# Optimizing Zinc Nutrition for Improved Tuberose (*Polianthes tuberosa* L.) Growth and Flowering

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## ABSTRACT

Tuberose (*Polianthes tuberosa* L.) is a highly valued ornamental and aromatic plant known for its elegant, fragrant white flowers, widely cultivated for use in the floriculture, landscaping and perfume industries. Its commercial success is closely linked to floral quality, yield and the uniformity of blooming, which are strongly influenced by nutrient management strategies. Among micronutrients, zinc plays an indispensable role in various physiological and metabolic processes, including enzyme activation, auxin synthesis, chlorophyll production, protein synthesis and membrane stability. Zinc deficiency, particularly in alkaline and calcareous soils, often leads to stunted growth, poor flower formation, reduced chlorophyll content and overall yield loss, making zinc nutrition a critical factor in tuberose cultivation. Precision zinc fertilization, a component of precision agriculture, offers a promising solution by enabling site-specific, need-based application of zinc using modern tools such as soil testing, GIS mapping, GPS-guided applicators and foliar diagnostics. This approach enhances zinc use efficiency, reduces environmental losses and supports sustainable floriculture practices. The review synthesizes findings from experimental studies evaluating the effects of various zinc sources (e.g., zinc sulfate, zinc-EDTA and nano-zinc) and application methods (soil, foliar and fertigation) on the growth, flowering and tuber development of tuberose. It further examines the challenges associated with adoption, such as farmer awareness, economic feasibility and interaction with other agronomic inputs. The paper concludes by identifying future research priorities, including the need for region-specific zinc recommendations, integration with other micronutrients and biostimulants and the development of smart delivery systems. This comprehensive review aims to provide a foundation for optimizing zinc nutrition in tuberose to enhance productivity and quality sustainably.

## INTRODUCTION

*Polianthes tuberosa* L., commonly referred to as tuberose, is an herbaceous, perennial ornamental plant native to Mexico and now cultivated extensively in tropical and subtropical regions of Asia, Africa and the Americas. It is renowned for its aesthetically pleasing waxy white flowers and its powerful, sweet fragrance, which make it highly desirable for ornamental use in garden landscapes, floral decorations and garlands. Beyond its ornamental appeal, tuberose holds significant value in the perfume industry due to the extraction of essential oils from its flowers, which are rich in aromatic compounds such as eugenol, methyl benzoate and geraniol[1].

As demand for naturally derived floricultural and aromatic products grows globally, the commercial cultivation of tuberose has gained momentum. However, optimizing its yield and quality remains a challenge due to a range of agronomic constraints.

One of the major concerns affecting tuberose cultivation is nutrient imbalance, particularly the deficiency of essential micronutrients. Soils in many floriculture-producing regions, especially those with intensive cropping systems and poor organic matter management, often suffer from micronutrient depletion. Among these, zinc deficiency has emerged as a critical factor limiting the growth, development and productivity of tuberose[2].

Zinc plays a fundamental role in plant metabolic activities, including enzyme activation, protein synthesis, auxin (a plant growth hormone) regulation and photosynthetic efficiency. It also contributes to membrane integrity and disease resistance. Zinc deficiency in tuberose can result in several morphological and physiological disorders such as chlorosis, reduced leaf size, malformed flower spikes and diminished floral longevity. This not only affects visual quality but also compromises market value and post-harvest performance[3].

In response to these challenges, precision fertilization strategies have gained traction in recent years. Precision agriculture, which integrates geospatial technologies, data analytics and advanced nutrient delivery systems, enables farmers to apply inputs such as fertilizers more accurately and efficiently. Precision zinc fertilization is an important subset of this approach, focusing on site-specific, need-based application of zinc through methods such as soil testing, foliar analysis and Variable Rate Application (VRA). By delivering the right amount of zinc at the right time and place, this technique can improve nutrient uptake, reduce environmental losses and enhance overall plant health[4].

Despite its proven efficacy in enhancing growth and yield in various crops, the adoption of precision zinc fertilization in ornamental horticulture, particularly in tuberose, remains limited. A lack of awareness, high initial costs of precision tools and insufficient localized research data are key barriers. Nonetheless, existing studies have shown promising results regarding the use of different zinc sources such as zinc sulfate, zinc-EDTA chelates and nano-zinc particles applied via soil, foliar spray, or fertigation methods[5].

This review aims to bridge the knowledge gap by consolidating current research findings related to zinc nutrition in tuberose. It evaluates application techniques, physiological responses and agronomic outcomes, while also identifying critical research gaps and proposing future directions. The overarching goal is to promote science-based, sustainable zinc management practices in tuberose cultivation to support higher productivity, better flower quality and improved economic returns for growers[6].

## Botanical and agronomic overview of tuberose

**Botanical classification and morphology:** Tuberose (*Polianthes tuberosa* L.), a member of the family Asparagaceae and subfamily Agavoideae, is a monocotyledonous, perennial herbaceous plant prized for its aesthetic and aromatic qualities. Native to Mexico, it thrives in tropical and subtropical climates and is widely cultivated for use in ornamental horticulture and the perfume industry. The plant features a bulbous underground structure composed of tuberous rhizomes that store nutrients and support perennial growth. Its long, narrow, linear leaves grow in a basal rosette and give rise to upright, unbranched flowering stalks. These stalks bear dense clusters of tubular, waxy white flowers renowned for their strong, pleasant fragrance. The flowers bloom sequentially, making tuberose a prolonged source of ornamental and commercial value. Morphologically, tuberose varieties are typically classified into three types: single, semi-double and double based on the number and arrangement of floral petals, which influence both appearance and essential oil yield[7].

**Growth stages and physiological requirements:** Tuberose (*Polianthes tuberosa* L.) progresses through distinct growth stages: sprouting, vegetative growth, floral initiation, flowering and corm maturation. Each phase is characterized by unique physiological and nutritional demands. The vegetative stage is marked by vigorous shoot and leaf development, requiring elevated uptake of macronutrients, especially nitrogen and essential micronutrients like zinc, which is critical for enzyme function, protein synthesis and cell division. During floral initiation and flowering, phosphorus and potassium become increasingly important to support floral differentiation, spike emergence and bloom quality. Zinc continues to play a pivotal role during these stages by enhancing flower formation, size and longevity. Environmental factors such as temperature, light intensity, soil moisture and photoperiod also profoundly affect plant development. Optimal growth occurs under warm temperatures (25-30°C), moderate light and well-drained, slightly acidic to neutral soils. A comprehensive understanding of tuberose's physiological needs at each stage is vital for implementing targeted agronomic practices and maximizing yield and flower quality[8].

**Optimal soil and climate conditions:** Tuberose (*Polianthes tuberosa* L.) performs best in well-drained, fertile sandy loam soils with a neutral to slightly acidic pH ranging from 6.5 to 7.5. Soil structure and nutrient composition significantly influence root development, nutrient uptake and overall plant vigor. Deficiencies in organic matter or essential micronutrients, particularly zinc, can impair physiological functions, leading to stunted growth and reduced floral output. Warm climatic conditions are ideal for tuberose cultivation, with optimal temperatures ranging between 25°C and 35°C. The plant exhibits a strong response to sunlight and requires full sun exposure for robust spike development and enhanced flower production. Although, tuberose demonstrates moderate drought tolerance due to its tuberous root system, consistent soil moisture is essential during the vegetative and flowering stages. However, waterlogging must be avoided, as it can cause bulb rot and adversely affect plant health. These soil and climatic preferences underscore the importance of site selection and irrigation management in maximizing tuberose productivity[9].

**Traditional cultivation practices:** Tuberose (*Polianthes tuberosa* L.) is conventionally propagated vegetatively using bulbs, with manual planting typically carried out at the onset of the growing season. Farmers commonly incorporate organic manure into the soil and apply basal doses of macronutrients such as Nitrogen (N), Phosphorus (P) and potassium (K) to support early plant development. Despite the recognized importance of micronutrients, particularly zinc, their application is frequently neglected in traditional farming systems. Irrigation is applied periodically based on soil moisture conditions, while key cultural practices, including weeding, earthing up and flower harvesting, are performed manually. Although these methods are widely practiced and cost-effective, the absence of precision in nutrient management, especially in micronutrient supplementation, often restricts the crop's yield potential and flower quality. This underlines the need for more targeted and balanced fertilization strategies to address hidden nutrient deficiencies and enhance productivity in tuberose cultivation systems[10].

## Role of zinc in plant physiology

### Importance of zinc in enzymatic and hormonal activities:

Zinc (Zn) is an essential micronutrient required for a wide range of biochemical and physiological functions in plants. It acts as a cofactor for more than 300 enzymes involved in carbohydrate metabolism, protein synthesis and auxin (a plant growth hormone) biosynthesis. Zinc-dependent enzymes such as carbonic anhydrase, alcohol dehydrogenase and superoxide dismutase are critical for maintaining cellular homeostasis and stress tolerance. Moreover, zinc stabilizes the structure of ribosomes and membranes, influencing growth and cell division (Fig. 1)[11].

**Role in photosynthesis, protein synthesis and cell elongation:** Zinc is directly involved in chlorophyll formation and influences the efficiency of photosynthesis by stabilizing the photosynthetic apparatus and protecting it from oxidative stress. It contributes to protein biosynthesis by enhancing RNA polymerase activity and facilitating ribosome function. Additionally, zinc plays a critical role in cell elongation and leaf expansion through its effect on

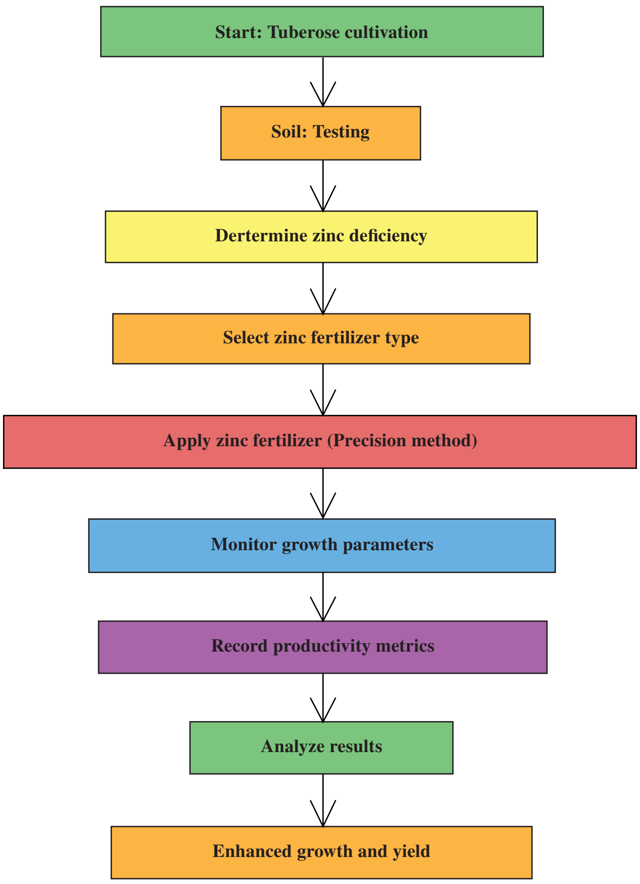


Fig. 1: The Flow diagram shows the role of zinc in plant physiology

auxin metabolism. It regulates internodal elongation, floral initiation and seed development, making it vital during both vegetative and reproductive growth phases[12].

**Zinc deficiency symptoms in plants (including tuberose):** Zinc deficiency is a widespread nutritional disorder in plants, especially in calcareous or alkaline soils with high phosphorus levels, which reduce zinc availability. General symptoms include interveinal chlorosis, reduced leaf size, shortened internodes (rosetting) and stunted growth. In tuberose, zinc deficiency may manifest as poor shoot elongation, pale or mottled leaves, reduced flowering and malformed or undersized floral spikes. Prolonged deficiency can result in decreased biomass and compromised bulb development, ultimately reducing the commercial value of the crop[13].

**Antagonism/synergism with other nutrients:** Zinc interacts both synergistically and antagonistically with other nutrients. High levels of Phosphorus (P) can induce zinc deficiency due to the formation of insoluble zinc phosphate compounds in the rhizosphere. Similarly, excess Calcium (Ca) or Iron (Fe) may compete with zinc uptake. On the other hand, zinc shows synergistic relationships with micronutrients such as Manganese (Mn) and Copper (Cu) when applied in balanced proportions. Understanding these interactions is crucial for optimizing fertilizer formulations and avoiding nutrient imbalances that could affect plant health and productivity[14].

## Zinc nutrition in tuberose: evidence from research

**Impact of zinc on growth, flowering and tuber formation:** Multiple experimental studies have confirmed the pivotal role of zinc in enhancing the vegetative and reproductive performance of *Polianthes tuberosa*. Zinc application has been associated with increased plant height, leaf number, chlorophyll content and flower spike length. Studies have shown that zinc supplementation improves floral yield by increasing the number of florets per spike and extending the blooming period. Furthermore, zinc enhances tuber development by promoting root elongation, nutrient uptake and carbohydrate translocation, ultimately contributing to better propagation material and commercial yield[2].

**Zinc sources in research studies:** Several forms of zinc fertilizers have been evaluated for their efficacy in enhancing tuberose growth and productivity. Among them, zinc sulfate ($ZnSO_4$) is the most commonly used inorganic source, valued for its cost-effectiveness and widespread availability. However, its solubility and effectiveness can be limited in alkaline and calcareous soils due to fixation and reduced plant uptake. To overcome such limitations, zinc chelates, particularly Zn-EDTA (ethylenediaminetetraacetic acid), have been employed. These chelated forms maintain zinc in a soluble and plant-available state, offering improved uptake under challenging soil conditions. Recently, nano-zinc formulations have emerged as innovative and sustainable alternatives. These nanoparticles possess slow-release properties, enhanced absorption efficiency and reduced environmental losses. Research indicates that nano-zinc not only improves photosynthetic activity and chlorophyll content but also enhances flower quality and yield at lower application rates compared to conventional sources. Selecting an appropriate zinc formulation is crucial for site-specific and efficient nutrient management in tuberose cultivation[1].

**Application methods:** Zinc has been applied through various methods in tuberose trials, each with varying levels of efficacy:

- **Soil application:** Provides long-term zinc availability but is prone to fixation in high pH soils
- **Foliar application:** Offers rapid absorption and correction of deficiency symptoms, especially during critical growth stages
- **Fertigation:** Integration of zinc into drip irrigation systems ensures uniform distribution and precision dosing, though less commonly used in tuberose studies.

Integrated application combining soil and foliar treatments has shown synergistic effects, enhancing both growth and flower production[15].

**Dose-response relationships and critical levels:** Research indicates a clear positive dose-response relationship between zinc application and tuberose growth, up to an optimal threshold. Zinc sulfate applied at rates of 5-10 kg/ha has consistently demonstrated improvements in vegetative vigor, flower yield and overall plant health. However, exceeding this range may lead to toxicity or antagonistic interactions with other essential nutrients such as iron and manganese, potentially impairing uptake and physiological functions. Foliar applications of $ZnSO_4$ at concentrations between 0.5 and 1.0% during critical vegetative and flowering phases have proven particularly effective in enhancing zinc availability and uptake efficiency. These sprays are often used to correct transient deficiencies and stimulate flower formation. The critical zinc concentration in tuberose leaf tissue is typically estimated at 20-30 mg/kg dry weight, although this threshold may vary depending on cultivar characteristics, soil pH and background nutrient levels. Accurate diagnosis and calibrated dosing are therefore essential for achieving optimal results in zinc fertilization programs[16].

Table 1: Key Parameters and findings in tuberose under precision zinc fertilization

| Parameter | Treatment (Zinc Source) | Application method | Observed Effect | References |
|---|---|---|---|---|
| Plant height | $ZnSO_4$ (5 kg/ha) | Soil | Increased height by 12-18% | Ashok[17] |
| Leaf number | Zn-EDTA | Foliar (0.5%) | Higher leaf count | Smith et al.[18] |
| Chlorophyll content | Nano-Zn | Foliar | Increased SPAD value | Kanavi et al.[19] |
| Spike length | $ZnSO_4$ | Soil+Foliar | Longer floral spikes | Biswas et al.[20] |
| Number of spikes/plant | Zn-EDTA | Foliar | More spikes per plant | Bhantana et al.[21] |
| Florets per spike | $ZnSO_4$ | Soil | Floret count increased | Yadav et al.[22] |
| Tuber yield | $ZnSO_4$ | Soil | 20–30% increase in tuber weight | Javanmardi and Rasuli[23] |
| Plant biomass | Zn-EDTA | Soil+Foliar | Enhanced biomass | Bahmanzadegan et al[24] |
| Flower quality | Nano-Zn | Foliar | Improved fragrance and petal thickness | Pahi and Rout[25] |
| Leaf area | Zn-EDTA | Foliar | Broader leaves recorded | Luís et al.[26] |
| Photosynthetic rate | Nano-Zn | Foliar | Improved photosynthesis rate | Jalal et al.[27] |
| Zinc uptake efficiency | Zn-EDTA | Soil | Higher Zn content in leaves | Montanha et al.[28] |
| Cost-benefit ratio | $ZnSO_4$ | Soil | ROI improved due to higher flower yield | Noufal et al.[29] |
| Soil zinc content post-harvest | $ZnSO_4$ | Soil | Slight residual increase | Yadav et al.[30] |
| Plant survival rate | $ZnSO_4$ | Soil | Better seedling establishment | Polwaththa and Amarasinghe[31] |
| Flowering initiation time | Zn-EDTA | Foliar | Earlier flowering observed | Dhaliwal et al.[32] |
| Multiplication rate | $ZnSO_4$ | Soil | Higher daughter bulb formation | Vinichuk et al.[33] |
| Market acceptability | Nano-Zn | Foliar | Increased due to improved uniformity | Liu et al.[34] |
| Compatibility with organic inputs | $ZnSO_4$ | Soil | Compatible with compost amendments | Maity et al.[35] |
| Zinc toxicity symptoms | High Zn (>10 kg/ha) | Soil | Leaf burn and stunting | Jeyakumar and Balamohan[36] |
| Synergism with iron | Zn+Fe | Foliar | Improved overall micronutrient uptake | Feizi et al.[37] |
| Precision tech feasibility | All zinc forms | GPS/VRA application | Technically feasible but cost-restrictive | Prom-u-thai et al.[38] |

## Precision zinc fertilization techniques

**Definition and principles of precision agriculture:** Precision agriculture is a modern farming approach that leverages technology and data analytics to manage crop inputs such as water, fertilizers and pesticides with pinpoint accuracy. The goal is to optimize input use efficiency, enhance crop productivity, reduce environmental impact and ensure sustainability. In the context of micronutrient management, precision fertilization refers to the application of the right nutrient, at the right dose, time and location based on spatial and temporal crop needs (Table 1)[39].

**Tools and technologies:**

- **Soil testing, GIS, GPS, remote sensing:** Several tools enable site-specific zinc fertilization
- **Soil testing:** Regular laboratory-based or on-site soil testing identifies zinc availability and helps establish baseline nutrient levels for targeted intervention
- **Geographic information systems (GIS):** GIS maps soil fertility variations and supports the identification of zinc-deficient zones in fields
- **Global positioning systems (GPS):** The GPS-enabled machinery ensures accurate spatial application of zinc fertilizers
- **Remote sensing and drones:** These technologies assess plant health and detect micronutrient deficiencies via vegetation indices such as NDVI (Normalized Difference Vegetation Index), which can indirectly indicate nutrient stress[40]

**Variable rate application (VRA) and site-specific nutrient management:** Variable Rate Application (VRA) technology allows the delivery of zinc fertilizers at different rates across a field based on localized requirements. The VRA systems can be integrated into mechanized sprayers or fertigation setups, ensuring efficient zinc use while preventing over-or under-application. Site-Specific Nutrient Management (SSNM) involves tailoring zinc doses to match the nutrient uptake potential of specific field zones, improving both economic returns and ecological sustainability. In floriculture, where aesthetics and quality matter as much as quantity, SSNM helps maintain uniformity in growth and flowering[41].

**Case studies and examples from floriculture or tuberose trials:** Although, the adoption of precision agriculture in floriculture remains in its nascent stages, early trials have demonstrated encouraging outcomes, particularly in micronutrient management. In tuberose, foliar zinc application tailored through leaf tissue analysis and timed to critical growth phases notably improved spike length and floret count compared to traditional blanket fertilization methods. Similar precision approaches in other floricultural crops have yielded comparable benefits. For instance, in gerbera and marigold cultivation, the use of GIS-based nutrient mapping and Variable Rate Application (VRA) of zinc and iron led to enhanced flower size, pigmentation intensity and postharvest shelf life. Furthermore, studies involving nano-zinc application in gladiolus reported superior zinc uptake efficiency, improved floral attributes and reduced environmental residues, presenting a replicable framework for tuberose production. These findings collectively underscore the transformative potential of precision zinc fertilization in optimizing yield, enhancing ornamental quality and promoting sustainability in tuberose cultivation systems[42].

## Benefits of precision zinc fertilization in tuberose

**Enhanced growth parameters:** Precision zinc fertilization significantly contributes to the vegetative vigor of *Polianthes tuberosa*. Targeted zinc application improves plant height, leaf number and leaf area, which are directly linked to greater photosynthetic capacity. Chlorophyll content is enhanced due to zinc's critical role in chlorophyll biosynthesis and membrane stability, resulting in healthier foliage and robust growth. Precision dosing ensures that the nutrient is available at the right growth stage, optimizing physiological functions and minimizing deficiency symptoms[1].

**Improved flowering characteristics:** Zinc application, particularly through foliar sprays at the right phenological stage, has been shown to boost flower spike production, increase the number of florets per spike and enhance flower size and weight. Flower longevity a critical trait for marketability is also positively influenced due to zinc's role in delaying senescence and promoting hormone regulation. These improvements translate into better aesthetic appeal and extended vase life, which are essential in commercial floriculture[2].

**Increased yield and market quality:** By ensuring adequate zinc availability throughout the growth cycle, precision fertilization enhances both quantitative and qualitative yield. Studies report increased number of spikes per plant, tuber multiplication rate and bulb weight, all of which contribute to the overall productivity of tuberose. Additionally, uniform flowering and improved fragrance intensity enhance the market value and consumer acceptance of the harvested flowers, especially in the cut-flower and perfumery industries[4].

**Resource efficiency and reduced environmental impact:** Precision zinc fertilization ensures maximum nutrient use efficiency, minimizing wastage and runoff losses that commonly occur with blanket applications. By applying zinc in the exact amounts needed, it reduces the risk of toxicity to plants and prevents soil and water contamination. This practice supports sustainable agriculture by conserving inputs and protecting ecological health while meeting the high-quality standards of ornamental horticulture. Furthermore, reduced input costs and enhanced crop value lead to improved economic returns for farmers[43].

## Constraints and challenges

**Limited farmer awareness and adoption in developing regions:** One of the primary constraints to the implementation of precision zinc fertilization in tuberose cultivation, particularly in developing countries, is the limited awareness among farmers regarding micronutrient deficiencies and their impact on crop health and yield. Many small-scale growers still rely on traditional practices and are unfamiliar with the specific role of zinc in plant physiology. Additionally, extension services often lack the technical capacity to promote micronutrient-specific management or train farmers on precision agriculture concepts, leading to low adoption rates despite demonstrated benefits[44].

**Cost and access to precision tools and zinc formulations:** The high initial cost of precision farming equipment such as GPS-enabled sprayers, soil sensors and remote sensing tools poses a significant barrier, especially for resource-constrained farmers. Moreover, advanced zinc formulations like zinc-EDTA chelates and nano-zinc fertilizers are often more expensive and less readily available in local markets compared to conventional zinc sulfate. This financial and logistical challenge limits widespread adoption and forces farmers to continue using inefficient or suboptimal fertilization practices[1].

**Interaction with other agronomic practices:** Precision zinc fertilization must be integrated with other agronomic practices such as irrigation scheduling, organic amendments and macro-nutrient management to be fully effective. However, inconsistent or inappropriate practices in these areas can affect zinc availability in the soil. For instance, over-irrigation may lead to leaching, while excessive phosphorus application can induce zinc deficiency through antagonistic interactions. Similarly, the use of composts or manures with unbalanced nutrient profiles can alter soil pH and microbial activity, influencing zinc solubility and uptake. Without a holistic management strategy, the effectiveness of zinc fertilization may be compromised[45].

## Future perspectives and research gaps

**Need for long-term field studies on economic viability:** While short-term studies have demonstrated the positive effects of zinc fertilization on tuberose growth and yield, there remains a significant gap in long-term, multi-season field trials that evaluate the economic sustainability and cost-benefit ratio of precision zinc application. Such studies are essential to understand the cumulative impact of zinc on soil health, tuber multiplication rates and profitability over successive growing cycles. Comprehensive economic assessments would help convince growers and policymakers of the long-term value of investing in precision micronutrient management[46].

**Development of region-specific zinc recommendation charts:** Zinc requirements vary based on soil type, climate, tuberose cultivar and existing nutrient status. Currently, there is a lack of localized zinc recommendation charts that guide dosage, timing and application method for specific agro-ecological zones. Future research should focus on developing diagnostic tools such as zinc sufficiency thresholds based on soil and tissue testing and translating this data into user-friendly recommendations tailored to regional growing conditions[47].

**Use of nano-fertilizers and smart delivery systems:** Nano-fertilizers, especially nano-zinc formulations, offer promising advantages such as higher absorption efficiency, targeted delivery and minimal environmental impact. However, their application in tuberose cultivation is still in its infancy. More research is needed to determine optimal nanoparticle size, coating materials and release dynamics to maximize efficacy and safety. Furthermore, smart delivery systems including controlled-release formulations and microencapsulation should be explored to improve nutrient uptake while reducing losses due to leaching or fixation[48].

**Integration with other micronutrients and biostimulants:** Zinc does not function in isolation but interacts with other micronutrients such as iron, manganese and boron, as well as with organic compounds like biostimulants and Plant Growth-promoting Rhizobacteria (PGPRs). Integrated nutrient management approaches that combine zinc with other micronutrients and biological agents can synergistically enhance plant health, stress tolerance and productivity. Further research is needed to identify compatible combinations, evaluate their interactive effects and develop integrated packages for sustainable floriculture production[49].

## CONCLUSION

Zinc plays an indispensable role in the growth, development and floral quality of *Polianthes tuberosa L.*, influencing key physiological processes such as enzyme activity, chlorophyll production, hormone regulation and tuber formation. Its deficiency not only limits vegetative vigor but also compromises flowering and overall yield, underscoring the need for targeted zinc management in tuberose cultivation. Precision zinc fertilization, rooted in the principles of sustainable agriculture, offers a scientifically sound strategy to optimize nutrient use efficiency while minimizing environmental impact. Through the integration of soil testing, GIS mapping, foliar nutrition and emerging technologies like nano-fertilizers, growers can address site-specific zinc needs with greater accuracy and effectiveness. To fully harness the benefits of zinc nutrition in tuberose, a shift toward evidence-based and regionally adapted nutrient management strategies is essential. Continued research, farmer training and policy support will be key to translating scientific knowledge into practice. By embracing precision approaches, the floriculture industry can significantly enhance tuberose productivity, quality and profitability in an environmentally responsible manner.

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