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Zinc Gluconate: A Promising Foliar Nutrient for Enhancing Crop Productivity

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Authors' contributions

This work was carried out in collaboration among all authors. Author JU conceptualized the review article, conducted an extensive literature survey, organized the manuscript structure, and prepared the initial and final drafts. Authors SBDS and APP contributed to technical discussions on foliar nutrition, literature analysis, and content refinement. Authors SBDS, AN and PNB assisted in writing specific sections related to zinc metabolism, plant uptake mechanisms, and helped in collecting and organizing references. Authors RKS and NRRL provided critical review, expert guidance on formulation strategies and foliar application practices, and supervised the overall manuscript development. All authors read and approved the final manuscript.

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ABSTRACT

Zinc (Zn) is a crucial micronutrient vital for various physiological and biochemical functions in plants, including enzyme activation, protein synthesis and growth regulation. Zinc deficiency, prevalent in many agricultural regions worldwide, leads to significant reductions in crop yield and quality. This review explores the potential of zinc gluconate as a foliar nutrient to enhance crop productivity. Foliar application, an effective method for addressing micronutrient deficiencies, ensures rapid absorption and utilization by plants, bypassing soil-related issues that limit zinc availability. Zinc gluconate, an organic compound, offers high solubility, stability, and bioavailability, making it a superior alternative to inorganic zinc sources. Studies have demonstrated the efficacy of zinc gluconate in improving yield and quality in various agricultural and horticultural crops, including rice, wheat, maize, cotton and tomato. Additionally, zinc's role in mitigating abiotic stresses such as drought, salinity, and extreme temperatures through enhanced antioxidant defense mechanisms and improved water-use efficiency underscores its significance in sustainable agriculture. The review highlights the benefits of integrating zinc gluconate foliar applications into nutrient management strategies, particularly in organic farming systems where synthetic chelates are restricted. The compatibility of zinc gluconate with other agrochemicals and its low phytotoxicity further enhances its appeal. This review underscores the need for further research to optimize application rates and methods, ensuring maximum benefits across diverse agro-ecological conditions. The adoption of zinc gluconate as a foliar nutrient presents a promising approach to improving crop health and productivity, contributing to global food security and sustainable agricultural practices.

Keywords: Zinc gluconate; foliar application; crop productivity; micronutrient deficiency; sustainable agriculture; abiotic stress; nutrient management.

1. INTRODUCTION

Zinc (Zn) is an essential micronutrient required for numerous physiological and biochemical functions in plants, including enzyme activation, protein synthesis, and growth regulation. Zinc deficiency is a widespread issue affecting crop productivity globally, particularly in calcareous soils, sandy soils, and regions with high pH levels (Alloway, 2008; Cakmak, 2008). The importance of zinc in agriculture cannot be overstated, as it directly influences plant health and yield. According to Hafeez et al., 2013, zinc-deficient plants exhibit stunted growth, chlorosis, and reduced leaf size, ultimately leading to significant yield losses. Soil factors such as low total Zn content, high pH, and elevated levels of calcite, organic matter, Na, Ca, Mg, bicarbonate, and phosphate inhibit Zn availability to plants. Maize is the most affected cereal crop, while wheat on calcareous soils and lowland rice on flooded soils also face severe Zn deficiency. The application of zinc fertilizers is essential for preventing Zn deficiency and enhancing the biofortification of cereal grains (Younas et al., 2023).

Recent studies have highlighted the critical role of zinc in mitigating abiotic stresses such as drought, salinity, and extreme temperatures. Zinc enhances the plant's antioxidant defense system, which protects cellular components from oxidative damage induced by environmental stresses (Cakmak and Kutman, 2018). Zinc plays a crucial role in the synthesis of superoxide dismutase (SOD), an enzyme that detoxifies reactive oxygen species (ROS) generated during stress conditions (Mousavi et al., 2011). Additionally, zinc helps maintain membrane integrity and stability under stress by stabilizing membrane proteins and lipids (Hamzah Saleem et al., 2022).

Furthermore, zinc has been shown to improve the plant's water-use efficiency and root development, which are vital for coping with drought stress (Farooq et al., 2020). Studies have demonstrated that zinc application can enhance the expression of stress-responsive genes, thereby improving the plant's ability to tolerate and recover from adverse conditions (Umair Hassan et al., 2020; Parashar et al., 2023). Moreover, zinc's role in the synthesis of auxin, a plant hormone involved in root development and stress response, underscores its importance in managing abiotic stresses (Hafeez et al., 2013). Hareem et al. (2024) explored the impact of zinc-quantum dot biochar (ZQDB) and proline on chili growth under drought stress, revealing that the combined treatment of

0.4% ZQDB and proline significantly improved plant dry weight, height, fruit yield, chlorophyll content, and nutrient concentration, suggesting its potential as a promising amendment for mitigating drought stress in various crops.

Jafir et al. (2024) highlighted the critical role of zinc (Zn) as an essential micronutrient for plant health, addressing the limitations of its soil availability through the innovative application of Zn nanoparticles (ZnNPs). Their bibliometric analysis, encompassing 6932 records from 2000 to 2020, identified China, India, and Iran as leading nations in ZnNPs research, with a focus on green synthesis methods. Singh et al. (2024) further elaborated on the impact of salinity stress on plant metabolism and the resistance strategies employed by plants, summarizing recent research efforts that demonstrate how zinc oxide nanoparticles can mitigate salt stress by modulating biochemical, physiological, and molecular processes to enhance plant resilience and productivity.

The synergistic effects of zinc in combination with other nutrients and stress management practices further highlight its potential in integrated stress management strategies. For example, foliar application of zinc has been reported to enhance the effectiveness of other micronutrients and improve overall plant resilience (Singh et al., 2024). These findings underscore the significance of zinc in enhancing plant stress tolerance and promoting sustainable agricultural practices.

2. IMPORTANCE OF ZINC FOLIAR APPLICATION

Foliar application of nutrients is an efficient method to quickly correct micronutrient deficiencies and improve crop performance. This technique involves the direct spraying of nutrient solutions onto plant leaves, facilitating rapid absorption through the stomata and cuticle (Fernández et al., 2013; Fageria et al., 2009). Foliar feeding is particularly advantageous for micronutrients like zinc, which can be immobilized in soil and become unavailable to plants due to soil pH, organic matter content, and other factors (Römheld and El-Fouly, 1999; Hafeez et al., 2013). Zinc application to crops, particularly through foliar spraying, has shown positive effects on growth indicators and grain yield in pulses. The application of zinc can enhance protein content, total and active nodule counts, and yield components per plant in crops (Pandey et al., 2024).

Several studies have demonstrated the effectiveness of foliar application in enhancing nutrient uptake and improving yield and quality in various crops. Foliar-applied zinc has been shown to increase grain zinc concentration in wheat, thereby addressing both agronomic and nutritional aspects of zinc deficiency (Zhang et al., 2010). In addition, zn foliar nutrition can complement soil fertilization, providing a quick remedy for nutrient deficiencies during critical growth stages. Zinc biofortification in pulses is essential to combat zinc deficiencies in major food crops, mitigating public health risks (Singh et al., 2025). A recent study found that foliar application of zinc increased the yield and nutritional quality of maize and rice (Singh and Pal, 2024). Ram et al. (2024) explored the impact of foliar application of zinc sulfate heptahydrate on grain zinc concentration in wheat, demonstrating a significant increase in zinc content. The results indicate that foliar application of zinc sulfate effectively enhances grain zinc concentration. Additionally, foliar application of zinc in saline irrigation conditions has been found to enhance plant growth and yield by overcoming root absorption issues, with recommendations for foliar zinc fertilization and the use of the Khatam variety to boost growth indices and barley grain yield under salinity (Mahlooji et al., 2024).

Moreover, foliar application allows for the precise and timely delivery of nutrients, reducing the risk of nutrient leaching and environmental contamination associated with soil applications (Rios et al., 2025). This method also ensures that nutrients are available during periods of peak demand, improving plant health and productivity (Farooq et al., 2020).

3. OVERVIEW OF ZINC GLUCONATE AS A FOLIAR NUTRIENT

Zinc gluconate, an organic zinc compound, has emerged as a promising foliar nutrient due to its high solubility, stability, and bioavailability. The gluconate ion chelates zinc, enhancing its absorption and translocation within the plant. Compared to inorganic zinc sources, zinc gluconate offers several benefits, including reduced phytotoxicity, improved compatibility with other agrochemicals, and better efficacy at lower application rates. Utilizing zinc gluconate in crop production could be a cost-effective and efficient way to enhance plant nutrition (Kumar et al., 2024).

Recent research has focused on the effectiveness of zinc gluconate in various crops. Study by Dhaliwal et al. (2021) reported significant improvements in chickpea yield and fruit quality following foliar application of zinc chelates. Similarly, foliar application of zinc gluconate in maize has been shown to enhance growth parameters and zinc content in grains. Another study indicated that zinc gluconate improved the physiological and biochemical attributes of lettuce, making it a valuable nutrient source for leafy vegetables (Rios et al., 2025). Applying Zn gluconate as a foliar spray could be integrated with PGPR treatments to synergistically improve nutrient uptake and stress resilience, thereby enhancing overall plant health and productivity (Abou Jaoudé et al., 2024).

Gourkhede et al. (2017) conducted an experiment to assess the effects of foliar feeding of gluconate and EDTA chelated plant nutrients on yield, plant pigments, and enzyme activity of Bt cotton under rainfed conditions. The study included sixteen treatments, with foliar applications at flowering and boll development stages. Results showed that zinc gluconate treatment produced the highest boll weight and significantly increased seed cotton yield, while foliar applications of Zn gluconate, Zn EDTA, and Fe gluconate enhanced chlorophyll a, b, and total chlorophyll content. Additionally, Fe gluconate treatment significantly improved plant pigments and enzyme activities, such as nitrate reductase and acid phosphatase, compared to the control.

López-Rayo et al. (2015) found that traditional chelates like DTPA were more effective than gluconate at maintaining higher Zn concentrations in calcareous soil. While gluconate kept both Mn and Zn levels low, novel chelates like S, S-EDDS showed promise for Zn fertilization. The study underscores the need for more stable Mn sources and the potential benefits of using novel chelates for multi-micronutrient fertilization.

Moreover, zinc gluconate's compatibility with sustainable agriculture practices makes it an attractive option for integrated nutrient management strategies. It can be effectively used in organic farming systems, where synthetic chelates are restricted, providing a natural and efficient solution to zinc deficiency (Alloway, 2009). The use of zinc gluconate as a foliar nutrient represents a significant advancement in plant nutrition, offering a practical and effective means to address zinc deficiencies, improve crop productivity, and enhance food quality.

4. CHEMISTRY AND PROPERTIES OF ZINC GLUCONATE

Zinc gluconate, a chelated form of zinc (Fig. 1), has garnered attention as an effective foliar nutrient due to its excellent solubility, stability, and bioavailability. The chelation of zinc ions with gluconate enhances its water solubility and facilitates efficient uptake and mobility within plant tissues. This chelation process ensures optimal distribution and utilization of zinc, which is crucial for various plant metabolic processes (Mousavi et al., 2013). Zinc gluconate appears as a white to off-white crystalline powder, readily soluble in water, making it suitable for liquid formulations and foliar sprays. Its stability under normal storage conditions further supports its use in agricultural applications, providing a reliable source of zinc for enhancing crop growth and productivity.

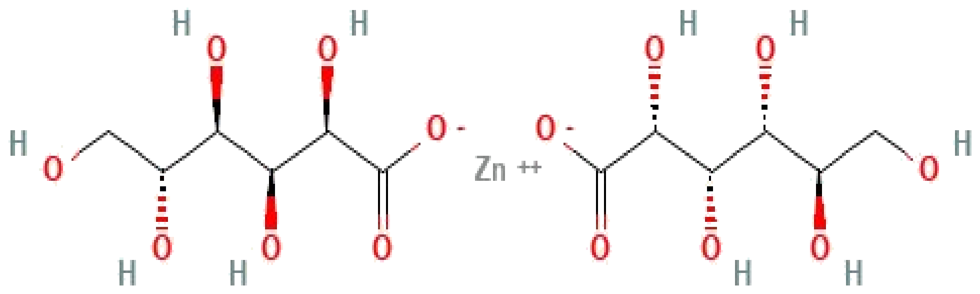

Fig. 1. Chemical Structure of Zinc Gluconate

5. COMPARISON WITH OTHER ZINC COMPOUNDS

Compared to other zinc sources such as zinc sulfate and zinc oxide, zinc gluconate offers several advantages in foliar applications. Firstly, zinc gluconate is less likely to cause phytotoxicity, making it safer for use at higher concentrations without harming plant tissues. Secondly, its organic nature enhances compatibility with other agrochemicals, allowing for tank mixing with pesticides or other nutrients without compromising efficacy. Thirdly, zinc gluconate has been shown to exhibit higher bioavailability and efficiency in improving plant zinc status compared to inorganic zinc sources (Dhaliwal et al., 2021).

6. MECHANISMS OF ACTION

6.1 Absorption and Translocation in Plants

The absorption of zinc gluconate by plants primarily occurs through the leaf surface, where it is absorbed into the epidermal cells through diffusion and active transport mechanisms (Niu et al., 2021). Once inside the leaf, zinc gluconate dissociates into zinc ions, which are then chelated with organic ligands to form stable complexes. These complexes facilitate the translocation of zinc within the plant via the xylem and phloem, ensuring systemic distribution to growing tissues and reproductive organs (Gao et al., 2025; Rios et al., 2025).

Certain plants, known as zinc hyperaccumulators, have developed adaptations that allow them to tolerate and accumulate high zinc levels, utilizing mechanisms like efficient root uptake, enhanced translocation, and detoxification. Zinc gluconate, as a foliar nutrient, leverages these mechanisms to improve zinc uptake and utilization in crops, enhancing growth and productivity while reducing toxicity (Balafrej et al., 2020).

Recent studies have further elucidated the mechanisms underlying zinc gluconate's absorption and translocation in plants. Research by Rios et al. (2025) demonstrated that the gluconate ligand in zinc gluconate enhances zinc's mobility within plant tissues compared to other zinc compounds. This enhanced mobility allows zinc to reach developing plant parts more efficiently, thereby promoting uniform growth and development.

The role of zinc transporters in facilitating zinc uptake and distribution in plants is crucial, as exemplified by Zlobin (2021), who identified specific zinc transporters responsible for the uptake and translocation of zinc from roots to shoots in rice plants treated with zinc gluconate. Their findings highlighted the molecular mechanisms involved in zinc uptake and transport, emphasizing the importance of transporter proteins in regulating zinc homeostasis and enhancing plant nutrient efficiency. Furthermore, Ulhassan et al, (2025), Hall and King (2023) explored the impact of zinc gluconate on the expression of genes involved in zinc metabolism and stress responses in maize. Their study revealed that zinc gluconate application upregulated the expression of genes associated with zinc uptake and translocation, leading to improved plant growth and yield under zinc-deficient conditions. These studies collectively provide insights into the mechanisms by which zinc gluconate enhances zinc uptake, translocation, and utilization in plants, highlighting its potential as an effective foliar nutrient for sustainable agriculture without phytotoxicity.

6.2 Biochemical and Physiological Roles of Zinc

Zinc (Zn) plays a critical role in various biochemical and physiological processes in plants. It is a key component of many enzymes and proteins that are essential for fundamental cellular activities. Zinc-dependent enzymes, such as carbonic anhydrase, alcohol dehydrogenase, and superoxide dismutase, are crucial for photosynthesis, respiration, and antioxidative defense (Broadley et al., 2012). Additionally, zinc is vital for the synthesis of auxin, a plant hormone that regulates growth and development (Marschner, 2012).

One of the primary biochemical roles of zinc is its involvement in the stabilization of ribosomal RNA and the integrity of ribosome structure, which are essential for protein synthesis and cell division (Cakmak, 2008). Zinc also acts as a cofactor for various transcription factors that regulate gene expression and signal transduction pathways. For instance, zinc fingers are structural motifs in proteins that interact with DNA and play a role in transcriptional regulation (Vallee and Auld, 1990).

Recent studies have highlighted the importance of zinc in mitigating oxidative stress by enhancing the plant's antioxidant defense system. Zinc-induced activation of superoxide dismutase (SOD) and catalase enzymes helps in scavenging reactive oxygen species (ROS) and protecting cellular components from oxidative damage (Mousavi et al., 2011). Furthermore, zinc is involved in maintaining the structural integrity of cell membranes and stabilizing membrane-bound proteins, thereby contributing to membrane function and cellular homeostasis under stress conditions (Hafeez et al., 2013).

Zinc also influences nutrient uptake and assimilation in plants. For example, zinc deficiency can impair the uptake of other essential nutrients like phosphorus and iron, leading to imbalances and reduced plant growth (Broadley et al., 2012). The role of zinc in regulating the expression of metal transporters and nutrient homeostasis genes further underscores its importance in maintaining overall plant health and productivity (Sinclair and Kramer, 2012).

6.3 Benefits of Zinc Gluconate Chelation

Zinc gluconate, a chelated form of zinc, offers multiple advantages over traditional inorganic zinc salts, particularly in terms of bioavailability, stability, and efficacy in plant nutrition. The chelation process involves the binding of zinc ions to gluconate molecules, which enhances zinc's solubility and availability for plant uptake. The continuous application of large amounts of Zn chelates to soil has caused concern regarding the possible accumulation of trace elements Zn (Obrador et al., 2003). One of the primary benefits of zinc gluconate chelation is improved solubility in water. Chelated zinc remains soluble across a wide range of pH levels, which is particularly beneficial in alkaline and calcareous soils where zinc availability is often limited (Chahal et al., 2023). This enhanced solubility ensures that zinc remains in a plant-available form, thereby facilitating its absorption by roots and leaves. Inorganic zinc salts tend to form insoluble compounds with soil constituents, which reduces their availability to plants. Chelation with gluconate prevents this precipitation, ensuring that zinc remains in a bioavailable form (Balafrej et al., 2020).

Zinc gluconate also exhibits lower phytotoxicity compared to other zinc compounds. This allows for higher application rates without the risk of damaging plant tissues, making it a safer option for foliar applications (Dabral et al., 2025). Additionally, the chelated form of zinc is less likely to cause leaf burn or other negative effects associated with high concentrations of zinc salts (Mahmoud et al., 2025; Zou et al., 2012).

Recent studies have demonstrated the superior effectiveness of zinc gluconate in enhancing plant growth and yield. For instance, foliar application of zinc gluconate has been shown to significantly increase zinc concentration in plant tissues, leading to improved physiological and biochemical functions. Muthukumararaja et al. (2025) reported that wheat plants treated with zinc gluconate exhibited higher zinc uptake and better growth parameters compared to those treated with inorganic zinc salts. Similarly, Khursheed et al. (2025) found that maize plants treated with zinc gluconate had improved chlorophyll content, photosynthetic efficiency, and overall biomass. Mahdieh et al. (2018) observed that twice foliar application compared to seed application and once foliar application improved growth and yield characteristics of both pinto bean cultivars with improved vegetative characteristics (such as plant height, internode length, root and shoot dry, and fresh weight), yield (pods number and seed weight) and quality (zinc content in seed) of both pinto bean cultivars.

A study conducted by Ahmed et al. (2023) evaluated the impact of foliar application of zinc (Zn) and zinc oxide nanoparticles (ZnO-NPs) chelates on tomato growth, yield, nutrient uptake, and fruit quality. The results demonstrated that foliar application of 100 ppm ZnO-NPs significantly improved growth parameters, yield attributes, and nutrient uptake, achieving the highest yield increment of 200% over the control. The study concluded that ZnO-NPs chelates are more efficient than conventional zinc fertilizers, with 100 ppm ZnONPs being recommended to enhance the quantity and quality of tomatoes in glasshouse conditions.

The chelation of zinc with gluconate also enhances its mobility within the plant. Once absorbed, chelated zinc is more readily translocated to different parts of the plant, including young leaves and reproductive organs, where it is needed the most (Kaur et al., 2025). This efficient distribution of zinc within the plant contributes to better growth, development, and yield.

Moreover, zinc gluconate is compatible with other agrochemicals, including pesticides, fungicides, and foliar fertilizers. This compatibility allows for integrated pest and nutrient management strategies, which can enhance overall crop productivity and reduce the number of applications needed (Ray et al., 2025). In conclusion, the chelation of zinc with gluconate provides several benefits, including enhanced solubility, bioavailability, reduced phytotoxicity, and improved mobility within the plant. These advantages make zinc gluconate an effective and efficient option for foliar fertilization, contributing to better plant health and higher yields.

6.4 Influence of Zinc Gluconate Foliar Application on Microbial Populations in Agricultural Systems

The foliar application of zinc gluconate can influence microbial populations in both the phyllosphere and rhizosphere, with significant implications for plant health. Zinc's antimicrobial properties help reduce pathogenic microbes on leaf surfaces, potentially decreasing foliar disease incidence (Singh et al., 2024). However, it may also impact beneficial phyllosphere microbes, depending on application concentration. In the rhizosphere, zinc can be translocated or washed off into the soil, where it promotes beneficial microbial growth at optimal concentrations but can be toxic at higher levels. Enhanced plant growth due to improved zinc nutrition leads to increased root biomass and exudation, stimulating microbial activity in the rhizosphere (Lowe et al., 2024; Haroon et al., 2022). Additionally, zinc's role in stress resistance supports a healthier microbial community by maintaining robust plant health. While studies have shown zinc gluconate's benefits in reducing foliar pathogens and enhancing soil microbial activity, detailed research on its specific effects on microbial populations remains limited. Proper management of application rates is crucial to avoid negative impacts on beneficial microbes, underscoring the need for further research to understand these complex interactions fully.

7. AGRONOMIC BENEFITS OF ZINC GLUCONATE

7.1 Improved Growth and Development

Research studies have demonstrated that foliar application of zinc gluconate leads to better vegetative growth, increased leaf area, and enhanced root development compared to traditional zinc sources (Ray et al., 2025). For example, foliar application of zinc gluconate in wheat resulted in improved chlorophyll levels, tillering and biomass accumulation, indicating better overall growth (Lisheng et al., 2023; Khursheed et al., 2025). Foliar application of zinc gluconate, especially combined with macronutrients like N, P, or K, significantly increases grain Zn concentration in winter wheat without adverse effects on yield or quality (Shaoxia et al., 2017).

Field experiments have compared the effectiveness of various zinc formulations on wheat growth, including bio-activated zinc-coated urea, zinc-coated urea, and zinc-blended urea (Nazir et al., 2021). These experiments have shown that bio-activated zinc-coated urea, prepared by inoculating organic material with zinc-solubilizing bacteria (Bacillus sp. AZ6) and mixing it with ZnO, significantly enhances growth parameters. The application of 1.5% bio-activated zinc-coated urea led to substantial increases in growth, physiological parameters, and quality, with notable improvements in oil content, protein levels, and nitrogen concentration compared to control treatments. This innovative approach not only boosts plant growth and yield but also contributes to zinc biofortification of wheat, making it a novel, economical, and eco-friendly solution for zinc supplementation in crops (Ali et al., 2021). The application of Zn Gluconate along with other micronutrients influenced the chlorophyll a, chlorophyll b, and total chlorophyll content significantly in the leaves of Btcotton plants (Gourkhede et al., 2017).

A study conducted by Ahmed et al. (2023) evaluated the impact of foliar application of zinc (Zn) and zinc oxide nanoparticles (ZnO-NPs) chelates on tomato growth, yield, nutrient uptake, and fruit quality. The results demonstrated that foliar application of 100 ppm ZnO-NPs significantly improved growth parameters, yield attributes, and nutrient uptake, achieving the highest yield increment of 200% over the control. The study concluded that ZnO-NPs chelates are more efficient than conventional zinc fertilizers, with 100 ppm ZnONPs being recommended to enhance the quantity and quality of tomatoes in glasshouse conditions.

In a field experiment aimed at wheat biofortification, zinc gluconate was evaluated as a source of zinc supplementation, and when applied alongside the recommended nitrogen rate, it effectively increased grain zinc concentrations (Montoya et al., 2020). However, comparative analysis revealed that the rise in grain zinc concentrations was more pronounced with zinc sulphate application. This difference was primarily attributed to the higher recommended application rate of zinc sulphate, which facilitated greater zinc uptake by wheat plants under study conditions (Mousavi et al., 2013).

7.2 Enhanced Yield and Quality of Agricultural and Horticultural Crops

Zinc gluconate not only promotes plant growth but also enhances the yield and quality of various agricultural and horticultural crops. The increased availability of zinc to plants leads to improved flowering, fruit set, and grain filling, which translates to higher yields. In tomato plants, foliar application of zinc gluconate has been shown to increase fruit weight, number of fruits per plant, and overall yield (Muthukumararaja et al., 2025). Similarly, in maize, zinc gluconate application improved kernel weight and yield per hectare. Additionally, the quality of produce is enhanced, with studies showing increased concentrations of essential nutrients and improved post-harvest shelf life (Prasad et al., 2015).

7.3 Stress Tolerance and Disease Resistance in Crops

One of the significant benefits of zinc gluconate application is its role in enhancing stress tolerance and disease resistance in crops. Research has shown that plants treated with zinc gluconate exhibit better stress tolerance, characterized by higher antioxidant activity and reduced oxidative damage under stress conditions (Pasala et al., 2021; Dabral et al., 2025). Moreover, zinc plays a crucial role in enhancing disease resistance by strengthening plant cell walls and activating defence-related enzymes. Studies have reported that zinc gluconatetreated plants have lower incidences of diseases such as powdery mildew and bacterial leaf spot, contributing to better plant health and productivity (Mahmoud et al., 2025).

8. APPLICATION TECHNIQUES

8.1 Foliar Application Methods

Foliar application of zinc gluconate is increasingly recognized as an effective method for delivering zinc directly to plant tissues, thus circumventing potential soil-related issues such as pH imbalance, zinc fixation, and leaching. The technique involves spraying a zinc gluconate solution directly onto the leaves, where it is rapidly absorbed and utilized by the plant. Studies have shown that foliar application can result in quicker and more efficient zinc uptake compared to soil application methods (Ray et al., 2025).

To ensure uniform coverage and optimal absorption, various types of spraying equipment and techniques have been optimized. High-pressure sprayers can improve the penetration and adherence of zinc solutions on leaf surfaces, enhancing the effectiveness of foliar applications. Additionally, the use of adjuvants has been found to enhance the effectiveness of foliar sprays by improving the spreading, sticking, and penetration of zinc gluconate on the leaf surface (Rashid et al., 2020).

Spraying should ideally be done during cooler parts of the day, such as early morning or late afternoon, to minimize evaporation and ensure maximum uptake by the plants. The droplet size and spray pattern are critical factors; finer droplets ensure better coverage but may drift, while coarser droplets reduce drift but may not cover as evenly. The application process should also consider the specific crop and its canopy structure to ensure efficient delivery of the nutrient (Singh et al., 2025).

8.2 Dosage and Timing

Determining the correct dosage and timing of zinc gluconate application is crucial for maximizing its benefits. The dosage often depends on the crop type, growth stage, and existing zinc levels in the soil and plant tissues. Research indicates that lower doses applied more frequently are generally more effective than higher doses applied less frequently. In wheat, a concentration of 0.5% zinc gluconate solution applied at key growth stages— tillering, booting, and grain filling resulted in significant improvements in growth and yield (Mousavi et al., 2011).

Timing of application is equally important. Foliar sprays are most effective when applied at specific growth stages where the demand for zinc is highest. In maize, applications at the V6 stage (six-leaf stage) and at tasseling have shown to be particularly beneficial (Mahmoud et al., 2025; Bhatti et al., 2021). For horticultural

Table 1. Best practices for zinc gluconate application across various crops

Crop	Application Stages	Concentration (%)	Application Method	References
Wheat	crown root initiation, booting, grain filling	0.5	High-pressure sprayer	El-Dahshouri, 2017; Kumar et al., 2022
Maize	V6 stage, tasseling	0.3-0.5	High-volume sprayer	Hisham et al., 2021; Esmaeili et al. 2016
Rice	Early tillering, panicle initiation	0.5	Early morning spraying	Muthukumararaja et al, 2025; Kundu et al., 2020
Cotton	Square formation, boll development	0.3-0.4	High-pressure sprayer	Gourkhede et al., 2017
Soybean	Early vegetative stage, pod filling	0.4	High-volume sprayer	Mousavi et al., 2013
Grapes	Pre-flowering, berry set	0.2-0.3	High-pressure sprayer	Ramya, S.H. and Subbarayappa, 2017
Citrus	Pre-bloom, fruit set	0.4	High-volume sprayer	Hippler et al., 2015
Cucumbers	Early flowering, fruit set	0.3	Fine mist sprayers	Javadimoghadam et al., 2015
Strawberries	Early flowering, fruit development	0.2-0.3	Fine mist sprayers	Bhatti et al., 2021

crops like Kinnow mandarin, foliar application during the flowering and fruit set stages enhances fruit development and quality (Prasad et al., 2015). Timing the applications to coincide with periods of active growth ensures that the plants can effectively utilize the zinc for metabolic and developmental processes (Khursheed et al., 2025).

8.3 Best Practices for Different Crops

The application techniques of zinc gluconate involve precise methods of foliar spraying, correct dosage, and timing tailored to the specific needs of different crops. Adhering to these best practices ensures that the plants receive the maximum benefit from the zinc chelates like zinc gluconate, leading to improved growth, yield, and quality. Different crops have varying requirements for zinc, and application practices must be tailored accordingly. Here are some best practices for the foliar application of zinc chelates across various crops (Table. 1).

In summary, zinc gluconate presents a viable option for enhancing crop productivity through foliar application. Its high solubility, stability, and bioavailability, coupled with its compatibility with sustainable farming practices, make it a promising solution for addressing zinc deficiencies in agriculture. Further research and field trials are essential to optimize application rates and methods, ensuring maximum benefits for various crops under diverse agro-ecological conditions.

9. CONCLUSION

Zinc gluconate has emerged as a promising foliar nutrient, offering significant benefits in enhancing crop productivity and mitigating zinc deficiencies. Its high solubility, stability, and bioavailability make it an effective alternative to traditional zinc sources. The foliar application of zinc gluconate improves nutrient uptake, enhances stress resilience, and boosts crop yield and quality. Studies have demonstrated its efficacy across various crops, indicating its potential to address both agronomic and nutritional challenges in agriculture. The compatibility of zinc gluconate with sustainable farming practices further underscores its value in integrated nutrient management strategies.

Future research should focus on optimizing application protocols, including dosage, frequency, and timing, to maximize the benefits of zinc gluconate. Investigating its synergistic effects with other micronutrients and biostimulants could provide insights into comprehensive nutrient management solutions. Long-term field trials across diverse agroecological zones are essential to validate its effectiveness and economic feasibility.

Additionally, exploring the molecular mechanisms underlying zinc gluconate uptake and translocation in plants can enhance our understanding of its role in plant physiology. These efforts will pave the way for the widespread adoption of zinc gluconate, contributing to sustainable agricultural practices and improved food security.

STUDY HIGHLIGHTS

Zinc gluconate is highly bioavailable and efficiently absorbed by plants, providing a more effective solution to zinc deficiencies than inorganic sources due to its organic chelation, which enhances translocation and uptake.

This formulation is compatible with various agrochemicals and remains stable across different pH levels, minimizing the risk of phytotoxicity and supporting its integration into diverse nutrient management practices.

The application of zinc gluconate significantly improves plant growth, yield, and resilience to abiotic stress, while promoting sustainable agriculture by enhancing micronutrient efficiency and reducing environmental impact, leading to better overall crop performance and long-term productivity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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