. 2024). The study comprehensively evaluated the effects of selenium on strawberry growth, antioxidant system, and fruit quality by foliar spraying with different concentrations of sodium selenite (10, 40, 70, 100 mg/L). Results indicated that a 40 mg/L selenium treatment showed the best performance, significantly increasing leaf area, chlorophyll content, and photosynthesis efficiency, as well as improving fruit weight, soluble sugar content, and vitamin C levels (Lin et al., 2024). It also optimized the sugar-to-acid ratio, enhancing the fruit's flavor. Furthermore, selenium treatment regulated sugar and acid metabolism by inhibiting citric acid production and promoting the activity of sugar metabolism-related enzymes (Figure 4).

Additionally, low to medium selenium concentrations significantly enhanced the activities of antioxidant enzymes (such as SOD, POD, and CAT) and reduced MDA levels, effectively alleviating oxidative stress (Lin et al., 2024). These findings suggest that foliar application of appropriate selenium concentrations is not only an effective strategy to enhance strawberry fruit quality but also provides scientific support for selenium's agricultural applications and nutritional fortification, contributing to the advancement of sustainable agriculture.

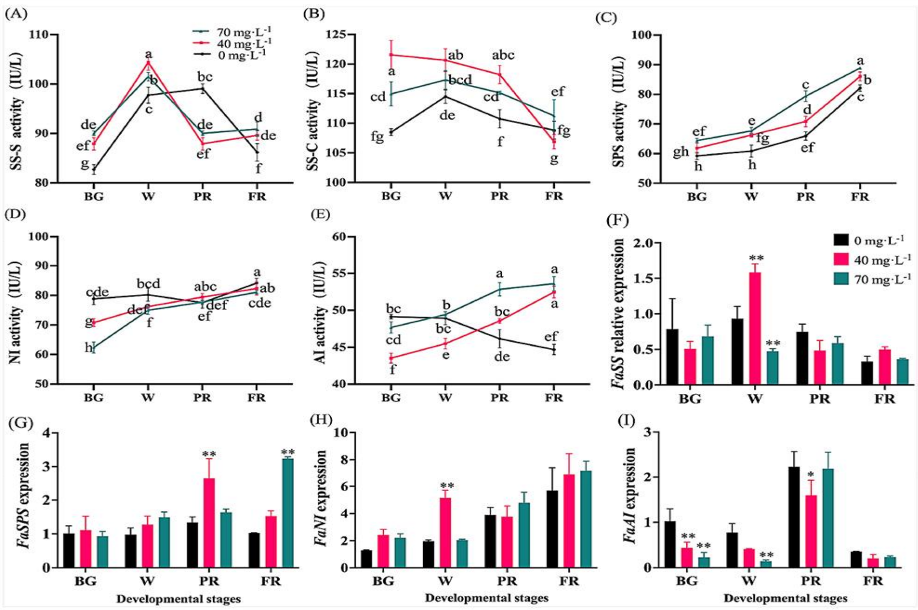

Figure 4 Changes of sugar metabolism-involved enzyme activities and gene expression during fruit development. (A), Sucrose synthase synthesis activity; (B), Sucrose synthase cleavage activity; (C), Activity of sucrose phosphate synthase; (D), Neutral invertase activity; (E), Acid invertase activity; (F), Sucrose synthase gene expression; (G), Sucrose phosphate synthase gene expression; (H), Neutral invertase gene expression; (I), Acid invertase gene expression. BG, W, PR, and FR indicate fruit at the big green, white, partial red, and full red stages, respectively. Columns with error bars represent the mean values of three biological replicates ± standard deviation. The LSD multiple comparisons test was used to compare the differences between control and treatment. The lower-case letters indicate a significant difference at the $P \leq 0.05$ level (Adopted from Lin et al., 2024)

Image caption: The figure illustrates the effects of different concentrations of sodium selenite (Na_2SeO_3) on key enzyme activities involved in sugar metabolism (A-E) and their related gene expressions (F-I) in strawberry fruits. The results show that selenium treatment significantly enhanced the activity of sucrose phosphate synthase (SPS) and acid invertase (AI), promoting bidirectional regulation of sugar metabolism, while the activities of sucrose synthase (SS) and neutral invertase (NI) showed no significant changes. Gene expression analysis revealed that the SPS-related gene (FaSPS) was significantly upregulated in the 40 mg/L and 70 mg/L treatment groups, whereas the expression of the AI-related gene (FaAI) was slightly inhibited. Overall, selenium primarily promoted sugar synthesis and degradation by enhancing the activity of key enzymes in sugar metabolism rather than significantly altering gene expression. This highlights selenium's critical role in regulating sugar metabolism, increasing sugar content, and optimizing flavor quality in strawberry fruits (Adapted from Lin et al., 2024)

7 Challenges and Future Research Directions

7.1 Insufficient research on selenium dosage and safety

The application of Se in enhancing the stress resistance and quality of strawberries has shown promising results, yet significant research gaps remain in determining the optimal dosage and safety of selenium application. Studies indicate that low concentrations of selenium effectively alleviate stress and improve plant quality, while excessive concentrations may cause toxic effects (Zhang et al., 2020; Hasanuzzaman et al., 2022). For example, under cold stress, 5 mg/L sodium selenite was found to provide the most significant stress resistance effects, but higher concentrations could lead to adverse outcomes (Huang et al., 2018).

Future research should focus on conducting field trials tailored to regional characteristics to identify optimal selenium application methods and strategies under varying environmental conditions. Moreover, leveraging modern sensing and monitoring technologies for real-time monitoring of selenium content and its effects throughout the strawberry production process could provide scientific evidence for optimizing selenium application schemes.

7.2 Evaluation of selenium efficiency under different cultivation conditions

The efficacy of selenium in improving strawberry stress resistance and quality may vary significantly under different environmental and cultivation conditions. For instance, studies have shown that selenium nanoparticles can mitigate the effects of salinity and drought stress, promote growth, and enhance fruit quality (Zahedi et al., 2019; 2020; Liu et al., 2024). However, variations in soil type, climate conditions, and cultivation practices may influence the effectiveness of selenium application. In field conditions, regional differences in soil selenium content can lead to inconsistencies in the efficiency of selenium uptake by strawberries (Mimmo et al., 2017). Additionally, the efficiency of selenium absorption and utilization under different cultivation systems, such as soil-based, substrate-based, and hydroponic methods, requires further evaluation.

Future research should emphasize field trials considering regional characteristics to explore optimal selenium application methods and strategies under diverse environmental conditions. The integration of modern sensing and monitoring technologies to achieve real-time tracking of selenium content and its effects throughout strawberry production can provide a scientific basis for refining selenium application schemes.

7.3 Exploration of molecular mechanisms enhancing strawberry quality through selenium

The role of selenium in enhancing strawberry quality has been validated in numerous studies, but the underlying molecular regulatory mechanisms remain inadequately understood. For instance, it is unclear how selenium regulates metabolic pathways to influence the accumulation of sugars, acids, and secondary metabolites in strawberry fruits. In recent years, the application of metabolomics and transcriptomics technologies has provided new avenues for uncovering the molecular mechanisms of selenium action (Lin et al., 2024).

Future research should integrate multi-omics analyses to investigate how selenium regulates the expression of key metabolic enzymes and related genes in strawberries, as well as their interaction networks. Additionally, the synergistic effects of selenium with plant hormone signaling pathways and its regulatory mechanisms on strawberry antioxidant capacity and quality enhancement deserve in-depth exploration. These studies will not only elucidate the molecular functions of selenium but also provide theoretical support for the development of more efficient selenium-enriched strawberry varieties and application techniques.

8 Concluding Remarks

This study systematically analyzed the mechanisms and application progress of selenium (Se) in enhancing strawberry stress resistance and improving fruit quality. The findings indicate that Se effectively mitigates the adverse effects of salinity stress, heavy metal contamination, and drought stress on strawberries by improving plant growth, promoting photosynthesis, enhancing oxidative stress tolerance, and maintaining cellular membrane stability. Under salinity stress, Se strengthens salt tolerance through osmotic regulation and the enhancement of antioxidant systems. In the presence of heavy metal stress, Se significantly reduces toxicity by limiting metal absorption and boosting antioxidant enzyme activity. During drought stress, Se improves drought tolerance by increasing water use efficiency and antioxidant enzyme activity. Additionally, Se biofortification not only enhances the selenium content in strawberries but also promotes the accumulation of functional compounds such as flavonoids and polyphenols, optimizing sugar-acid balance and flavor characteristics.

As a functional trace element, Se plays an indispensable role in strawberry production. Through biofortification techniques, Se not only improves stress resistance in strawberries but also significantly enhances fruit quality and nutritional value, providing critical support for the development of high-value agricultural products. The application of Se enables strawberries to exhibit stronger adaptability under adverse conditions while enhancing fruit market competitiveness to meet the growing consumer demand for selenium-enriched foods. Furthermore, Se promotes strawberry growth and development in extreme environments by regulating metabolic and molecular mechanisms, demonstrating broad agricultural application potential.

Despite the widely recognized benefits of Se in strawberry production, its practical application still faces several challenges that require further optimization and refinement. For instance, it is crucial to focus on the application dosage and safety thresholds of Se under different cultivation conditions to ensure both improved fruit quality and the avoidance of potential toxicity. Optimizing Se application techniques is also essential, such as integrating nanotechnology or leveraging synergistic interactions with other nutrients to enhance Se utilization efficiency and strawberry uptake. Moreover, large-scale field trials are needed to validate laboratory findings and explore best practices applicable to diverse environmental conditions, ensuring the universality and economic feasibility of Se technologies. In-depth investigations into the molecular regulatory mechanisms of Se in improving strawberry quality are equally important. By elucidating key genes and metabolic pathways, targeted improvement of strawberry varieties can be achieved. These initiatives will further expand the application potential of Se in agriculture, providing robust support for sustainable agricultural development and the production of high-quality agricultural products.

Authors' Contributions

ZXL was the primary author of this study, responsible for data collection, analysis, and drafting the manuscript. FCZ was contributed to the study design. ZXH, XS, TZX, ZY, and WHY participated in revising the manuscript. All authors read and approved the final manuscript.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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