

**EFFECTS OF MACRONUTRIENT NANOFERTILIZERS ON THE
GERMINATION OF TOMATO (*Solanum lycopersicum* L.) SEEDS**



BY

Jane Adandu MADUAKOLAM (Miss)

LSC2104160

DEPARTMENT OF PLANT BIOLOGY AND BIOTECHNOLOGY

FACULTY OF LIFE SCIENCES

UNIVERSITY OF BENIN

BENIN CITY

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**A PROJECT THESIS SUBMITTED TO THE DEPARTMENT OF
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CERTIFICATION

We certify that this research work was carried out by **Jane Adandu MADUAKOLAM** of the Department of Plant Biology and Biotechnology, Faculty of Life Sciences, University of Benin, Benin City, Nigeria.

Prof. H.O. Shittu

Project Supervisor

Signature and Date

Prof. B. Ikhajagbe

Head of Department

Signature and Date

Prof. J. Erhabor

--

Project Coordinator

Signature and Date

DEDICATION

This project is dedicated to God Almighty for being a constant source of strength, guidance and motivation.

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ABSTRACT

The increasing global demand for food, coupled with the imperative for sustainable agricultural practices, has driven interest in nanofertilizers as efficient alternatives to conventional chemical fertilizers. This study examined the effects of macronutrient nanofertilizers synthesized from banana peels on the germination of tomato (*Solanum lycopersicum* L.) seed. Macronutrient nanofertilizer was biosynthesized. Five treatment concentrations (0%, 25%, 50%, 75%, and 100%) were evaluated for germination performance, including the first day of germination (FDG), the last day of germination (LDG), the peak period of germination (PPG), the median germination time (MeGT), the mean daily germination (MDG), the time spread of germination (TSG), and the final germination percentage (FGP). The results showed that moderate concentrations (25–50%) improved germination speed and uniformity. The 25% treatment had the earliest FDG (4.5 days), and the 50% treatment had the highest MDG (33.30). In contrast, excessive application (100%) reduces final germination percentage (12%) compared to the control (22%), indicating inhibitory effects at higher levels. The relatively stable LDG across treatments suggested that nanofertilizers primarily influenced initiation and rate of germination rather than completion. Overall, the findings highlight that nanofertilizers can enhance the dynamics of tomato seed germination when applied at optimal concentration, but over-application compromises seed germination. This study underscores the potential of banana peel-based nanofertilizers as a sustainable agricultural input, emphasizing the importance of dosage optimization for improved crop establishment.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Tomato (*Solanum lycopersicum* L.) is one of the most significant vegetable crops cultivated globally due to its high industrial, nutritional and economic value (Kumar *et al.*, 2020). It serves as a rich source of essential minerals, dietary fiber, antioxidants like lycopene, and important vitamins (especially A and C). In addition to its nutritional advantages, tomato production has a major impact on agro-based industries, household income, and food security. However, successful cultivation of tomato largely depends on effective nutrient management, particularly during the early growth stages such as seed germination and seedling establishment. Inadequate nutrient availability at these stages often results in poor germination, weak seedling vigor, and consequently, low yield of crops. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are fundamental to plant growth and development. Nitrogen is essential for vegetative growth and chlorophyll formation, phosphorus promotes root development and energy transfer, while potassium regulates water balance and enhances resistance to biotic and abiotic stresses (Osman *et al.*, 2012). Conventional fertilizers that supply these macronutrients are commonly used to support tomato production; however, they often suffer from inefficiencies such as nutrient leaching, volatilization, and low nutrient-use efficiency (Jat *et al.*, 2011). These restrictions not only lower crop yields but also exacerbate environmental issues like water pollution and soil erosion.

In recent years, nanotechnology has emerged as a promising innovation in agriculture, offering novel approaches to improve fertilizer efficiency and crop productivity (Yadac *et al.*, 2023). Nanofertilizers are fertilizers engineered at the nanoscale to provide controlled nutrient release, enhance nutrient uptake, and minimize losses to the environment. Due to their small particle size, large surface area, and high reactivity, macronutrient nanofertilizers can deliver essential nutrients more effectively to plant cells compared to conventional formulations. Several studies have reported improved germination rate, root elongation, and early seedling vigor in crops treated with nanofertilizers. However, research on their specific effects on tomato seed germination remains limited. A better understanding of how macronutrient nanofertilizers influence tomato seed germination is crucial for optimizing nutrient delivery at the earliest stages of plant development. This study, therefore, aims to evaluate the effects of macronutrient nanofertilizers on the germination and early growth of tomato, providing insights into their potential as a sustainable alternative to conventional fertilizers in tomato production.

1.2 PLANT CULTIVATION

The cultivation of plants began during the era of human civilization and marked a pivotal shift from nomadic hunting and gathering to settled agricultural communities. This major transformation, often referred to as the Neolithic Revolution, started about 10,000 to 12,000 years ago in regions such as the Fertile Crescent, China, and Mesoamerica. It represented one of the most significant steps in human evolution, as the ability to grow and manage crops provided a stable food source and supported the rise of complex societies (FAO, 2020). Early cultivation practices involve the deliberate planting and tending of wild

edible plants, gradually leading to the domestication of species through selective breeding for desirable traits such as larger fruits, higher yields, or improved resistance to pests and diseases (Diamond, 1997). This fundamental change in human-environment interaction laid the foundation for population growth, the establishment of permanent settlements, and the subsequent rise of complex societies.

Plant cultivation, in its broadest sense, refers to the systematic practice of growing and managing plants, primarily for human benefits which include food, fiber, fuel, and medicinal purposes. It encompasses a wide array of activities, from preparing the soil and sowing seeds to irrigation, fertilization, pest control, and harvesting. Modern plant cultivation inculcates principles from various scientific disciplines, including agronomy, horticulture, soil science, genetics, and biotechnology, to optimize plant growth and productivity (Tilman *et al.*, 2002). It transcends traditional farming methods by incorporating advanced scientific knowledge and technological innovations. These approaches are crucial for enhancing crop resilience, nutritional value, and overall productivity, thereby contributing significantly to global food security and sustainable agricultural practices in the face of environmental changes and increasing population demands (Foley *et al.*, 2005).

1.2.1 Role of Plant Cultivation in Food Security.

Plant cultivation plays an indispensable role in ensuring global food security, which is defined as the condition where all people at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2006). Understanding these roles is

paramount to developing innovative solutions for sustainable food systems. The key roles include:

- a) Primary source of nutrition:** Cultivated plants, including cereals (e.g., maize, rice, wheat), legumes, vegetables, and fruits, form the foundation of human diets worldwide, providing essential carbohydrates, proteins, fats, vitamins, and minerals. Without deliberate cultivation, societies would lack a stable and predictable supply of these fundamental dietary components, leading to widespread malnutrition and famine.
- b) Economic stability and livelihoods:** Agriculture, which is built upon plant cultivation, is of major economic importance globally, particularly in developing countries. It provides direct employment and income for billions of people, from farmers and agricultural laborers to researchers and those in food processing and distribution. Stable agricultural production fostered by effective cultivation practices contributes significantly to reduce poverty.
- c) Genetic resource conservation and improvement:** Modern plant cultivation also involves the continuous selection and breeding of crops, inadvertently contributing to the preservation and enhancement of plant genetic diversity. Valuable traits from wild relatives are identified and utilized, integrating them into new varieties improve yield, disease resistance, and adaptability to changing climates, thereby securing future food supplies (Frankel *et al.*, 1981).
- d) Sustainable resource management:** Effective plant cultivation practices are vital for sustainable management of natural resources, including soil and water. Techniques like crop rotation, no-till farming, and precision agriculture, informed by

plant physiological and ecological understanding, help maintain soil fertility, prevent erosion, optimize water use efficiency, and minimize the environmental footprint of food production, ensuring long-term agricultural viability.

- e) **Buffer against environmental stresses and climate change:** Through advanced plant breeding and genetic engineering, plant cultivation enables the development of crop varieties resilient to various abiotic stresses (e.g., drought, salinity, heat) and biotic stresses (e.g., pests, diseases). This adaptive capacity is critical in the face of climate change, allowing agricultural systems to withstand extreme weather events and emergent threats, thus maintaining consistent food production in challenging environments.

1.2.2 Challenges Associated with Sustainable Plant Cultivation

Achieving sustainable plant cultivation faces challenges that encompasses environmental, economic, and social dimensions. Addressing these issues is critical for ensuring long-term food security and ecological balance. These challenges include:

- a) **The impact of climate change:** This leads to increasingly erratic patterns weather; Rising global temperatures, altered precipitation regimes, and more frequent extreme weather events such as droughts, floods, and heatwaves directly threaten crop yields and agricultural productivity worldwide (Ortiz-Bobea *et al.*, 2021; Ray *et al.*, 2019).
- b) **Soil degradation and loss of fertility:** Decades of intensive farming practices, including excessive tillage, monocropping, and reliance on synthetic fertilizers, have contributed to soil erosion, depletion of organic matter, loss of beneficial microbial diversity, and salinization in many agricultural regions (Montanarella *et al.*, 2016).

This diminishes the natural capacity of soils to support healthy plant growth, leading to reduced yields and increased reliance on external inputs, thereby undermining sustainability efforts.

- c) **Water scarcity and inefficient water use:** Water scarcity presents a critical barrier to sustainable cultivation, especially in arid and semi-arid regions. Agriculture accounts for a significant proportion of global freshwater withdrawals, and unsustainable irrigation practices contribute to the depletion of aquifers and surface water bodies (Connor *et al.*, 2020). Furthermore, water pollution from agricultural runoff, laden with nutrients and pesticides, degrades water quality for both human consumption and aquatic ecosystems, highlighting the need for more precise and water-efficient irrigation technologies. (Rosa *et al.*, 2020).
- d) **Pest and disease management:** The evolving challenges in pest and disease management significantly hinder sustainable plant cultivation. The continuous evolution of pests and pathogens, coupled with the widespread development of resistance to conventional pesticides and fungicides, necessitates constant adaptation (Fisher *et al.*, 2018). This puts pressure on agricultural systems to develop integrated pest management strategies, bio-pesticides, and genetically resistant crop varieties to minimize losses while reducing reliance on harmful chemical inputs and preserving beneficial biodiversity.

1.2.3 Techniques for Enhancing Soil Fertility

Various techniques have been applied to enhance soil fertility. These include;

- a) Organic manure and compost:** Organic manures, such as farmyard manure (FYM) and green manures, along with composts, are vital for replenishing soil organic matter, which is the cornerstone of soil health. These materials decompose in the soil, slowly releasing essential macro- and micronutrients in plant-available forms (Goyal *et al.*, 2018). Compost enhances soil health by adding organic material, which enhances soil texture, helps retain moisture, and supports the natural recycling of nutrients. (Singh *et al.*, 2022). Compost amendments stimulate microbial activity by providing essential organic matter and nutrient that support beneficial microbes such as bacteria, fungi and protozoa. (El Hayany *et al.*, 2022). Higher microbial activity helps important soil processes like breaking down nitrogen, releasing phosphorus, and decomposing organic matter, all of which are essential for keeping the soil fertility. (Wie *et al.*, 2024). The application of these organic amendments is a regenerative approach that builds long-term soil resilience.
- b) Crop rotation:** Crop rotation involves systematically changing the type of crops grown in a particular field over successive seasons. This practice is highly effective in improving soil fertility by diversifying nutrient demands and returns. For instance, incorporating leguminous crops (e.g., peas, beans, alfalfa) in the rotation allows for biological nitrogen fixation, enriching the soil with atmospheric nitrogen naturally (Preston *et al.*, 2017). Different root structures of rotating crops can also enhance soil structure, break up hardness, and improve water penetration. Moreover, rotating crops helps in disrupting pest and disease cycles that are specific to certain plant families, reducing the need for chemical interventions and fostering a healthier soil environment (Foyer *et al.*, 2016; Kong *et al.*, 2020).

- c) **Cover cropping:** Cover crops are plants grown primarily to cover the soil rather than for direct harvest as a cash crop. They are typically sown between cash crop cycles or intercropped. Their benefits to soil fertility are numerous: they prevent soil erosion by wind and water, suppress weed growth, and capture residual nutrients that might otherwise leach away, making them available for the subsequent cash crop (Meena *et al.*, 2020). When cover crops are terminated and incorporated into the soil (or left as mulch), they significantly add organic matter, improving soil structure, water-holding capacity, and microbial biomass. Certain cover crops, particularly legumes, also contribute fixed nitrogen to the soil (Adhikari *et al.*, 2021; Blanco-Canqui & Ruis, 2018).
- d) **No-till and reduced tillage practices:** No-till or reduced tillage farming involves minimizing or eliminating mechanical disturbance of the soil, such as plowing and harrowing. By leaving the soil largely undisturbed, this technique helps maintain the soil's natural structure, reduces compaction, and significantly decreases soil erosion by wind and water (Powlson *et al.*, 2014; Verhulst *et al.*, 2020). The undisturbed soil also promotes the accumulation of organic matter, enhances the activity of soil microorganisms, including fungi and bacteria that form stable aggregates, and improves water infiltration and retention (Gajri *et al.*, 2020; Jabro *et al.*, 2020). Over time, no-till systems lead to increased soil carbon sequestration and overall improved soil health and fertility.
- e) **Chemical fertilizers:** Chemical fertilizers, also known as synthetic or inorganic fertilizers, are compounds manufactured to supply essential plant nutrients (primarily nitrogen (N), phosphorus (P), and potassium (K)) in highly concentrated

and readily available forms. These fertilizers are crucial for boosting agricultural productivity, especially in high-demand food systems, by providing a quick and precise nutrient boost to crops. Examples include urea (for nitrogen), diammonium phosphate (DAP) (for nitrogen and phosphorus), and muriate of potash (for potassium). Their high nutrient content and rapid release ability allow for targeted nutrient management, significantly contributing to the high yields seen in modern agriculture, which is essential for sustaining a growing global population (Liu *et al.*, 2021). While chemical fertilizers offer immediate and substantial benefits to crop growth and yield, their long-term and excessive use can present sustainability challenges (Galloway *et al.*, 2008). Over-application can lead to nutrient leaching into groundwater and runoff into surface waters, causing eutrophication and environmental pollution (Ju *et al.*, 2009). Furthermore, the production of nitrogen fertilizers is energy-intensive, relying heavily on fossil fuels, which contributes to greenhouse gas emissions. Continuous reliance solely on chemical fertilizers can also negatively impact soil microbial communities and may not adequately replenish soil organic matter, potentially leading to a decline in soil health over time if not balanced with organic amendments and other sustainable practices (Chen *et al.*, 2019). Therefore, their use must be optimized through precise application methods and integrated nutrient management strategies to maximize benefits while minimizing environmental decline.

1.2.4 Challenges Associated with the Use of Chemical Fertilizers

The widespread reliance on chemical fertilizers has been a fundamental aspect of modern agriculture, dramatically increasing crop yields and feeding a growing global population. However, there are significant challenges associated with its use that poses environmental, economic, and human health impacts. One of the most pressing environmental challenges is the contribution of chemical fertilizers to water pollution. When applied to fields, excess nitrogen and phosphorus, the key components of most synthetic fertilizers, can be washed away by rain into nearby rivers, lakes, and coastal areas. This process, known as nutrient runoff, leads to a phenomenon called eutrophication. Eutrophication causes an excessive growth of algae, or "algal blooms," which deplete the water's oxygen, creating "dead zones" where fish and other aquatic life cannot survive. A 2021 study in the journal *Nature Food* highlighted that agricultural nutrient runoff remains a major driver of aquatic ecosystem degradation globally, with nitrogen and phosphorus from fertilizers being the primary culprits (Lassaletta *et al.*, 2021).

In addition to water pollution, the production and use of chemical fertilizers contribute significantly to greenhouse gas emissions. The manufacturing process for nitrogen fertilizers, in particular, is highly energy-intensive, relying on fossil fuels and releasing carbon dioxide (CO₂) into the atmosphere. Furthermore, the application of nitrogen fertilizers to soil can lead to the release of nitrous oxide (N₂O), a greenhouse gas with a global warming potential approximately 300 times that of carbon dioxide over a 100-year period. A 2022 report by the Intergovernmental Panel on Climate Change (IPCC) emphasized that reducing the use of synthetic nitrogen fertilizers is a critical strategy for

mitigating agricultural sector emissions (IPCC, 2022). From an economic standpoint, the reliance on chemical fertilizers presents a major challenge for many farmers, especially those in developing regions. The cost of these inputs is often volatile and subject to global market fluctuations. This makes small-scale farming highly vulnerable to price shocks, which can severely impact profitability and food security. The high cost of fertilizers also acts as a barrier to entry for new farmers and can trap existing ones in a cycle of debt. A farmer's profit margin is reduced when he uses chemical fertilizers. (Gade *et al.*, 2023). The COVID-19 pandemic and subsequent supply chain disruptions have further exacerbated these issues, leading to sharp price increases that have made fertilizers unaffordable for many producers (FAO, 2023).

Finally, there are growing concerns about the long-term impact of continuous chemical fertilizer use on soil health and biodiversity. While these fertilizers provide essential nutrients, they do not contribute to the organic matter content of the soil. Over time, this can lead to a decline in soil structure, microbial activity, and overall fertility. The overuse of fertilizers can also acidify the soil, making it less hospitable for certain crops and beneficial microorganisms. A review published in *Agronomy* in 2020 pointed out that the long-term application of synthetic fertilizers can disrupt the delicate balance of soil ecosystems, thereby reducing the diversity of soil microbes and compromising the soil's natural ability to support plant growth (Pudasaini & Sapkota, 2020).

1.2.5 Alternative Methods for Improving Soil Fertility Without the Use of Chemical Fertilizers

In the pursuit of sustainable agriculture, the negative impacts of conventional chemical fertilizers have prompted a shift towards alternative methods for enhancing soil fertility.

These approaches aim to improve soil health, increase nutrient availability, and boost crop productivity while minimizing environmental damage.

- a) **The use of organic amendments:** These amendments enrich the soil with organic matter, which in turn improves its structure, water-holding capacity, and microbial activity. These include materials like compost, manure, and green manure (Zafar *et al.*, 2021). The decomposition of these materials releases essential nutrients gradually, providing a steady supply for plants and reducing nutrient leaching (Sadiq *et al.*, 2023).
- b) **Crop rotation and intercropping:** Crop rotation involves growing different types of crops in the same area in sequential seasons, which helps to break pest and disease cycles and replenish specific nutrients in the soil (Mupfupi *et al.*, 2020). For instance, rotating a nitrogen-fixing legume crop with a nutrient-demanding cereal crop can naturally restore nitrogen levels in the soil, reducing the need for synthetic nitrogen fertilizers. Similarly, intercropping, the practice of growing two or more crops in close proximity, can enhance nutrient utilization and suppress weeds, leading to a more balanced and fertile soil ecosystem (Sadeghpour *et al.*, 2023).
- c) **Biofertilizers:** These are products containing living microorganisms that, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere or interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant (Mishra *et al.*, 2022). These represent a significant advancement in sustainable soil management. Examples include nitrogen-fixing bacteria such as *Rhizobium* and *Azotobacter*, which convert atmospheric nitrogen into a form usable by plants, and phosphate-solubilizing bacteria, which make

locked-up phosphorus available to plant roots (Kumar *et al.*, 2021). The application of biofertilizers not only boosts plant growth but also enhances soil biodiversity and improves soil structure over time (Ullah *et al.*, 2023).

d) Nanofertilizers: The emerging field of nanotechnology has introduced nanofertilizers as a promising alternative to chemical fertilizers. These are nano-scale materials that deliver nutrients to plants more efficiently, precisely, and with less waste compared to traditional fertilizers (Khot *et al.*, 2021). Nanofertilizers can be formulated to release nutrients slowly, ensuring a prolonged supply for the plant throughout its growth cycle and minimizing the risk of nutrient runoff into water bodies (Davarpanah *et al.*, 2022). Furthermore, their small size allows them to be readily absorbed by plants, leading to enhanced nutrient use efficiency and reduced application rates (Ibrahim *et al.*, 2023). The targeted delivery and slow-release properties of nanofertilizers make them a highly effective and environmentally friendly approach to improving soil fertility and plant growth (Fayyaz *et al.*, 2021).

1.3 NANOFERTILIZERS

Nanofertilizers are a novel class of agricultural inputs that utilize advanced nanotechnology to address the inefficiencies and environmental challenges associated with conventional fertilizers (Kumar *et al.*, 2021). They are essentially nutrient formulations engineered at the nanoscale, meaning that at least one of their dimensions is between 1 and 100 nanometers (Ibrahim *et al.*, 2023). This minute size imparts unique physicochemical properties to these fertilizers, such as a significantly larger surface area-to-volume ratio, which profoundly affects how they interact with plants and the soil (Davarpanah *et al.*,

2022). The core principle behind nanofertilizers is the controlled and precise delivery of nutrients to crops, which minimizes waste and maximizes nutrient use efficiency (NUE) (Sadiq *et al.*, 2023). Unlike traditional bulk fertilizers that are often lost to leaching, runoff, and volatilization, nanofertilizers can be formulated to release nutrients slowly and steadily over an extended period (Khot *et al.*, 2021). This "smart" delivery system ensures that plants receive the required amount of nutrients at the right time, thereby supporting their growth throughout their lifecycle (Fayyaz *et al.*, 2021). This technology is a cornerstone of precision agriculture, aiming to optimize resource use and boost crop yields sustainably.

1.3.1 Types of Nanofertilizers

Nanofertilizers can be classified in several ways, but a key distinction is based on the type of nutrient they deliver which include; macronutrients and micronutrients. They are both essential for plant growth, but are required in vastly different quantities (Ibrahim *et al.*, 2023). Macronutrients like nitrogen, phosphorus, and potassium are needed in large amounts, while micronutrients such as zinc, iron, and manganese are only required in trace quantities (Sadiq *et al.*, 2023). The development of nanofertilizers addresses the unique challenges of delivering both types of nutrients efficiently.

- a) **Macronutrient nanofertilizers:** These nanofertilizers are designed to deliver essential elements that plants need in large quantities for their primary growth functions. The use of nanotechnology for macronutrients like nitrogen (N), phosphorus (P), and potassium (K) is particularly important because conventional fertilizers for these elements often have very low nutrient use efficiency (NUE) (Davaranah *et al.*, 2022). For example, more than 50% of applied nitrogen from

conventional fertilizers can be lost to the environment through leaching and volatilization. Nano-nitrogen fertilizers, such as nano-urea, are engineered to slowly release nitrogen, significantly reducing these losses and allowing plants to absorb a much higher percentage of the applied nutrient (Ullah *et al.*, 2023).

Similarly, phosphorus fertilizers often become "fixed" in the soil, becoming unavailable to plants (Sadiq *et al.*, 2023). Nano-phosphorus formulations, like nanohydroxyapatite, can overcome this by making the phosphorus more soluble and accessible for plant uptake. Research has shown that these nano-forms can enhance plant growth and nutrient content more effectively than traditional phosphorus sources (Fayyaz *et al.*, 2021). Nano-potassium fertilizers also improve nutrient absorption, strengthening plant tissues and enhancing resistance to stress, which is crucial for overall crop health and yield (Khot *et al.*, 2021). The relevance here is that nanotechnology provides a way to deliver these high-demand nutrients with unprecedented efficiency and reduced environmental impact.

b) Micronutrient nanofertilizers: Micronutrient deficiencies in soil are a global problem that significantly affects crop yield and nutritional quality (Kumar *et al.*, 2021). Since plants only need small amounts of these elements, precise delivery is critical to avoid both deficiency and toxicity. Nanoparticles of micronutrients like zinc oxide (ZnO), iron oxide (Fe_3O_4), and manganese oxide (MnO_2) are highly effective because their small size allows for easy absorption and translocation within the plant (Ibrahim *et al.*, 2023). Foliar application of micronutrient nanofertilizers has been shown to be particularly effective, as the nanoparticles can

penetrate the stomata of leaves and be directly utilized by the plant (Davaranpanah *et al.*, 2022).

These nanofertilizers are crucial for addressing micronutrient deficiencies that often go uncorrected by conventional methods (Sadeghpour *et al.*, 2023). For example, nano-zinc fertilizers can improve maize and wheat yields and increase the zinc content of the grains, enhancing their nutritional quality for human consumption (Zafar *et al.*, 2021). The relevance of these nanofertilizers is that they provide a targeted solution for delivering tiny but essential amounts of nutrients, boosting plant health and crop yield while avoiding the heavy metal accumulation that can sometimes occur with over-application of conventional micronutrient fertilizers.

1.3.2 Mechanism of Action of Nanofertilizers

The high efficacy of nanofertilizers is a result of their unique physical and chemical properties, which allow them to interact with plant systems in a fundamentally different way than conventional fertilizers (Saurabh *et al.*, 2024). The mechanism involves diverse processes of physical absorption, physiological processes, and molecular signaling, all of which are enhanced by the nanoscale size of the particles.

a) Modes of Uptake and Translocation: Nanofertilizers can be applied through two primary methods: soil application and foliar spray. Their nanoscale size allows them to be absorbed efficiently through multiple pathways.

Root Uptake from Soil Application: In the soil, nanoparticles can be taken up by plant roots through two main pathways. The first is passive diffusion through the apoplast, the space between the cell walls of the root cortex (Davaranpanah *et al.*,

2022). The second, and more efficient, is through endocytosis, where the plant cell membrane engulfs the nanoparticles, or via specific membrane transport channels like aquaporins (Rai *et al.*, 2021). The smaller size of the nanoparticles enables them to move freely through the cell wall pores, which typically range from 5 to 20 nm, a size constraint that larger, conventional fertilizer particles cannot overcome (Davaranah *et al.*, 2022).

Foliar Uptake from Spray Application: When applied as a foliar spray, nanofertilizers can enter the plant leaves by penetrating the stomatal pores, which range from 5 to 10 nm in diameter, or through the less-researched cuticular cracks. Once inside the leaf, the nanoparticles are translocated through the plant's vascular system (xylem and phloem) to various parts, including the stem, flowers, and fruits, ensuring an even distribution of nutrients (Rai *et al.*, 2021).

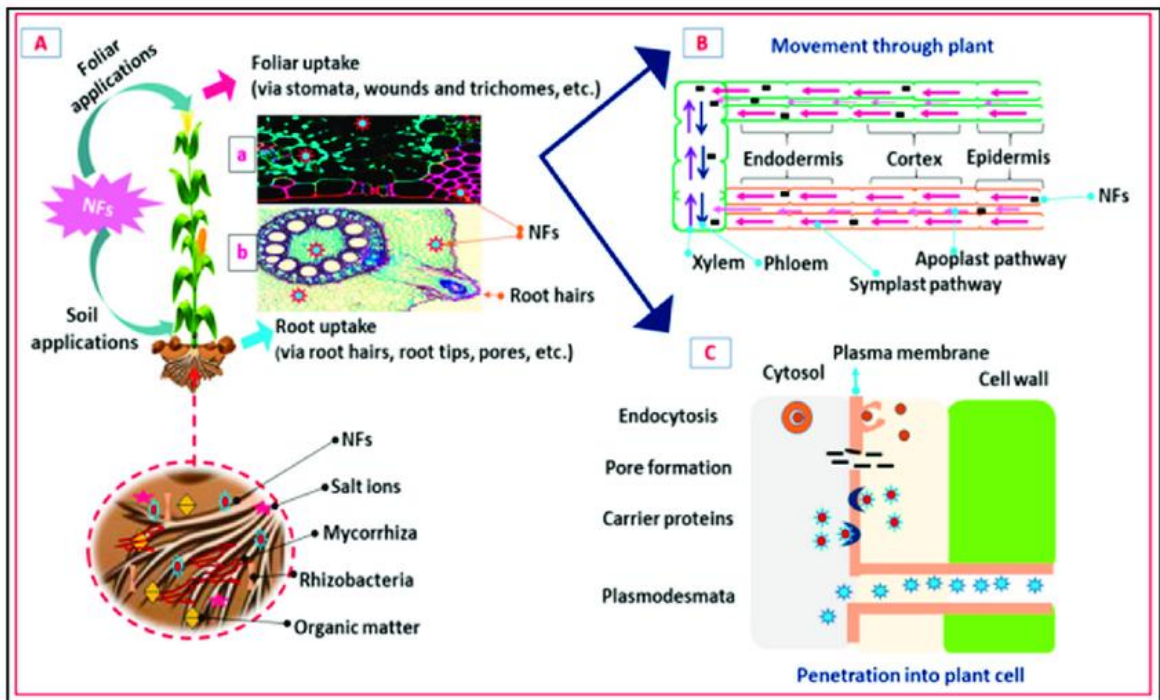


Plate 1.1: The uptake of nanofertilizers (NFs) via various channels and their translocation channels.

- b) Controlled release and bioavailability:** The most significant advantage of nanofertilizers is their ability to provide a sustained supply of nutrients. Many nanofertilizers are designed as slow-release systems, often by encapsulating nutrients in a biodegradable polymer matrix (Fayyaz *et al.*, 2021).

Slow-Release Mechanism: These encapsulated nutrients are released gradually over an extended period in response to environmental cues, such as changes in soil pH, temperature, or the presence of specific root exudates. This controlled release minimizes nutrient loss through leaching, volatilization, and runoff, which is a major problem with conventional fertilizers. It also increases the nutrient use efficiency (NUE) of the plant, as nutrients are available throughout its entire growth cycle, not just in an initial burst (Saurabh *et al.*, 2024).

- c) Physiological and genetic impact:** Beyond simple nutrient delivery, nanofertilizers also have a direct impact on plant physiology and gene expression, leading to enhanced growth and stress tolerance.

Metabolic and Photosynthetic Enhancement: Nanofertilizers can act as catalysts for various metabolic processes within the plant. For instance, nanoparticles of zinc and iron can increase the activity of key enzymes involved in photosynthesis, leading to higher chlorophyll content and improved photosynthetic efficiency (Davaranah *et al.*, 2022). This results in greater biomass accumulation and increased crop yield (Sadiq *et al.*, 2023).

Stress Tolerance and Gene Regulation: Studies have shown that some nanofertilizers can activate plant defense mechanisms and upregulate genes associated with stress tolerance. This allows plants to better withstand abiotic stresses like drought, salinity, and heavy metal toxicity (Kumar *et al.*, 2021). This effect is attributed to the nanoparticles' ability to modulate reactive oxygen species (ROS) and induce the production of antioxidant enzymes, which protect the plant from cellular damage (Mishra *et al.*, 2022).

1.3.3 Benefits of Nanofertilizers

The application of nanofertilizers in plant cultivation offers numerous advantages over conventional methods, leading to enhanced crop productivity, improved sustainability, and reduced environmental impact.

- a) **Increased nutrient use efficiency (NUE):** Nanofertilizers significantly boost the efficiency with which plants absorb and utilize nutrients. The ultra-small size of nanoparticles allows for easier uptake through root and leaf pores, leading to a much higher absorption rate compared to chemical fertilizers (Ibrahim *et al.*, 2023).

Nanofertilizers significantly boost the efficiency with which plants absorb and utilize nutrients. The ultra-small size of nanoparticles allows for easier uptake through root and leaf pores, leading to a much higher absorption rate compared to chemical fertilizers (Ibrahim *et al.*, 2023). Studies have shown that nanofertilizers can enhance nutrient utilization by 20–30%, which is a substantial improvement over the low efficiency of traditional fertilizers (Saurabh *et al.*, 2024). This high NUE means that

less fertilizer is needed to achieve the same or better results, lowering cultivation costs and reducing waste (Fayyaz *et al.*, 2021).

- b) Enhanced crop yield and quality:** By ensuring a steady and targeted supply of nutrients, nanofertilizers can dramatically improve plant growth and overall crop yield. They stimulate key physiological processes, such as photosynthesis and metabolism, leading to increased biomass and higher-quality produce. For example, research on maize has shown that nanofertilizer application can increase grain yield by 22-50%, while applications on rice have shown increases of 30-40% (Saurabh *et al.*, 2024; El-Sheekh *et al.*, 2021). Additionally, the use of micronutrient nanofertilizers like nano-zinc can improve the nutritional content of grains, making them more beneficial for human consumption (Kumar *et al.*, 2021).
- c) Reduced environmental pollution:** One of the most critical benefits of nanofertilizers is their ability to minimize environmental damage associated with conventional farming. The controlled-release mechanism of nanofertilizers prevents the rapid leaching and runoff of nutrients like nitrogen and phosphorus into water bodies (Khot *et al.*, 2021). This reduction in nutrient runoff helps to combat eutrophication, a major cause of water pollution and aquatic ecosystem damage (Sadiq *et al.*, 2023). By requiring lower application rates and reducing nutrient losses, nanofertilizers also contribute to a smaller carbon accumulation and less soil contamination (Saurabh *et al.*, 2024).
- d) Improved plant stress tolerance:** Nanofertilizers can help plants become more resilient to various environmental stresses, including drought, salinity and heavy metal toxicity. The nanoparticles can activate a plant's natural defense systems and

upregulate genes that help it cope with harsh conditions (Davaranah *et al.*, 2022). For instance, nano-silicon has been shown to alleviate drought stress by improving water use efficiency and enhancing antioxidant defense systems within the plant (Kumar *et al.*, 2021). Similarly, the application of certain nanofertilizers has been proven to increase a plant's ability to withstand saline soil, which would otherwise inhibit growth (Saurabh *et al.*, 2024).

- e) **Controlled and sustained nutrient release:** Unlike traditional fertilizers that release a large amount of nutrients at once, many nanofertilizers are engineered to release nutrients gradually over time (Fayyaz *et al.*, 2021). This sustained release ensures that plants have access to a continuous supply of nutrients throughout their growth cycle, preventing both nutrient starvation and the negative effects of over-fertilization (Davaranah *et al.*, 2022). This "smart" delivery system is highly effective in providing the right amount of nutrients at the right time, leading to more consistent and robust plant development (Ibrahim *et al.*, 2023).

1.4 THE TOMATO PLANT (*Solanum lycopersicum* L.)

The tomato plant, scientifically known as *Solanum lycopersicum* L., is one of the most widely cultivated and economically important vegetable crops globally. It is a diploid herbaceous annual or perennial belonging to the Solanaceae family, a diverse group containing over 2,700 species (Mishra *et al.*, 2022). As a globally significant food crop, the tomato is of significance for both fresh consumption and the processed food industry, with an annual production volume surpassing 180 million tons worldwide (Sadiq *et al.*, 2023). The cultivation of this plant has a long history, originating from Western South America,

and it has since become a staple in diets worldwide due to its versatility and nutritional value. Its economic importance is matched by its biological significance; the tomato serves as a model plant for studying fruit development, ripening, and disease resistance, particularly due to its well-characterized genome and a vast collection of genetic resources (Davaranah *et al.*, 2022). Its relatively small genome size and short life cycle make it an ideal subject for genetic engineering and breeding programs aimed at improving crop traits (El-Sheekh *et al.*, 2021).

1.4.1 Scientific Classification of Tomato

Kingdom:	Plantae
Division:	Magnoliophyta
Class:	Magnoliopsida
Order:	Solanales
Family:	Solanaceae
Genus:	<i>Solanum</i>
Species:	<i>lycopersicum</i>
Botanical name:	<i>Solanum lycopersicum</i> L.

Source: (Saurabh *et al.*, 2024).

1.4.2 Importance of Tomato Production

Tomato production is of immense global importance. Economically, it is one of the most valuable vegetable crops, with global trade reaching billions of dollars annually (El-Sheekh *et al.*, 2021). The crop is grown in virtually every country, with major producers contributing to a robust international market for fresh tomatoes and processed products like sauces, pastes, and canned goods (Davaranah *et al.*, 2022). Its versatility allows it to be grown in various systems, from large-scale open fields to controlled greenhouses, which helps to meet consistent consumer demand (Sadiq *et al.*, 2023). From a nutritional standpoint, the tomato is often referred to as a "protective food" due to its rich content of essential vitamins, minerals, and antioxidants (Kumar *et al.*, 2021). It is an excellent source

of Vitamin C and Vitamin A and is particularly known for its high concentration of lycopene, a potent antioxidant that gives the fruit its red color (Saurabh *et al.*, 2024). Lycopene has been extensively studied for its potential to reduce the risk of chronic diseases, including various forms of cancer and cardiovascular disease (Fayyaz *et al.*, 2021). The regular consumption of tomatoes therefore plays a significant role in promoting public health and food security worldwide (Ibrahim *et al.*, 2023).

1.4.3 Importance of Nanofertilizers on the Production of Tomato

The incorporation of nanofertilizers into tomato cultivation is gaining significant importance due to their potential to overcome the limitations of conventional farming and boost production sustainably. Traditional fertilizers often suffer from low nutrient use efficiency, with a large percentage of applied nutrients being lost to the environment (Khot *et al.*, 2021). Nanofertilizers, with their enhanced absorption and slow-release mechanisms, directly address this problem by ensuring that tomato plants receive a continuous and targeted supply of essential nutrients (Saurabh *et al.*, 2024). This improved nutrient delivery leads to more vigorous vegetative growth, increased fruit set, and ultimately, higher yields (Davaranah *et al.*, 2022).

Moreover, the application of nanofertilizers has been shown to enhance the nutritional quality of tomatoes. Studies have documented that nano-NPK and micronutrient nanoparticles can increase the content of key phytochemicals like lycopene and β -carotene, along with vitamins and minerals, making the tomatoes more nutritious for consumption (Kumar *et al.*, 2021; Sadiq *et al.*, 2023). Beyond nutrition, nanofertilizers can also help tomato plants combat both biotic and abiotic stresses. For instance, nanoparticles can

enhance a plant's resistance to pathogens and improve its tolerance to environmental challenges like salinity and drought, which are major threats to global tomato production (Mishra *et al.*, 2022).

1.5 RESEARCH JUSTIFICATION

The research on the effects of nanofertilizers on the germination of tomatoes is highly justified by the pressing need for sustainable and efficient agricultural practices. Conventional farming methods, particularly the reliance on bulk chemical fertilizers, are limited by environmental drawbacks, including soil degradation, water pollution from nutrient runoff, and high production costs (Khot *et al.*, 2021). This study aims to investigate the potential of nanofertilizers as a superior alternative to traditional fertilizers specifically for tomato cultivation. By focusing on the germination phase, a critical period for crop establishment, this research seeks to demonstrate how nanotechnology can improve the fundamental start of the plant's life cycle. The findings will contribute to the growing body of knowledge on precision agriculture and provide a strong evidence base for the adoption of nanofertilizers by farmers. Ultimately, this research is justified by its potential to enhance food security, promote environmental health, and provide a more economically viable solution for tomato production worldwide (Saurabh *et al.*, 2024).

1.6 AIM AND OBJECTIVES

The aim of this study was to evaluate the effects of nanofertilizers on the *in vitro* germination of tomato (*Solanum lycopersicum* L.) seeds.

The objectives of this study were, to:

- a)** Synthesize nanofertilizers using banana peels.
- b)** Apply different concentration of the synthesized nanofertilizers to the tomato plants.
- c)** Collect and evaluate the germination parameters.

CHAPTER TWO

MATERIALS AND METHODS

2.1 MATERIALS USED

2.1.1 Source of Soil Used

The soil sample was collected from Ekosodin farm, Ekosodin, Benin City, Edo state.

2.1.2 Source of Plant Materials

Banana peels used for the synthesis of nanofertilizer were gotten from Ekosodin market, Ugbowo, Benin City, Nigeria.

2.1.3 Source of Chemicals Used

Potassium hydroxide, Urea, Citric acid, Ethanol and Distilled Water, was Purchased from Pyrex Nigeria Limited in Benin City, Edo State, Nigeria.

2.1.4 Source of Seeds.

The Tomato seeds used for the study were gotten from New Benin Market, Benin City, Nigeria.

2.1.5 Equipment Used

Magnetic stirrer, Buchner conical flask, Buchner funnel, Thermostat water bath, Weighing balance, Foil paper, Filter paper, Cotton Wool, Scissors, Syringe, Beakers, Mechanical Blender, Mesh cloth, Spatula, Conical flasks, Beaker, Glass rods, Test tubes, Crucibles, Bowls, Vacuum filter, Petri dishes, Inoculation cabinet, U.V light, Mechanical shaker, pH meter, Laboratory pot, Gas cooker, Weighing scale, Thermometer, Masking tape, Ruler and Measuring cylinders.

2.2 EXPERIMENTAL METHODOLOGY

2.2.1 Synthesis of Nanofertilizers

Four hundred grams(400g) of the banana peels was washed well with tap water to remove the dust and any impurities adhered to the outer surface. The cleaned peels were shredded to small pieces and blended with tap water using a high-speed mechanical blender. The obtained viscous slurry was mixed with 4g of Potassium hydroxide and stirred for 1 minute to get a homogenous slurry. The alkaline blended peel slurry was subjected to boiling with stirring for 30 minutes. After boiling, the slurry was kept for cooling at room temperature to be ready for further processing. The cold slurry was subjected to vacuum filtration using buchner funnel, buchner conical flask and filter paper to get a clear brown filtrate and thick brown sludge. The clear filtrate was heated to about 70 °C with continuous stirring at 300rpm with the use of a thermostat water bath. Urea and citric acid (5% solution) were added dropwise till pH 5 was obtained. The nanofertilizers (plate 2) were stored until required.

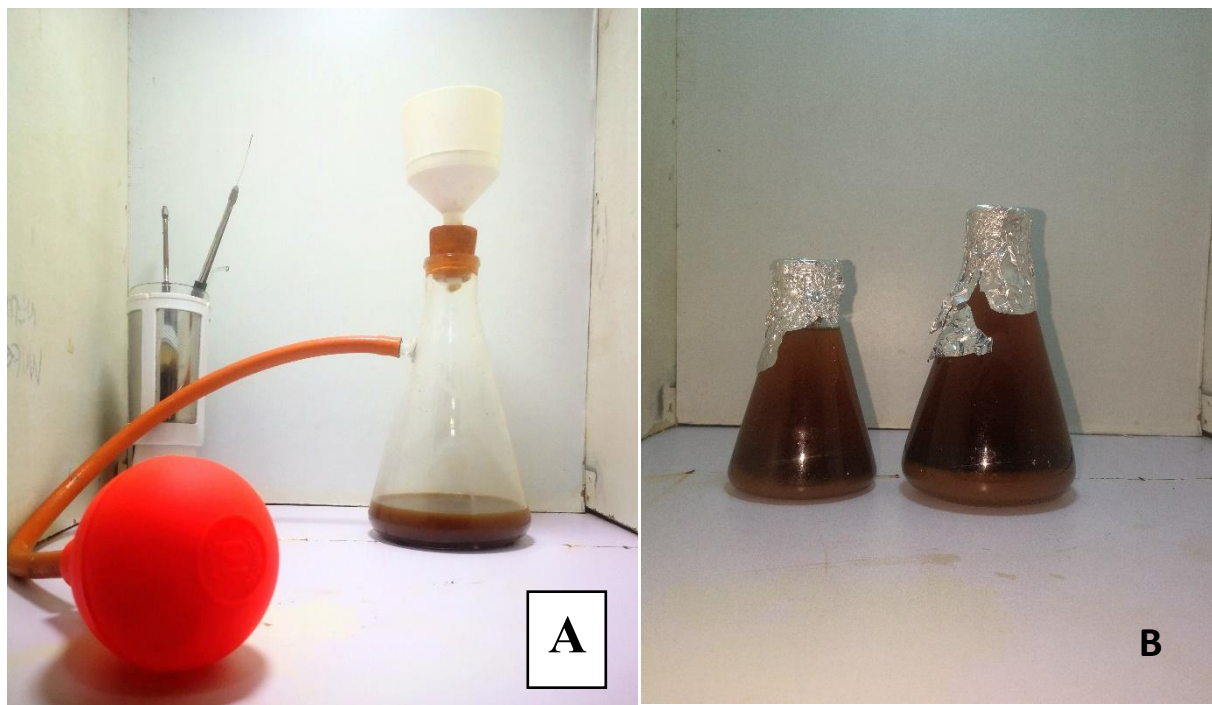


Plate 2.1: Visual representation of synthesized nanofertilizers using banana peels

LEGEND

A: Extraction of nanofertilizer using a Buchner conical flask and vacuum filter

B: Already extracted nanofertilizer stored in conical flasks.

2.2.2 Seed Preparation.

- a) **Viability test:** Prior to the experiment, the viability of tomato seeds was assessed using the water soak test. Seeds were placed in distilled water at room temperature for 30 minutes. Viable seeds sank to the bottom, while non-viable seeds floated. Only the viable seeds were selected for subsequent treatments

- b) Seed surface sterilization:** To prevent microbial contamination during germination, seeds were surface-sterilized. At first, seeds were rinsed under running tap water to remove dust and debris. They were then immersed in 70% ethanol for one minute, followed by rinsing with sterile distilled water for 3 times to remove residual disinfectant. Subsequently, seeds were soaked in 1% sodium hypochlorite solution for five minutes and rinsed 3–4 times with sterile distilled water. This sterilization procedure was to ensure that the observed effects on germination could be attributed only to the nanaofertilizer treatments.
- c) Seed priming:** Viable sterilized seeds were subjected to nanofertilizer priming at different concentrations: 100%, 75%, 50%, 25%, and 0% (control) for four hours at room temperature. After priming, seeds were drained and blotted dry using sterile filter paper to remove excess solution before sowing.

2.2.3 Seed Germination Setup

The experiment was divided into five groups, each with the different nanofertilizer treatments at concentrations: 100%, 75%, 50%, 25%, and 0% (control). Each treatment was replicated twice, with ten seeds per replicate, twenty seeds per treatment in total. The experiment was conducted under controlled laboratory conditions, maintaining consistent temperature, humidity, and light to minimize environmental variability. Primed seeds were placed on sterile, moistened Whatman filter papers in Petri dishes. Filter papers were regularly moistened with distilled water to maintain adequate moisture levels. The Petri dishes were incubated at a controlled environment with a 12/12 hr. light/dark cycle at 25–28°C. Germination was monitored daily for seven days. A seed was considered to be

germinated when the radicle was visible. Key parameters recorded included germination percentage, mean germination time, daily germination speed and other relevant germination indices.

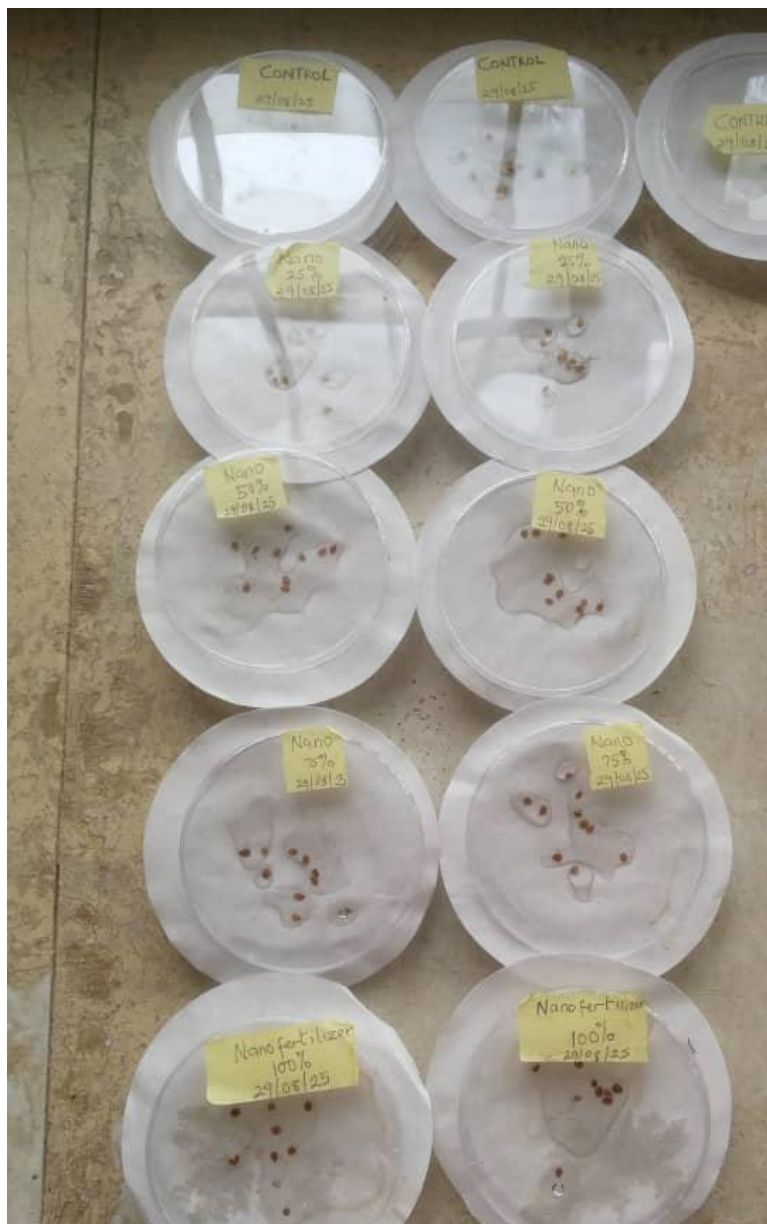


Plate 2.2 First day of germination of tomato seeds after treatment with nanofertilizer.



Plate 2.3 Effect of nanofertilizer on last day of germination of tomato seeds.

CHAPTER THREE

RESULTS

The effect of nanofertilizer treatment concentration on the germination timing of tomato seeds was evaluated by measuring the first day of germination (FDG) and last day of germination (LDG) across five different treatment concentrations (100%, 75%, 50%, 25%, and 0%). Analysis of the data revealed that LDG values remained relatively constant at higher concentrations (75%, 50%, and 0%), with approximately 10 days recorded. However, a reduction in LDG was observed at the highest concentration (100%) and at 25%, with values of approximately 5.5 and 9.5 days, respectively. Conversely, FDG values showed marked variation depending on nanofertilizer concentration. The earliest germination occurred at 25% concentration, with an FDG of approximately 4.5 days, indicating that this concentration promoted a faster initiation of germination compared to the others. Higher concentrations (100%, 75%, and 50%) resulted in significantly delayed FDG values, ranging from approximately 0.5 to 1.5 days. The absence of nanofertilizer (0% concentration) showed an FDG similar to that of 50%. These results suggest that moderate nanofertilizer concentrations (around 25%) enhance the speed of germination initiation in tomato seeds, while very high or zero concentrations do not notably improve or may even delay the onset of germination. The relatively stable LDG across treatments indicates that the completion of germination is not substantially affected by concentration.

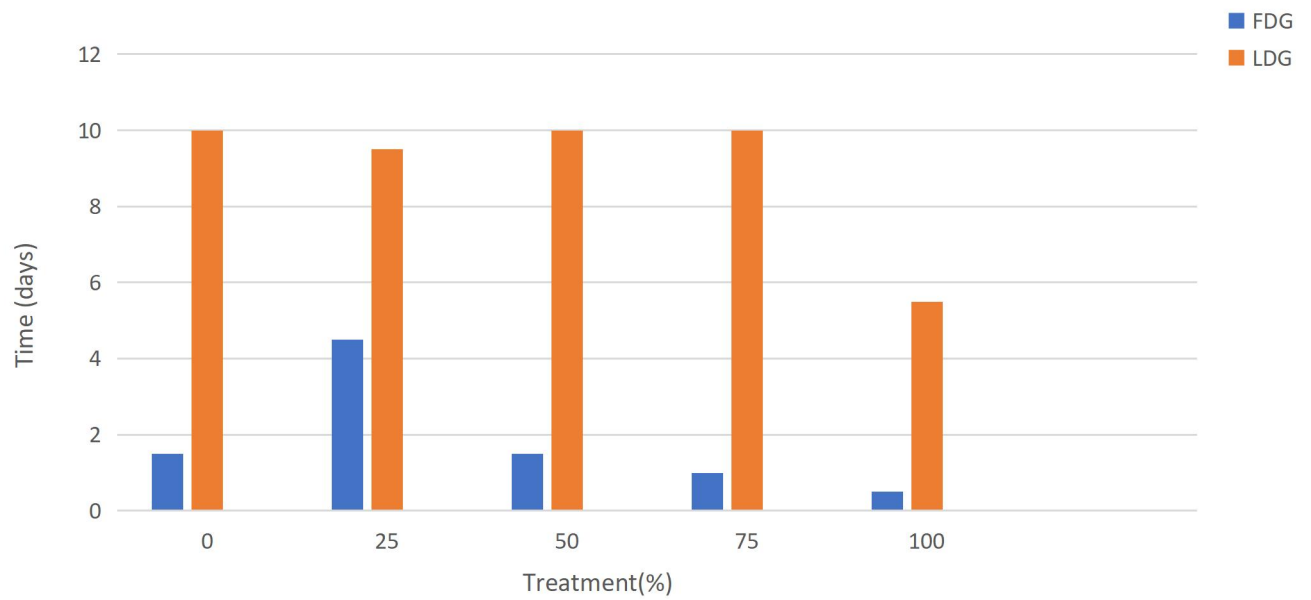


Figure 3.1: Effect of nanofertilizer concentration on the first and last days of germination of tomato seeds.

LEGEND

FDG – First Day of Germination

LDG – Last Day of Germination

The effect of nanofertilizer application on the germination percentage of tomato seeds by determining the final germination percentage across different treatment groups, as visually summarized in Figure 3.2. The experiment included five groups corresponding to the following nanofertilizer concentrations: 100%, 75%, 50%, 25%, and 0% (control). A pie chart was utilized to visually compare the final germination percentages among the treatment groups. The data reveals slight variations in germination rates with respect to the nanofertilizer concentrations, detailed as follows:

100% Nanofertilizer: Seeds subjected to the highest concentration of nanofertilizer exhibited a germination rate of 12%. This comparatively low value suggests that excessive application of nanofertilizer may inhibit the germination process.

75% Nanofertilizer: In this group, the germination percentage was observed to be 22%, indicating an improvement over the 100% concentration.

50% Nanofertilizer: This concentration also resulted in a germination percentage of 22%, suggesting that a moderate reduction from higher concentrations does not adversely impact seed germination.

25% Nanofertilizer: The 25% nanofertilizer group had a germination percentage of 21%, which is similar to the 50% and 75% groups, illustrating a relatively stable response in this concentration range.

0% Nanofertilizer (Control): The control group, which did not receive any nanofertilizer, achieved the highest germination percentage of 22%. This finding highlights the need for careful consideration regarding the optimal dose of nanofertilizer, as excessive application may not provide additional benefits and may even reduce seed germination relative to the untreated control. The data indicate that tomato seed germination generally remained consistent across most nanofertilizer concentrations except for the highest concentration tested (100%), which resulted in a lower germination rate. These results suggest that while nanofertilizer application at moderate concentrations (25%–

75%) does not negatively affect germination compared to the control, excessive amounts may inhibit this critical developmental stage. Therefore, optimization of nanofertilizer application is pivotal to avoid reduced seed viability and maximize agricultural output. Figure 3.2 clearly demonstrates that judicious use of nanofertilizer is key to sustaining healthy tomato seed germination, as both over-application and under-application have distinct impacts on germination percentages as seen in the presented data.

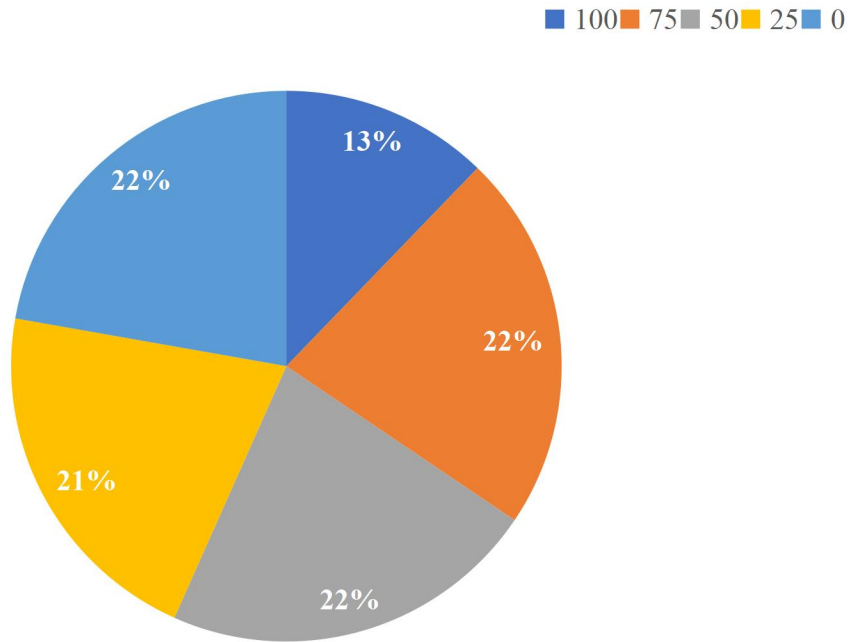


Figure 3 1:Final germination percentage of tomato seeds treated with nanofertilizer after five days.

The germination parameters presented in table 3.1 for tomato seeds exposed to five different treatments of nanofertilizer, reported as Peak Period of Germination (PPG), Median Germination Time (MeGT), and Mean Daily Germination (MDG). These metrics are critical for evaluating the temporal dynamics and efficiency of germination as affected by varying nanofertilizer levels. The treatments examined included nanofertilizer concentrations of 100%, 75%, 50%, 25%, and 0% (control). Peak Period of Germination (PPG) measures the time corresponding to the highest daily germination count. The highest PPG value was recorded for the 75% nanofertilizer treatment (9.50 days), followed by the 25% (6.50 days) and 50% (6.00 days) concentrations. The lowest PPG values occurred in the 100% and control (0%) groups (5.50 days each), indicating that moderate levels of nanofertilizer may delay the germination peak compared to no fertilizer or excessive fertilizer. Median Germination Time (MeGT) reflects the time by which half of the seeds have germinated. The trend in MeGT mirrors that of PPG, with the 75% treatment again requiring the longest median time (9.50 days), while other groups aggregated between 5.50 and 6.50 days. This finding suggests that high concentrations or the absence of nanofertilizer do not prolong the median germination time. Mean Daily Germination (MDG) reveals the average number of seeds germinated per day within each treatment. The greatest MDG was measured in the 50% nanofertilizer group (33.30), indicating optimal daily germination at moderate nanofertilizer concentration. The lowest MDG was found in the 100% group (18.30), with intermediate values in the 75%, 25%, and control groups (25.00, 23.75, and 20.00, respectively). The results illustrate that the application of nanofertilizer impacts both the timing and rate of tomato seed germination. While moderate nanofertilizer (50%) yields the highest mean daily germination, higher concentrations (75% and 100%)

increase the peak period and median germination times, indicating delayed germination. The data suggest an inverted U-shaped response curve, where optimal germination parameters are achieved at intermediate nanofertilizer levels, while both under- and over-application are less effective for daily germination rates.

Table 3.1: Germination parameters represented by peak period, median time and mean daily germination.

Treatment (%)	PPG	MeGT	MDG
0	5.50	5.50	20.00
25	6.50	6.50	23.75
50	6.00	6.00	33.30
75	9.50	9.50	25.00
100	5.50	5.50	18.30

LEGEND

PPG – Peak Period of Germination

MeGT -- Median Germination Time

MDG – Mean Daily Germination

Figure 3.3 presents the time spread of germination (TSG) for tomato seeds across various concentrations of nanofertilizer. The TSG parameter reflects the duration, in days, over which germination events occurred within each treatment group. This parameter offers insight into the uniformity and synchronicity of germination responses as influenced by nanofertilizer application.

The bar chart compares the TSG for groups with nanofertilizer concentrations of 100%, 75%, 50%, 25%, and 0% (control): 100% Nanofertilizer: The time spread of germination was observed to be 5 days, indicating a relatively narrow germination window at the highest fertilizer concentration.

75% Nanofertilizer: The TSG increased to 9 days, representing the widest germination window among all treatment groups. This extended duration suggests a more staggered germination process under this treatment.

50% Nanofertilizer: The TSG was recorded at 8 days, similar to the 75% treatment, indicating notable variation in germination timing among seeds.

25% Nanofertilizer: The TSG at this concentration returned to 5 days, matching the value at 100% nanofertilizer, which implies more synchronized germination.

0% Nanofertilizer (Control): The control group showed a TSG of 8 days, suggesting a broader spread of germination in the absence of nanofertilizer. These findings

reveal that both very high (100%) and relatively low (25%) concentrations of nanofertilizer produce the most synchronized (narrowest spread) seed germination, with all seeds emerging within a 5-day window. In contrast, intermediate concentrations (75% and 50%)

as well as the control group exhibit wider germination spreads of 8 to 9 days, indicating less uniformity and potentially less predictability in the seedling emergence process. This pattern

suggests that nanofertilizer concentration not only affects the overall percentage and rate of

germination, but also the time frame over which germination occurs. Highly synchronized germination (short TSG) is often desirable for agricultural management, as it can lead to more uniform crop establishment and easier scheduling of subsequent cultivation practices. Consequently, these results point to the importance of optimizing nanofertilizer application rates to achieve the desired balance between total germination, germination rate, and germination uniformity for efficient crop production.

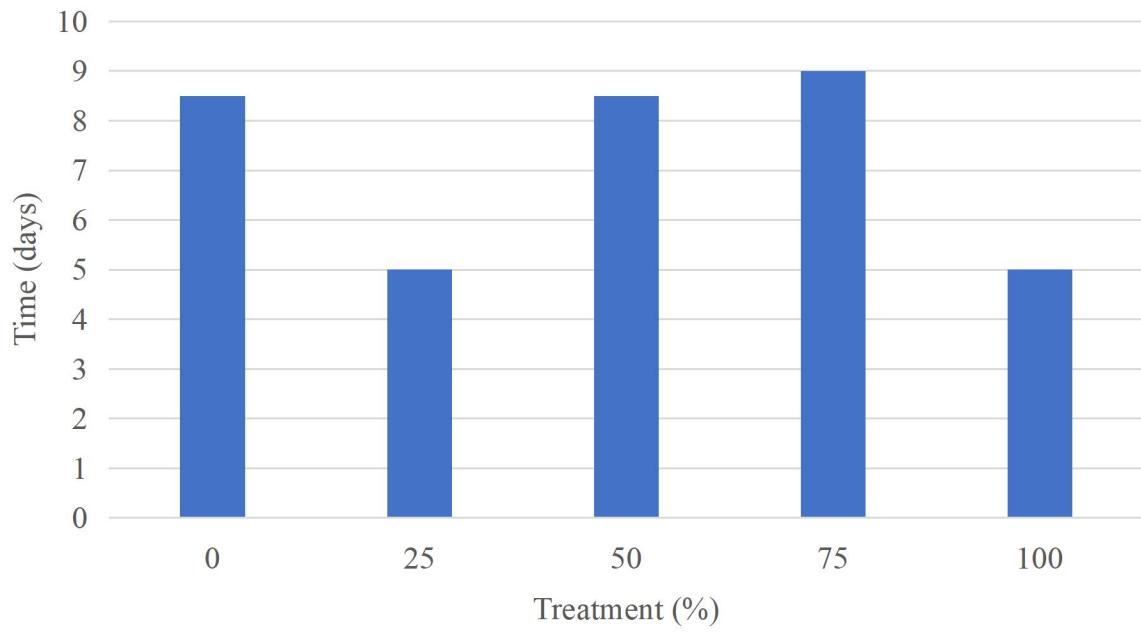


Figure 2.3: Time spread of germination of tomato seeds treated with nanofertilizers after five days.

Figure 3.4 illustrates the distribution of daily germination speeds of tomato seeds under the experimental conditions involving nanofertilizer treatment. The pie chart categorizes the seeds based on their relative germination speed percentages: 0%, 25%, 50%, 75%, and 100%. The data reveals that 24% of the tomato seeds achieved a germination speed of 100%, indicating a full and rapid germination response. Another 24% of the seeds did not germinate at all during the observation period, representing a 0% germination speed. Seeds with intermediate germination speeds comprised 54% of the sample, with 19% germinating at 75%, 14% at 50%, and 19% at 25%. These results suggest that the nanofertilizer treatment elicited a variable effect on the germination behavior of tomato seeds. While a significant portion of seeds responded positively with optimal germination speeds, a comparable fraction failed to germinate, and the remainder showed moderate germination rates. This heterogeneity in germination outcomes may be attributed to factors such as seed viability differences, variable absorption or efficacy of the nanofertilizer, or environmental influences during the experiment.

Overall, the findings indicate that nanofertilizer has the potential to enhance germination rates in tomato seeds, but the variability observed underscores the need for further optimization of the treatment dosage and application methods to improve consistency in germination performance. Additional quantitative analyses, including germination rate index or mean germination time, are recommended to better characterize the influence of nanofertilizer on seed germination kinetics.

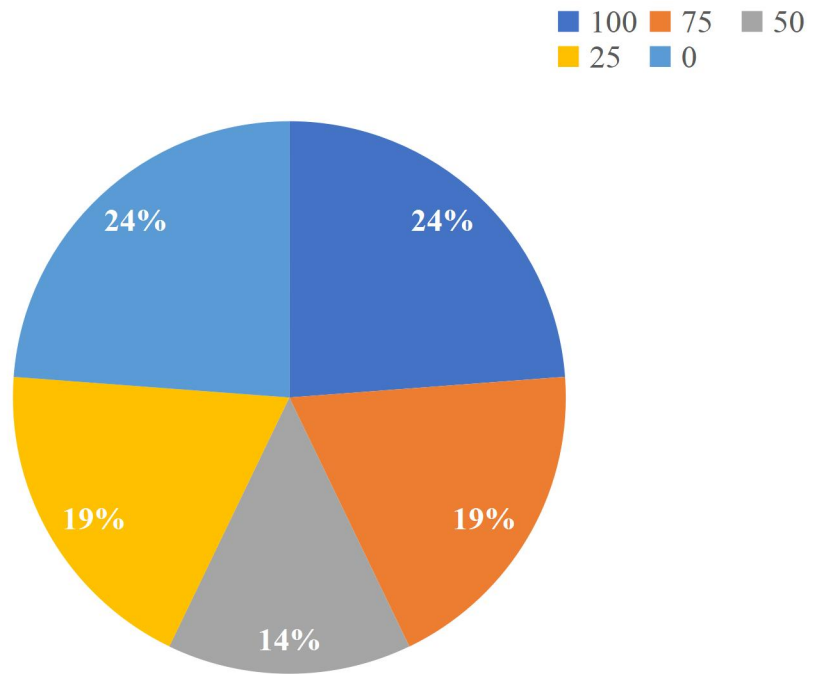


Figure 3.3: Daily germination speed of tomato seeds treated with nanofertilizer after five days.

CHAPTER FOUR

DISCUSSION

This study evaluated the effects of macronutrient nanofertilizers, synthesized from banana peels, on the germination of tomato seeds (*Solanum lycopersicum* L.). The results revealed differential responses of germination parameters such as first day of germination (FDG), last day of germination (LDG), germination percentage, peak period of germination (PPG), median germination time (MeGT), mean daily germination (MDG), and time spread of germination (TSG) to varying concentrations of nanofertilizer (100%, 75%, 50%, 25%, and 0%). These findings demonstrate that nanofertilizer exert concentration-dependent effects on seed physiology, with implications for sustainable tomato cultivation. The earliest germination was observed at 25% concentration, with an FDG of approximately 4.5 days, whereas higher concentrations (100% and 75%) delayed germination onset (Figure 3.1). Interestingly, LDG values were largely stable (around 10 days) for most treatments, except for the 100% and 25% concentrations, where LDG was shorter (5.5 and 9.5 days, respectively). These results suggest that while moderate nanofertilizer levels accelerate the initiation of germination, excessive application exerts a phytotoxic effect, delaying or suppressing seedling emergence. Similar findings have been reported by (Davarpناه *et al.*, 2022), who noted that nano-NPK improved early germination at moderate levels but reduced germination when applied excessively due to osmotic stress and potential nutrient toxicity.

Germination percentage varied across treatments (Figure 3.2), with the control group (0%) showing the highest germination rate (22%), while the 100% concentration exhibited the lowest (12%). Moderate concentrations (25%–75%) produced germination percentages

similar to the control, indicating that nanofertilizer did not significantly enhance seed viability relative to untreated seeds. The reduced germination observed at the highest concentration is consistent with previous reports that excessive nanofertilizer application may impair seed physiology by altering water uptake and creating ion imbalances (Khot *et al.*, 2021; Ibrahim *et al.*, 2023). Therefore, while nanofertilizers have potential benefits, their concentration-dependent effects are critical in determining germination success. The analysis of germination dynamics provided deeper insights into the temporal patterns of seed emergence (Table 3.1; Figures 3.3-3.4). Peak germination occurred latest in the 75% treatment (9.5 days), whereas the control and 100% treatments peaked earliest (5.5 days). Similarly, MeGT was longest in the 75% group (9.5 days), while the other groups fell within 5.5–6.5 days. MDG was maximized in the 50% treatment (33.3), suggesting that intermediate nanofertilizer concentrations optimize the daily germination rate. These patterns agree with (Kumar *et al.*, 2021), where moderate levels enhance germination vigor, while very high or very low concentrations are less effective. The TSG results further emphasized the role of nanofertilizer concentration in synchronizing germination. Seeds treated with 25% and 100% concentrations germinated within a narrow 5-day window, whereas those in the 75% and 50% groups had broader germination spreads (8–9 days). This observation implies that both high and low concentrations can synchronize seedling emergence, but with differing implications: while 25% promotes early uniform germination, 100% may force synchrony by limiting viable seed germination. Such findings align with (Mishra *et al.*, 2022), who reported that synchronization in germination can be beneficial for uniform crop establishment, but reduced germination percentages at high concentrations undermine agricultural productivity. The present results corroborate earlier studies on

nanofertilizers in tomatoes and other crops. For instance, (Kumar *et al.*, 2021) demonstrated that nano-urea improved seed vigor indices at moderate doses, while higher doses inhibited germination. Similarly, (Zafar *et al.*, 2021) reported that nano-phosphorus improved germination and seedling biomass in maize when applied at optimal concentrations, but excessive application reduced growth performance. These comparisons suggest that the positive effects of nanofertilizers are dose-dependent and species-specific, reinforcing the importance of careful optimization.

The findings from this study carry important implications for sustainable agriculture. Moderate concentrations of nanofertilizers (particularly 25%–50%) enhanced germination speed and uniformity without compromising seed viability, supporting their role in improving crop establishment. Optimized nanofertilizer use could contribute to higher nutrient use efficiency, reduced environmental pollution, and cost-effective input management compared to conventional fertilizers (Fayyaz *et al.*, 2021; Saurabh *et al.*, 2024). However, indiscriminate use, especially at high concentrations, risks reduced seed viability and diminished yields, counteracting the sustainability benefits.

One limitation of the current study is the variability observed in daily germination speed (Figure 3.4), as nearly one-quarter of seeds failed to germinate, while others showed diverse rates of emergence. This variability may be attributed to differences in seed viability, heterogeneous nanofertilizer absorption, or experimental conditions. Future studies should therefore evaluate long-term effects of nanofertilizer on seedling growth, biomass accumulation, and fruit yield. Additionally, molecular studies could also clarify how nanofertilizers influence gene expression during germination (Mishra *et al.*, 2022). Overall, the study demonstrates that nanofertilizers exert concentration-dependent effects on tomato

seed germination. Moderate levels (25%–50%) promote faster and more uniform germination, whereas excessive application (100%) suppresses germination percentage and delays initiation. These findings underscore the importance of dosage optimization for maximizing the benefits of nanofertilizers in sustainable agriculture.

CONCLUSION

This study was conducted to evaluate the effects of macronutrient nanofertilizers, synthesized from banana peels, on the germination of tomato (*Solanum lycopersicum* L.) seeds. The specific objectives were to synthesize the nanofertilizers, test their effects on germination of tomato seeds, collect relevant germination parameters, and perform statistical analysis of the results. The synthesis of nanofertilizers was successfully achieved using banana peels, confirming the feasibility of producing low cost and environmentally friendly nutrient inputs. The germination study revealed that nanofertilizer concentration has a clear influence on germination performance. Moderate concentration (25%-50%) promoted earlier germination, higher mean daily germination. In contrast, very high concentration (100%) significantly reduced germination percentage and delayed initiation, indicating that excessive application exerts inhibitory effects. The control group (0%) generally performed comparably to the moderate treatments, suggesting that nanofertilizers, while beneficial at certain levels must be optimized for practical use.

The discussion of these results highlights that the effects of nanofertilizers on tomato germination are strongly dose-dependent. While moderate levels improved germination speed and uniformity, excessive amounts suppressed viability. These findings are consistent with previous research emphasizing that nanofertilizers enhance nutrient use efficiency and sustainability only when applied judiciously. The study demonstrates that nanofertilizers synthesized from banana peels hold a promise as a sustainable alternative to conventional fertilizers in tomato production. They can support faster and more uniform germination when used at optimal concentrations. However, over-application reduces their effectiveness and may compromise seed viability. Recommendation includes future research

which should extend beyond germination to evaluate seedling vigor, biomass accumulation, and yield performance under field conditions. Farmers should apply nanofertilizers at moderate concentration (25%-50%) to improve germination and crop establishment. Molecular studies are recommended to investigate how nanofertilizers influence gene expression and stress tolerance during germination. Large-scale trials should be conducted to validate these findings and support the adoption of nanofertilizers in sustainable agriculture.

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