ZIBELINE INTERNATIONAL™ PUBLISHING
ISSN: 2682-7786 (Online)
CODEN: BDAIDR

Big Data in Agriculture (BDA)

DOI: http://doi.org/10.26480/bda.02.2025.62.72

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REVIEW ARTICLE

NANO FERTILIZER: A REVOLUTION IN PRECISION AGRICULTURE AND CROP PRODUCTIVITY

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ARTICLE DETAILS

Article History:

Received 10 January 2025
Revised 15 February 2025
Accepted 19 March 2025
Available online 14 April 2025

ABSTRACT

One recent development in contemporary agriculture that helps get around the drawbacks of the traditional fertilizer system is nano-fertilizer. This kind of fertilizer, which ranges in size from 1 to 100 nanometers, is incredibly effective at giving plants nutrients. The plant's nutritional absorption process is consistent and waste is minimal because of their small size, which allows them to enter the tiny hole in the soil and release the nutrient gradually. Nano-fertilizer uses extremely small amounts to guarantee high yields and superior quality. Numerous studies have demonstrated that the nutritional absorbent efficiency of nano-fertilizers is roughly 20–30% higher than that of conventional fertilizers, which results in a discernible increase in crop productivity and growth. Additionally, by lowering the possibility of environmental contamination and preserving the soil's chemical equilibrium, this technology is crucial to the advancement of sustainable agriculture. The broad use of the nano-fertilizer is not without its difficulties, though. This technology takes time to become widely accepted because of its high production costs, technical complexity, and security issues. There is a need for scientific research, advanced technology and clear policy making to overcome these challenges. This review will be discussed extensively on the scientific basis, procedure, types, benefits, limitations and future prospects of the nano-fertilizer. By applying this technology in modern perfect agriculture and analyzing its potential impact, readers have aimed to provide evidence of a new horizon of sustainable development through nano-fertilizer.

KEYWORDS

nano-fertilizer, environmental contamination, soil's chemical, agriculture

1. INTRODUCTION

Nano-fertilizers are a type of agricultural fertilizer with particle sizes ranging from 1 to 100 nanometers and which deliver nutrients to plants through tiny, bio-mappable particles. As can be understood from this definition, the main characteristics of nano-fertilizers are their ultra-small size and high efficiency, which create opportunities for much more efficient nutrient absorption compared to conventional fertilizer systems. Agriculture is an important pillar of human civilization. Improving agricultural productivity is essential for food security and economic development (*Nanofertilizers and Nanopesticides for Agriculture | Environmental Chemistry Letters*, n.d.). However, conventional fertilizer systems have several limitations that pose various problems to farmers. In conventional nitrogen, phosphorus and potassium (NPK) based fertilizer systems, only 30-50% of the nutrients can be absorbed by plants; the rest is wasted or accumulated in the soil, resulting in environmental pollution and reduced soil quality. Overuse of chemicals due to excessive fertilizer use disrupts the chemical balance of the soil and also creates the possibility of pollution of water sources. Nano-fertilizers have opened a new horizon of possibilities to address these limitations.

The main feature of nano-fertilizers is their slow nutrient release process. The small particles penetrate the fine pores of the soil and slowly spread the nutrients to the area near the plant roots. As a result, the nutrient absorption process of the plant is consistent and it is possible to ensure higher yields even with the use of less fertilizer (*Nanofertilizers for Agricultural and Environmental Sustainability - ScienceDirect*, n.d.). This slow release process ensures continuous supply of nutrients as per the needs of the plant, which helps in reducing the problems of chemical waste and environmental pollution caused by excessive use of fertilizers. The concept of precision agriculture is gaining popularity in modern agriculture. It plays a significant role in improving the growth and quality of crops by providing the right amount of nutrients at the right time. Nano-fertilizers are particularly helpful in achieving this precision, because their slow and controlled release process is consistent with the nutrient needs of the plant. Studies have shown that the nutrient absorption efficiency of plants based on nitrogen, phosphorus and potassium is about 20-30% higher than that of conventional fertilizers. As a result, crop yields increase and waste is reduced, providing a sustainable alternative for farmers. However, there are some challenges in the use of nano-fertilizer technology (Avila-Quezada et al., 2022).

High production costs, technical complexity and long-term environmental impacts are still required for extensive research. Although there are questions about the acceptability, safety and ease of use of this new technology among farmers, it is believed that these challenges can be overcome with the right policymaking and innovation. The main objective of this paper is to discuss in detail the scientific basis, mechanism of action, types, advantages, challenges and future prospects of nano-fertilizers (Jakhar et al., 2022) . The paper will explain the dissolution process of nano-fertilizers in the soil, plant absorption methods and strategies for gradual controlled nutrient release. In addition, its practical aspects, such as its application in precision agriculture and analysis of successful case studies, will also be included. In the entire chapter, we want to highlight how the technological and environmental advantages of nano-fertilizers are taking modern agriculture to a new horizon. This technology is not just a new innovation, but is being considered as an important step towards sustainable development in agriculture (Babu et al., 2022). In the next

Quick Response Code	Access this article online	
	Website: www.bigdatainagriculture.com.my	**DOI:** 10.26480/bda.02.2025.62.72

Cite The Article: Md. Nahid Mahmud, Nuzhat Tabassum Muniza, Rafiya Raidah (2025). Nano Fertilizer: A Revolution in Precision Agriculture and Crop Productivity. *Big Data in Agriculture, 7(2): 62-72.*

section, we will discuss in detail the different types of nano-fertilizers, their scientific structure, efficacy, comparative advantages and challenges. This discussion will help us understand how nano-fertilizers can increase the potential for food security and sustainable development in agriculture. Thus, this review will provide readers with a clear understanding of the technical, environmental and economic aspects of nano-fertilizers, which will serve as the beginning of a new horizon in modern agriculture and sustainable development (Abdalla et al., 2022a).

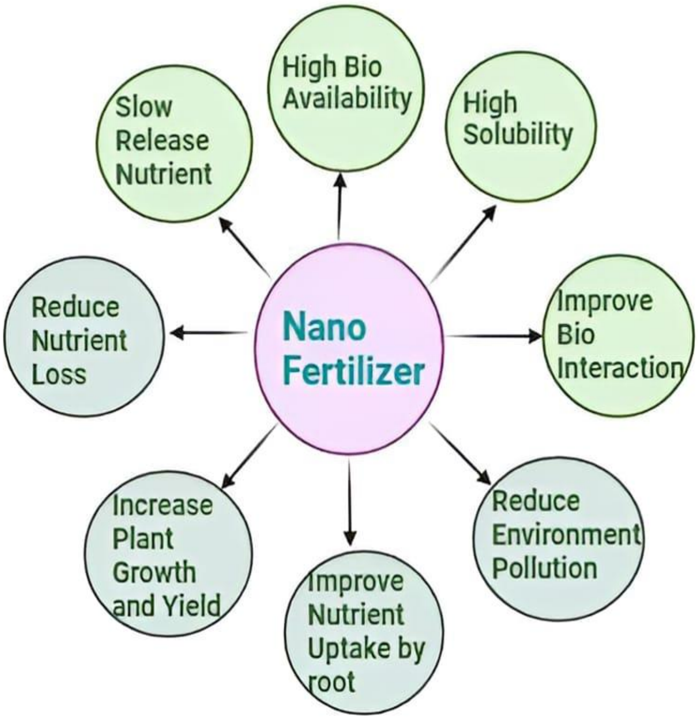


Figure 1: Working Mechanism of Nano- Fertilizer

2. The Science Behind Nano-Fertilizers

The science behind nano-fertilizers is based on their small size, high surface area ratio, and special physical and chemical properties. Since the size of nano-fertilizer particles ranges from 1 to 100 nanometers, their surface area is greatly increased, which helps in rapid contact with plants. Through these ultra-small particles, the nutrient mixture is deeply mixed with the soil and reaches the plant roots. First, the preparation process and synthesis method of nano-fertilizers are very important. These particles are prepared through various chemical and physical methods, such as sol-gel process, chemical reduction, and micro-emulsification methods (*Response of Rice Yield and Quality to Nano-Fertilizers in Comparison with Conventional Fertilizers: Journal of Plant Nutrition: Vol 44, No 13*, n.d.). These methods control the size of the particles, determine the surface structure, and chemical properties, which then affect the gradual release and absorption process of nutrients. Second, a key feature of nano-fertilizers is their controlled release mechanism. Due to the large surface area of the particles, nutrients The material is easily bound and released gradually according to the soil environment and plant needs.

This process optimizes the plant's nutrient absorption, resulting in significant yield improvements with less fertilizer use compared to conventional fertilizer systems. Controlled release greatly reduces the waste of excess chemicals and environmental pollution (*Nanotechnology in Fertilizers | Nature Nanotechnology*, n.d.-a). Third, the chemical and physical properties of nanoparticles, such as high reactivity, high crystallinity, and special surface properties, enhance interaction with plants. The particles easily penetrate the region near the plant roots, where they create a micro-environment for nutrients. This environment facilitates the plant's absorption process and, in turn, directly affects plant growth and yield . In addition, the effectiveness of nano-fertilizers depends on the interaction of the particles with soil pH, moisture, and other chemical elements. Studies have shown that the nutrient absorption process is much more efficient through the structure and surface properties of certain nanoparticles, which have a positive effect on plant growth. In addition, it is possible to combine these particles with various bioactive ingredients to ensure even better efficacy. In short, the science of nano-fertilizers plays an important role in plant nutrient absorption and soil fertility through their small size, improved surface properties, and controlled release mechanism. This scientific explanation shows how nano-fertilizers are establishing themselves as a part of sustainable development and precision agriculture systems in agriculture (Guo et al., 2018).

Table 1: Comparison: Conventional Fertilizers vs Nano-Fertilizers

Feature	Conventional Fertilizers	Nano-Fertilizers	Reference
Particle Size	Larger, micron-sized	Nano-scale (<100 nm)	(Sadati Valojai et al., 2021)
Nutrient Efficiency	Low, high wastage	High, controlled release	(Abdalla et al., 2022b)
Absorption Rate	Slow, requires higher doses	Fast, more bioavailable	(Abdalla et al., 2022b)
Environmental Impact	High pollution, leaching issues	Low pollution, targeted delivery	(Khalid et al., 2022)
Cost	Relatively cheaper initially	Higher initial cost, but cost-effective long term	
Soil Health Impact	Can degrade soil over time	Enhances soil microbial activity	
Water Solubility	Varies, often leads to runoff	Higher solubility, better uptake	
Application Frequency	Frequent applications needed	Less frequent due to slow release	

3. Classification of Nano-Fertilizer

Nano-fertilizers can be classified based on different ingredients, composition, application method and origin. The aim of each classification is to ensure proper application of the fertilizer and increase agricultural productivity. Proper classification of nano-fertilizers helps farmers to choose the right fertilizer, which can maintain proper crop growth and soil health .

3.1 Classification based on ingredients

Nano-fertilizers are classified based on their nutrient content. These include macro and micro nutrient fertilizers. Macro nutrient fertilizers provide major nutrients, such as nitrogen (N), phosphorus (P) and potassium (K), which are helpful in basic plant growth and energy production. They help in fulfilling the major nutrient needs of plants. On the other hand, micro nutrient fertilizers are used in small quantities, but they are essential for plant disease resistance, enzyme activity and physical activities. For example, zinc (ZN), iron (FE) and copper (CU). These are helpful in ensuring plant growth and improved yield (*Nano-Fertilizers and Their Smart Delivery System | SpringerLink*, n.d.).

3.2 Classification by structure

Nano-fertilizers can be divided into three categories based on their structure. The first category is nano-particulate fertilizers. This type of fertilizer delivers nutrients through single nanoparticles, which are slowly released to the plant and this ensures long-term supply of nutrients to the crop. The second category is nano-emulsion or nano-encapsulated fertilizers. The particles of this type of fertilizer are covered with polymers or other coatings, which slowly release the nutrients. This system is helpful in controlling the rate of nutrient release. The third category is nano-fertilizer mixtures, which are made up of different types of particles and can provide multiple nutrients. Through this, the plant gets nutrients over a long period of time (*Nanotechnology in Fertilizers | Nature Nanotechnology*, n.d.-b).

3.3 Classification based on application method

Nano-fertilizers can be divided into three categories based on the application method. The first category is soil-based nano-fertilizers. These fertilizers are applied directly to the soil, which slowly releases nutrients. It is effective for a long time and helps in maintaining soil fertility. The second category is foliar nano-fertilizers. These fertilizers are applied by spraying on the leaves and are quickly absorbed, thereby accelerating plant growth. The third category is nano-encapsulated slow-release fertilizers. These fertilizers are coated with polymers or other coatings, which slowly release nutrients to the plants and remain effective for a long time (Alrbaihat, 2023).

3.4 Classification by origin

Nano-fertilizers can be divided into two categories based on their origin. The first category is synthetic nano-fertilizers, which are produced through artificial chemical processes. These fertilizers are capable of providing high efficiency and specific nutrients. The second category is bio-nano-fertilizers, which are produced by natural means and are safe for the environment. These fertilizers are usually produced using organic materials or other natural sources, such as nano-biochar or nano-algal fertilizers. These are helpful in plant growth and maintaining soil health (Nanofertilizers | SpringerLink, n.d.).

4. Categories of Nano-Fertilizers

The nanosized elements present in NF enable plants to utilize them for improving their productivity. NP developed by NT uses likely agricultural applications though their scientific classification remains inconsistent. The definitions of nanotechnology sometimes include supplementary nanoproducts like nano-biosensors and nanoscale approach systems. NF constitutes both NT section along with fertilizer classification. Due to this lack of clarity there are presently no straightforward definition or classification standards for NF therefore creating assessment confusion about their use and appropriate compensation models. The categorization of NF depends on the materials used for their preparations. NF exist either as carbon nanotube or metal-based or polymer-based products. The various assets of NF and their different effects on plant growth produce unique characteristics among these materials. Understanding the characteristics of NF enables users to find optimal application methods because how NF work depends on their nutrients and actions and structural features. NF exists in different forms for plant application including soil, water and foliar methods. NF are classified per action-based traits to include controlled-release as well as targeted transportation and plant growth-stimulating and water and nutrient loss organizing systems. The group of NF based on nutrients contains hybrid along with nutrient coated and inorganic but also organic types. NF consists of surface coated, synthetic polymer, organic materials coated and nano carrier groups according to their composition. The innovative NF systems provide multiple benefits including optimized nutrient use efficiency together with controlled nutrient discharge functions and targeted deliver mode alongside enhanced plant growth and diminished nutrient waste which support sustainable agricultural development. The nano-biofertilizer contains several types that are distinguished through their nutritional composition (Yadav et al., 2023a).

4.1 Nitrogen nano-fertilizers

The essential plant nutrient nitrogen (N) experiences varying accessibility depending on the environmental conditions. The high level of reactivity in nitrogen makes it difficult for plants to use the nutrient directly. Agricultural soil receives nitrogen-bearing fertilizers used cross-sectorially as solid and liquid forms including ammonia (NH_3), urea [$CO(NH_2)_2$], and ammonium nitrate (NH_4NO_3). To grow plants require nitrogen supplements from soil-based NH_3, HNO_3, and urea compounds since plants lack the capability to obtain nitrogen from the atmosphere. The compounds added to soil establish a chemical reaction with water molecules that produces ammonium (NH_4^+) ions before soil bacteria transforms them into nitrates for plant absorption. Farmer application of nitrogen fertilizers beyond necessary levels diminishes the quality of soil texture and mineral composition.

Excessive nitrogen fertilizer leaching into water bodies causes eutrophication through which environmental damage occurs. Research indicates that nitrification inhibitors and stabilizers together with additives as effective solutions to reduce nitrogen loss by slowing down nitrogen release while enhancing soil absorption. Research indicates that using ammonium ions as a nitrogen application method proves superior to nitrate-based fertilizers because nitrates fail to produce effective bond formations with soil particles. Ammonia has a high tendency to escape into the air but deep soil placement techniques with correct irrigation systems help farmers maintain nitrogen levels in the soil. Urea stands as the most popular nitrogen fertilizer because it offers high nitrogen content and compatibility with other nutrients as well as simple handling capabilities . The negative charge of nitrogen fertilizers leads to weak soil particle binding of nitrate ions thus increasing their risk of water-driven movement.

The development of coated urea fertilizers with polyolefin resin, neem, and sulfur coatings has been done to achieve controlled and gradual nitrogen release. These slow-release fertilizers prove effective but remain expensive and need time to reach their availability to plants. Zeolites serve as positive ion exchangers in fertilizer applications to control ammonium ion release during its slow time-dependent nutrient availability improvement phase. Soil retention of essential nutrients and precise fertilizer treatment functions are both fundamental features of the naturally occurring mineral zeolite that advance agricultural output while decreasing ecological strain. Stockpiles of alkali and alkaline earth aluminosilicates known as zeolite attract researchers evaluating its application in nano-fertilizer systems because of its cost-effectiveness and practical source nature together with its effective fertilizer delivery traits. Zeolite improves fertilization performance by specifically keeping N and K nutrients in the soil for extended crop nutrient supply while preventing unnecessary loss. Soil fertility rises and crop productivity increases when zeolite receives mixtures with humus.

Soil fertility enhancements from zeolite-based nano-composites increase when N, P and K are added with essential micronutrients including calcium (Ca), iron (Fe), zinc (Zn), amino acids, and mannose. The main drawback of zeolite occurs from its weak performance in anion absorption rate. Researcher have investigated modified biopolymers as a solution to improve zeolite's ability to hold nutrients effectively . Researchers have developed modified zeolite products which release ammonium substances at specific rates in order to enhance nitrogen utilization. The combination of SMZ treated with hexadecyltrimethyl ammonium together with dioctadecyldimethyl ammonium exhibits superior performance for both nitrate absorption and slow-release functionality. Zeolite-based nano-fertilizers extend their nutritive availability to 1200 hours which contrasts with the 300–350-hour period of traditional fertilizers (Verma et al., 2023). The prolonged release period of zeolite-based nano-fertilizers establishes them as efficient tools for boosting nitrogen use efficiency and cultivating sustainable agricultural systems while minimizing environmental threats .

4.2 Phosphorus nano-fertilizers

Negligenec of phosphorus leads to weak plant structures while it serves as a several catalyst in the several crucial biochemical process during growth. Plants require phosphorus for their cellular division procedures and tissue building operations and energy storage networks. The energy pool requires phosphorus-based complexes which are created through the photosynthesis process and carbohydrate energy synthesis and subsequently help plants grow before supporting reproduction. The presence of sufficient phosphorus in the ground helps roots grow faster and speeds up the process of becoming a mature plant. Plant growth becomes impaired when phosphorus supply falls short which causes higher sugar production and reddish-purple anthocyanin pigment formation. Studies have explored the behavior of rock phosphorus solutions when combined with NH4+ and K+ saturated clinoptilolite because these interactions lead plants to receive phosphorus through continuous dissolution and ion-exchange steps. The presence of NH4+ and K+ (monovalent cations) on clinoptilolite surface increases the release of rock phosphorus from the mineral. Raw phosphorus availability for plant consumption stands at about 18 to 20% per year while 78 to 80% of it joins the future soil phosphorus reserves after yearly use. Fertilizer-loaded unmodified zeolite and SMZ and solid KH2PO4 reveal that SMZ has optimal properties for releasing H2PO4 through a staggered mechanism according to research findings.

Researchers find that the chemical formula that explains this reaction is (P-rock) + (NH4-zeolite) = (Ca-zeolite) + (NH4) + (H2PO4). Under suitable conditions zeolite removes Ca2+ ions from rock phosphorus so it releases simultaneously phosphorus and NH4+. The release mechanism of highly soluble phosphorus reaches equilibrium while the phosphorus leaching process operates differently. Soil acidification allows the transformation of NH4+ into NO3- thus triggering phosphorus release from rock phosphorus. Zeoponics, a nutrient transfer system, facilitates the release of PO_4^{3-} and other nutrients through controlled dissolution. Through dissolution together with ion-exchange events the procedure brings benefits for plant nutrients by conserving soil nutrients. Nutrients remain safe within zeoponic systems while preventing environmental nutrient loss and cutting down the need for fertilizers because they distribute nutrients effectively to plant root zones. Surface-modified zeolite functions as a potential tool to enhance phosphorus efficiency in agriculture because conventional systems manage to use only 18-20% of phosphorus nutrients (Zhu et al., 2023) .

4.3 Potassium nano-fertilizers

Plants need Potassium (K) to perform different metabolic processes like photosynthesis as well as protein synthesis and maintaining ionic balance and stomata regulation and water management and enzyme activation. When potassium is enclosed inside zeolite it releases potassium over time in successive stages according to research. Researchers have studied how nano-clays exchange cations with different ions after substituting Si^{4+} with Al^{3+} to increase their negative ionic characteristics for ammonium, sodium, calcium, and potassium replacement. Photosynthesis requires potassium fertilizers to work properly while these substances additionally control stomata function. Research has shown that potassium fertilizer treated with polyacrylamide emits its nutrients at a controlled rate to support 35–40% of agricultural yield. The overall fertilization effectiveness of nitrogen (N) and phosphorus (P) and potassium (K) stands at 30–35% and 18–20% and 35–40% respectively. The development of nano-based fertilizers aims to deliver nutrients effectively to specific target sites while resolving issues related to multi-nutrient deficiencies, over-fertilization, inefficient usage of fertilizers and reduced organic manure content in the soil.

Incredible yield improvements of cluster bean along with pearl millet have been observed through the application of nano-potassium (NF) through foliar sprays at 640 mg/ha and 40 ppm. The scientific evidence demonstrates that nanotechnology may deliver persistent fertilization methods because it improves the process of nutrient uptake. The market provides nano-fertilizers for commercial agricultural use. The eco-friendly nano-leucite potassium material (Al_2SiO_6) delivers multiple benefits including timed substance delivery and high cation exchange functions as well as better soil nutrient conservation because of its resistance to salt damage. Plant development along with stem enlargement happens when farmers apply 300 kg/ha of nano-based potassium fertilizers. Scientists conducted testing of zeolite-supported potassium-phosphorus nano-fertilizers with Ipomoea aquatica in laboratory research spanning 30 days. The experiment revealed that potassium phosphorus nano-fertilizers yielded superior performance than traditional fertilizer variants (Hamza et al., 2019).

4.4 Zinc nano-fertilizers

The micronutrient element zinc (Zn) functions as a necessary ingredient during the tryptophan synthesis process and photosynthesis cycle while serving as a catalytic agent in dehydrogenases and aldolases and isomerases. The impacts of zinc nanoparticles (Zn-NP) on Punica granatum L. cv. Ardestani plants have been positively documented by research studies. Fruits per tree showed remarkable growth when treated with Zn-B-NP at 60 and 120 mg/L concentrations resulting in 63–66 observed fruits while the control yielded 51 fruits. The development of pollen and growth of tubes along with improved flowering occurs through zinc leading to larger more abundant fruits (Sturikova et al., 2018).

4.5 Magnesium nano-fertilizers

As a micronutrient magnesium (Mg) facilitates the functioning of plant enzymes ATPase and RNA polymerases. The rate of photosynthesis experience significant adverse effects when magnesium levels fall below normal. Scientific investigations prove that magnesium treatments on leaves enhance seed production while improving plant protein levels. Research showed that Nano-Mg added to tomato irrigation water at 0.1–1.0% at 0.5 mg/L concentration improved photosynthetic activity and increased growth and yield and displayed comparable effects in cowpea. Seed weight together with plasma membrane stability and chlorophyll content demonstrated noticeable improvements when Nano-Mg solutions were applied. Scientists observed black-eyed pea seed yields increase by 13.4% after combining 0.5 g/L iron salt treatments with 0.5 g/L Mg-NP applications in comparison to other experimental conditions (Salcido-Martínez et al., 2024).

4.6 Nano porous fertilizers

The unique structural details found in nano-porous zeolites (NPZ) include both high surface area ability and sizable pore capacity that solve issues of natural zeolites because of their limited micropore availability. Multiple state-of-the-art synthetic approaches starting with post-demetallation and including soft and hard templating and dual-pore formation resulted in the production of NPZ. Relevant industrial processes including isomerization, cracking and alkylation and oxidation utilize these materials for their applications. Zeolites represent an essential mineral category of aluminosilicate crystals having organized micropore structures because their uniform pores enable separation of substances based on their pore dimensions. Zeolites demonstrate high importance in host–guest chemistry and separation methods through molecular selective adsorption which relies on the characteristics of size and shape and size selection. Zeolites maintain outstanding stability as crystalline materials since their structure endures against harsh reaction conditions and thermal and hydrothermal stress and mechanical forces (Yanovska et al., 2022).

4.7 Calcium nano-fertilizer

Ca plays a significant role as an essential plant nutrient because it plays a pivotal function in cell wall synthesis as well as plant growth regulation. The plant cell wall needs calcium as a structural element because it forms crosslinks that strengthen the pectin-polysaccharide matrix. Plants protected by calcium are shielded against bacterial along with viral infections. Research shows nano-calcium applications produce substantial enhancements to plant development as well as physical growth improvements. The available studies about nano-calcium demonstrate its exceptional potential to function as a fertilizer despite limited research in this area (Carmona et al., 2022).

Table 2: Different Types of Nano-Fertilizers and Their Functions

Nano-Fertilizer Type	Function	Reference
Nano Urea	Enhances nitrogen use efficiency and promotes plant growth.	(Yadav et al., 2023b)
Nano Zinc	Improves enzyme function, chlorophyll production, and plant metabolism.	
Nano Phosphorus	Increases root development and energy transfer in plants.	
Nano Iron	Prevents iron deficiency and enhances chlorophyll synthesis.	
Nano Copper	Boosts plant disease resistance and enzyme activity.	

Table 2 (cont): Different Types of Nano-Fertilizers and Their Functions		
Nano Silica	Strengthens plant cell walls and improves stress tolerance.	
Nano Potassium	Enhances water retention, enzyme activation, and disease resistance.	
Nano Magnesium	Plays a key role in photosynthesis and enzyme activation.	
Nano Calcium	Strengthens cell walls and prevents calcium deficiency.	
Nano Sulfur	Aids in amino acid synthesis and enzyme activation.	

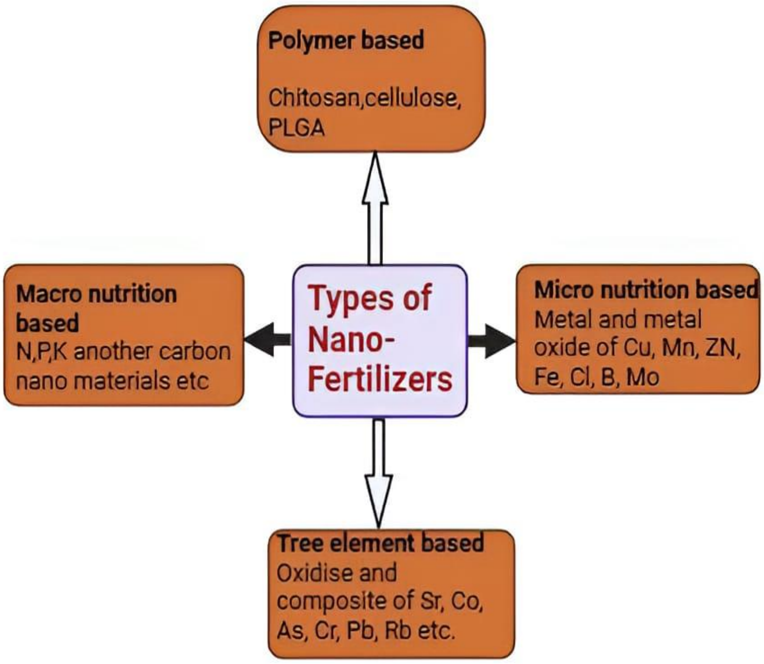


Figure 2: Several types of nano-fertilizers

5. Advantage of Nano-Fertilizers Over Coventional Fertilizers

Nano-fertilizers have ushered in a new era in agriculture. Compared to conventional fertilizers, nano-fertilizers are more effective, environmentally friendly and cost-effective. They help increase the nutrient uptake capacity of plants and reduce the negative impact on the environment. Firstly, a major advantage of nano-fertilizers is their small size. These small particles can easily penetrate the roots of plants, which increases the absorption of nutrients. Conventional fertilizers often leave some nutrients deep in the soil after being mixed with the soil and cannot be absorbed by the plant. However, due to the small particle size of nano-fertilizers, they are easily absorbed by plant cells and provide the right amount of nutrients at the right time. Secondly, nano-fertilizers are characterized by slow release properties. The nutrients in conventional fertilizers are released quickly, which results in excessive fertilizer use and can cause pollution in the environment. However, nano-fertilizers release nutrients slowly, thus ensuring a long-term supply of nutrients to the plants. This helps in maintaining soil health and reduces the wastage of fertilizer use. Thirdly, through the use of nano-fertilizers, farmers can get more yield with less fertilizer. Compared to conventional fertilizers, the effectiveness of nano-fertilizers is much higher.

This helps in reducing the cost of farmers, as it is possible to get more yield with less fertilizer. As a result, the cost of fertilizer use is reduced and the farmer's profit increases. Also, another major advantage of nano-fertilizers is their eco-friendly nature. Conventional fertilizers contain large amounts of nitrogen, phosphorus and potassium, which can be harmful to the soil if used in excess. However, nano-fertilizers have less harmful effects on the environment and are safer for environmental health. They are beneficial for the soil and reduce pollution in water or air. Nano-fertilizers help in increasing the immunity of plants, as it helps in meeting the nutritional needs of plants and helps in improving their physical protection. As a result, plants are protected from diseases and insect attacks, which is a major improvement in productivity. Finally, nano-fertilizers are suitable for use in environments that are not suitable for conventional fertilizers.

They are also able to work effectively in high temperatures, dryness and low nutrient soils. In developing countries where there are environmental challenges, the use of nano-fertilizers can be an important solution for agriculture (Ali et al., 2021).

Table 3: Efficiency comparison between nano-fertilizers and traditional fertilizers

Aspects	**Nano-Fertilizers**	**Traditional Fertilizers**	**References**
Nutrient efficiency	High (80-90%)	Low (30-35%)	(Khalid et al., 2022)
Absorption rate	Faster due to nanoscale size	Slower, often lost in soil and water	
Dosages requirement	Low (small quantity needed)	High (large quantity required0	
Environmental impact	Minimal (less runoff and pollution)	High (causes soil/water pollutions)	

Table 3 (cont): Efficiency comparison between nano-fertilizers and traditional fertilizers

Cost-effectiveness	Higher initial cost but more efficient	Lower cost but frequent applications needed	
Plant growth response	Enhanced due to better uptake	Moderate due to nutrient losses	
Shelf life and suitability	Higher stability and longevity	Shorter effectiveness over time	

6. NPK Ratio of Nano-Fertilizers

Nano Fertilizers are an innovative new technology that have been developed in agriculture, allowing nutrients to be rapidly absorbed in soil and plant cells. It is typically composed of nitrogen (n), phosphorus (P), and potassium (K). Nano Fertilizers have a different NPK ratio, but the NPK ingredients are generally from 3 to 5%, depending on the manufacturer and the used purpose of the manufacturer. For instance, the NPK ratio in Nano Fertilizers is visible 25-5-20, 3-5-6, which is needed for the growth and yield of the plant. The main advantage of Nano Fertilizers is its small size, which is able to reach the roots of the plant more effectively than other ordinary fertilizers (Ashraf et al., 2022).

7. Preparation Method of Nano Fertilizers

The field of agricultural science relies on nano-fertilizers (NF) as an emerging advanced technology because they deliver improved efficiency and controlled release attributes alongside environmental benefit reductions. Researchers employ different synthetic methods to make nano-fertilizers because these methods help them maintain precise control over particle size as well as surface charge and chemical properties to optimize nutrient delivery to plants. Several preparation techniques serve for the synthesis of nano-fertilizers.

7.1 Top-down processes

The top-down approach involve the reduction of bulk materials to nanometer-sized particles by mechanical, physical, or chemical methods. The pivotal algorithm is thus reducing larger messenger particles to smaller nanostructures by methods such as grinding and milling or high-energy ball milling.

7.1.1 Ball Milling

This process involves the grinding of larger particles with the help of a rotating ball mill leading to the size reduction of the material on a nanoscale. Mechanical forces applied during the process of milling break down particles into nanoparticles.

7.1.2 Ultrasonication

In this process, high-frequency sound waves are employed to break up larger particles into smaller sizes by the action of cavitation bubbles that form microscopically and exert pressure on the material. These methods find application in the production of nanoparticles of different inorganic materials, such as metal oxides, silicates, and other minerals (Padhan et al., 2024).

7.2 Bottom-Up Approach

Nanostructures are built up from atoms or clusters of atoms by self-assembly in the bottom-up approach. The formation of nanomaterials emerges from chemical reactions which the process is based on. This is the method most often used in making nanoparticles with precipitation, solgel, chemical vapor deposition, and hydrothermal synthesis.

7.2.1 Sol-Gel Process

This is the process of gel-making from suspensions under the influence of a chemical solution. At a relatively higher temperature, i.e., when the gel is subjected to heat, the nanoparticle that is needed is generated. Most of the time, this method is adopted for generating nano-fertilizers based on metal oxides such as zinc oxide (ZnO), calcium oxide (CaO), and magnesium oxide (MgO) among others.

7.2.2 Chemical Vapor Deposition (CVD)

In CVD technologies, gaseous precursors are first chemically reacted on the substrate to form nanoparticles. CVD is a technology commonly used in the preparation of metal oxide thin films and nano-fertilizers such as zinc oxide.

7.2.3 Hydrothermal and Solvothermal Methods

In these methods, nanoparticles are obtained from precursor solutions through solvents at high temperature and pressure. The potentially most widely propagating method used to prepare metal-based nanoparticles (i.e., copper oxide (CuO) and silver (Ag) nanoparticles) (Ayenew et al., 2025).

7.3 Green synthesis (Eco friendly)

During green synthesis, the nano-fertilizers are synthesized using natural resources in an environmentally safe manner. The term itself is gradually becoming popular given that it is sustainable and has a low environmental impact.

7.3.1 Plant Extracts

Various plant materials such as leaves, flowers, and stems are used to extract secondary metabolites such as polyphenols, flavonoids, and alkaloids that will act as reducing agents in the formation of nanoparticles. For instance, zinc nanoparticles (ZnNPs) and copper nanoparticles (CuNPs) have been synthesized from plant extracts such as aloe, moringa, and neem.

7.3.2 Microbial Synthesis

Several microorganisms including bacteria and fungi have been found to be a dominant force within certain realms of the biosynthesis of nanoparticles. As such these microorganisms will reduce certain metal ions to make nanoparticles, making this a more viable and sustainable route of nano-fertilizers production (Ayenew et al., 2025).

7.4 co-precipitation method

The co-precipitation method has to do with dissolving a mixture of metal salts in some solvent and adding a precipitating agent to the solution to obtain nanoparticles. During the precipitation reaction, the metal salts give rise to the formation of solid nanoparticles. The method is appropriate for the synthesis of mixed-metal-oxide nanoparticles (Jiao et al., 2017).

7.5 Microemulsion technique

One procedure of microemulsion is the small droplets that are formed in the nanometer scale involving the mixture of oil or water, acting as microreactors which are involved in nanoparticle synthesis. The surfactants are used to stabilize the nanoparticles enclosed in the droplets that bring about the formation of equal nano-fertilizers. This is a unique method for metal nanoparticles, and metal oxide nanoparticles are prepared using this way (Malik et al., 2012).

7.6 Electrical synthesis

Electrochemical methods involve the application of an electric current or potential to induce a redox reaction at the electrodes, leading to the formation of nanoparticles. This method can be used to synthesize a wide variety of nanoparticles, including metals, metal oxides, and carbon-based nano-materials (Ayenew et al., 2025).

7.7 Polymeric Nanoparticles

Polymeric nanoparticles are another form of nano-fertilizers, where polymers like poly(lactic acid) (PLA), poly(lactic-co-glycolic acid) (PLGA), and polyvinyl alcohol (PVA) are used as carriers for the controlled release of nutrients. The polymers can be loaded with essential plant nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium. These polymers slowly release the nutrients over time, ensuring a sustained supply to plants.

7.8 Surface Modification of nanoparticles

To promote the interactions between nanoparticles and plant roots, it is inevitable to change the surface of nano-fertilizers, which undergo the process of surface modification. Various types of surface coating agents like chitosan, alginate, silica, and polyethylene glycol (PEG) are commonly used to fabricate nanoparticle surfaces. These coatings are responsible for the improvement of the nanoparticle's stability, dispersibility , and controlled release properties (Ayenew et al., 2025).

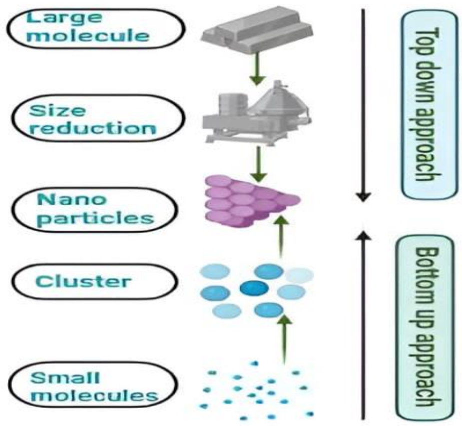


Figure 3: Top down approach and bottom up approach of nano particles synthesis

Table 4: Synthesis of Plant-Based Nanoparticles by using plants

SL	Types of NPs	Plant Type	Part of Plant Used	Particle Size	Usage	References
1	Gold and Silver	Aloe vera	Leaf	10–30 nm	Optical coatings and cancer hyperthermia	(Ayenew et al., 2025)
2	Gold	*Syzygium Aromaticum* (clove buds)	–	5–10 nm	Detection and destruction of cancer cells	
3	Silver	Lemon	Lemon extract	<50 nm	–	
4	TiO2	Aloe vera	Leaf	60 nm	–	
5	TiO2	*Psidium guajava*	Leaf	32.58 nm	–	
6	TiO2	*Annona squamosa*	Peel	23 nm	–	
7	ZnO	*Albizia lebbeck*	Stem bam	66.25 nm	Antimicrobial, antioxidant	
8	ZnO	*Trifolim pratense*	Flower	100–190 nm	–	
9	ZnO	*Azadirachta indica*	Leaves	40 nm	–	
10	Cu	*Tinospora cordifolia*	Leaves	50–130 nm	Catalytic degradation	
11	Cu	*Citrus medica Linn*	Juice	33 nm	Antimicrobial	
12	Cu	*Ixoro coccinea*	Leaves	80–110 nm	–	
13	Fe	Pomegranate	–	100–200 nm	–	
14	Fe	Plantain	Peel	<50 nm	–	

Table 5: Fingal strains for synthesis of several NP

Type of NPs	Fungal Strain	NP Size	Shape	References
ZnO	*Aspergillus strain*	50–120 nm	Spherical	(Ayenew et al., 2025)
ZnO	*Aspergillus terreus*	29 nm	Hexagonal	
ZnO	*Candida Albicans,*	15-25 NM	Hexagonal	
Ag	*Trichoderma viride*	2–4 nm	Spherical	
Ag	*Fusarium Axysporum*	5–13 nm	Spherical	
Ag	*Arthroderma Fulvum*	20.56 nm	Spherical	
Au	*Collectotrichum sp*	8–40 nm	Spherical	
TiO2	*Aspergillus flavus*	62–74 nm	Spherical	
Pt	*Fusarium axyporum*	70–180 nm	Rectangular, triangular and spherical	

Table 6: By using bacteria synthesis of NP

SL	Types of NPs	Name of Bacteria	Size	Morphology	References
1	Silver	*Bacillus cereus*	20–40 nm	Spherical	(Ayenew et al., 2025)
2	Silver	*Lactobacillus casei*	20–50 nm	Spherical	
3	Gold	*E. coli*	8–50 nm	Spherical	
4	Gold	*Bacillus subtilis*	5–50 nm	Hexagonal-Octahedral	
5	Iron oxide	*Magnetospirillum magneto tacticum*	47 nm	–	
6	Iron oxide	*Aquaspirillum magneto tacticum*	40–50 nm	Octahedral prism	

8. Comparetive Analysis of Natural and Nano Porous Zeolite as Soil Amendment

pH (1:6.25 ml ratio) | Natural Zeolite: 9.6 | Nano porous Zeolite: 8.14 |. Here the pH value refers to how acidic or alkaline something is. Natural Zeolite has a pH of 9.6, making it highly alkaline, while Nano porous Zeolite has a pH of 8.14, which is relatively less alkaline. A higher pH means that it can react with an acidic environment to produce alkali easily. Reference indicates that this information was taken from a specific study or source.

ECe (dSm^{-1}) (saturated paste) | Natural Zeolite: 0.17 | Nano porous Zeolite: 0.06, ECe (Electrical Conductivity of Extract) refers to the electrical conductivity of a substance due to the presence of dissolved salts. It is used to indicate the salinity or mineral content of soil. Natural Zeolite has an ECe of 0.17 dSm^{-1}, which is higher than Nano porous Zeolite (0.06 dSm^{-1}). This means that Natural Zeolite can carry a relatively high number of ions, which can affect the plant's nutrient uptake.

Moisture (%) | Natural Zeolite: 10 | Nano porous Zeolite: 12, This value shows how much moisture the Zeolite can hold. Natural Zeolite can hold 10% moisture, but Nano porous Zeolite can hold up to 12%. Due to its porous structure, Nano porous Zeolite can absorb and store more water, which can be important for soil moisture retention in agriculture.

Bulk density (Mgm^{-3}) | Natural Zeolite: 0.57 | Nano porous Zeolite: 0.50, Bulk density refers to the total density of a substance, i.e. how heavy or light it is. Natural Zeolite has a bulk density of 0.57 Mgm^{-3}, which is higher than Nano porous Zeolite’s 0.50 Mgm^{-3}. This means that Nano porous Zeolite is less dense and relatively lighter. Due to its low bulk density, it can help improve soil structure and increase aeration.

Particle density (Mgm^{-3}) | Natural Zeolite: 0.66 | Nano porous Zeolite: 0.39, Particle density refers to the density of individual particles. Natural Zeolite has a particle density of 0.66 Mgm^{-3}, which is higher than Nano porous Zeolite’s 0.39 Mgm^{-3}. This means that Natural Zeolite particles are relatively dense and hard, while Nano porous Zeolite particles are relatively hollow and lighter.

Pore space (%) | Natural Zeolite: 34 | Nano porous Zeolite: 45, Pore space refers to the amount of empty space or pores within a material. Pore space of Natural Zeolite is 34%, but Nano porous Zeolite is 45%. This means that Nano porous Zeolite has more pores, which makes it suitable for holding more water and air. This can increase the oxygen supply to plant roots.

Total organic carbon (%) | Natural Zeolite: 1.9 | Nano porous Zeolite: 1.03, total organic carbon is the amount of organic carbon present in the soil or material. Natural Zeolite has 1.9% and Nano porous Zeolite has 1.03%. This means that Natural Zeolite contains relatively more organic matter, which can help increase soil fertility.

Total Nitrogen (%) | Natural Zeolite: 0.02 | Nano porous Zeolite: 0.03, this value shows the total percentage of nitrogen (N) in the material. Natural Zeolite has 0.02% nitrogen, while Nano porous Zeolite has 0.03%. Nano porous Zeolite is slightly ahead in terms of nitrogen retention, which can be helpful in plant growth.

Total Phosphorus (%) | Natural Zeolite: 0.06 | Nano porous Zeolite: 0.02, Phosphorus is a very important nutrient for plants. Natural Zeolite has 0.06% phosphorus, while Nano porous Zeolite has 0.02%. This means that Natural Zeolite can provide relatively more phosphorus, which is important for plant root growth.

Total Potassium (%) | Natural Zeolite: 0.09 | Nano porous Zeolite: 0.02, Potassium plays an important role in the cell division and growth process of plants. Natural Zeolite has 0.09% potassium, while Nano porous Zeolite has 0.02%. This shows that Natural Zeolite can retain relatively more potassium.

Calcium (%) | Natural Zeolite: 5.25 | Nano porous Zeolite: 0, Natural Zeolite contains 5.25% calcium, but there is no standard for Nano porous Zeolite. This means that Nano porous Zeolite may not have any or very little calcium. Calcium helps in soil structure and increases the strength of plant cells.

Magnesium (%) | Natural Zeolite: 6.03 | Nano porous Zeolite: 0

Natural Zeolite contains 6.03% magnesium, which is helpful in the production of chlorophyll in plants. There is no standard for Nano porous Zeolite, so it may not contain magnesium.

Silica (%) | Natural Zeolite: 4.78 | Nano porous Zeolite: 1.49, Silica increases the resistance of plants to diseases. Natural Zeolite has 4.78% and Nano porous Zeolite has 1.49%. This means that Natural Zeolite can provide more silica.

Aluminum (%) | Natural Zeolite: 1.02 | Nano porous Zeolite: 1.59, high aluminum content can be harmful to some plants. Nano porous Zeolite has 1.59%, which is higher than Natural Zeolite (1.02%).

CEC ($cmol(P)Kg^{-1}$) | Natural Zeolite: 100 | Nano porous Zeolite: 106, CEC (Cation Exchange Capacity) refers to the ability of a substance to retain nutrients. Nano porous Zeolite has 106 $cmol(P)Kg^{-1}$, which is higher than Natural Zeolite (100 $cmol(P)Kg^{-1}$), so it can retain more nutrients.

Bulk density (Mgm^{-3}) | Natural Zeolite: 0.57 | Nano porous Zeolite: 0.50, bulk density refers to the total density of a substance, i.e. how heavy or light it is. The bulk density (Mgm^{-3}) of Natural Zeolite is 0.57, which is higher than the 0.50 Mgm^{-3} of Nano porous Zeolite. This implies, as easy as it is to understand, Nano porous Zeolite is significantly less dense and lighter. Carbon products incorporating this will aid in better plants soil tillage and nutrient action.

Particle density (Mgm^{-3}) | Natural Zeolite: 0.66 | Nano porous Zeolite: 0.49, particle density refers to the density of individual particles. Natural Zeolite has a particle density of 0.66 Mgm^{-3}, which is higher than the 0.49 Mgm^{-3} for Nano porous Zeolite. This means that the Natural Zeolite particles are relatively dense, hard, and heavy, while the hired the Particle density refer to the density of particles. Nano porous Zeolite particles are relatively hollow, and the Nano porous Zeolite is also lighter.

Pore space (%) | Natural Zeolite: 34 | Nano porous Zeolite: 45, Pore space is the amount of empty space or pores within the material. Pore space of Natural Zeolite is 34% but Nano porous Zeolite is 45%. It is recognized that primary factor size and whether the material is gas or rock related functionalities as a water and air flow promoter will strictly depend on its being a good pore structure. It is capable of multiplication of the roots as well.

Total organic carbon (%) | Natural Zeolite: 1.9 | Nano porous Zeolite: 1.03, total organic carbon is the amount of organic carbon present in the soil or material. Natural Zeolite has 1.9% and Nano porous Zeolite has 1.03%. As a result, the Nano porous Zeolite contains fewer pore spaces, therefore, it can not be used for water and nutrient retention. Over the years, it is known that haughty mighty shoals aside from natural things quaking to the ground underneath have been enslaved. And has thus given birth to a long-awaited factor of fertility.

Total Nitrogen (%) | Natural Zeolite: 0.02 | Nano porous Zeolite: 0.03, It is the percentage of the sum in the water and the percentage of nitrogen in the soil. The Natural Zeolite has 0.02% nitrogen, whereas the Nano porous Zeolite goes up to 0.03%. Even if it is small by comparison, Nano porous Zeolite has the edge to holding on to nitrogen which promotes the growth of new plants.

Total Phosphorus (%) | Natural Zeolite: 0.06 | Nano porous Zeolite: 0.02, Phosphorus is an important plant nutrient which has to be present. Natural Zeolite has 0.06% phosphorus, whereas Nano porous Zeolite goes down to 0.02%. This in turn means that Natural Zeolite can supply a relatively higher amount of phosphorus, the nutrient required for proper root development in a plant.

Total Potassium (%) | Natural Zeolite: 0.09 | Nano porous Zeolite: 0.02, It is necessary for the plants to have potassium in order to accomplish cell division and growth. Natural Zeolite has 0.09% potassium, while Nano porous Zeolite has 0.02%. This result indicates that Natural Zeolite can immobilize potassium to a larger extent.

Calcium (%) | Natural Zeolite: 5.25 | Nano porous Zeolite:0, natural zeolite acquires 5.25% of calcium in it along with the absence of its counterpart Zeolite. Therefore, no data is available for Nano porous Zeolite, thereby Nano porous Zeolite may not contain any or very little amount of calcium. Calcium is beneficial to the soil, as it improves its structure and cell walls are less susceptible to breaking and diseases are controlled.

Magnesium (%) | Natural Zeolite: 6.03 | Nano porous Zeolite: 0, The percentage of magnesium is 6.03% in the natural zeolite that comes in handy for the production of chlorophyll. The nano porous zeolite is not included in the standard, but it may not include magnesium in it because it is nano porous grade.

Silica (%) | Natural Zeolite: 4.78 | Nano porous Zeolite: 1.49, silica increases the resistance of plants to diseases. Natural Zeolite has 4.78% and Nano porous Zeolite has 1.49%. This means that Natural Zeolite can provide more silica.

Aluminum (%) | Natural Zeolite: 1.02 | Nano porous Zeolite: 1.59, high aluminum content can be harmful to some plants. Nano porous Zeolite has 1.59%, which is higher than Natural Zeolite (1.02%).

CEC (cmol(P)Kg^{-1}) | Natural Zeolite: 100 | Nano porous Zeolite: 106, CEC (Cation Exchange Capacity) refers to the ability of a substance to retain nutrients. Nano porous Zeolite has 106 cmol(P)Kg^{-1}, which is higher than Natural Zeolite (100 cmol(P)Kg^{-1}), so it can retain more nutrients.

Inorganic Carbon (%) | Natural Zeolite: 28 | Nano porous Zeolite: 45, nano porous zeolite contains 45% inorganic carbon, which is higher than natural zeolite's 28%. Inorganic carbon generally plays a role in controlling soil pH and structure (Ayenew et al., 2025).

9. Challenges and Constrains in The Use of Nano-Fertilizers

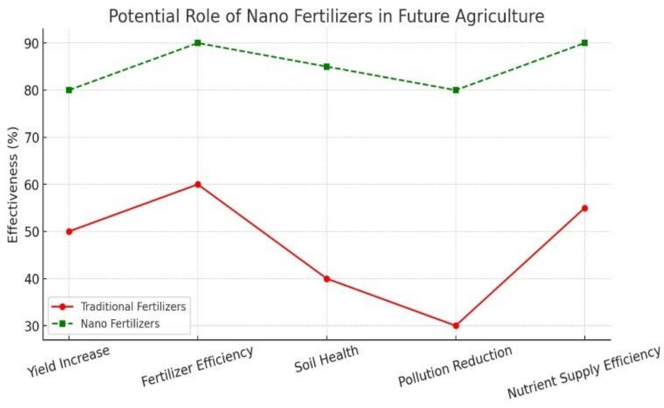
The overall adoption of nano-fertilizers in agriculture is without any scope for hindrances which are reasons for their ineffective and non sustainable use. To begin with, the cost of the manufacturing methodology of the nano-fertilizers is too difficult and steep. Farmers who want to use nanotechnology face economic constraints because they lack the needed machinery and skill sets. Additionally, use in developing nations would be further limited due to low production capacity of farmers. There are some gaps that need to be filled regarding long-term impacts of nano-fertilizers. Current research shows that nano-fertilizers can be effective for enhancing plant growth, but thorough studies must be conducted to analyze the adverse effects it may have on the soil and ecosystem. Too much reliance on these nano-fertilizers can foster conditions that are destructive to the soil or the ecosystem. Lastly, insufficient knowledge and inadequate education on the techniques required to use nano-fertilizers is also a daunting challenge (Zulfiqar et al., 2019).

Without any proper training, the farmers will remain ignorant of how to apply these advanced techniques. Farmers are not well informed on the correct dosage, method of application, and timing of nano- fertilizers, which is a great hurdle to them. Another very important challenge is also the very low market penetration of nano-fertilizers as well as the absence of sufficient policies. Because nano-fertilizers are a relatively new concept, farmers have issues obtaining effective and useful fertilizers which makes crop production more difficult. This lack of government policies, standards, and regulations stifles farmers' commitment towards the adoption of this new technology. All these obstacles aside, if proper policies are established and followed, including adequate preparation, technological innovation afterwards, and education for farmers, the use of nano-fertilizers can be successful. Scientists and Government departments working together can bring a brighter future for this technology (Rehmanullah et al., 2020).

10. Nano-Fertilizer Recent Innovations and Future Prospects

The development and research of nano-fertilizers has recently become an exciting prospect in the agricultural sector. Several countries and research institutions are actively working towards developing new nano-fertilizers that have the potential to transform agricultural practices. These innovations include reducing fertilizer use, increasing plant nutrient uptake and dialysis, as well as reducing its negative impact on the environment. The use of nano-fertilizers is expected to be very important for the agricultural sector in the future. Some important breakthroughs have been made in research, one of which is the development of slow-release technology for nano-fertilizers. Compared to conventional fertilizers, nano-fertilizers are more effective because they are released slowly to the plant and are used over a long period of time. Since the particles are so small, they easily penetrate the plant roots and help in more effective absorption of nutrients. This reduction in fertilizer use allows farmers to get more yield at lower cost (Pandey, 2018). In addition, researchers are working to produce nano-fertilizers that are less harmful to the environment. Eco-friendly nano-fertilizers do not have any adverse effects on soil biodiversity and other natural elements.

Such fertilizers quickly stop being seriously harmful to the environment, thus reducing the possibility of soil and water pollution. It can be ensured that the use of such fertilizers already contributes to sustainable development in agriculture, which will be very important for farmers in the future. Many new studies have emerged as a new topic, which is the use of nano-fertilizers to prevent the effects of climate change. A breakthrough in the effects of nano-fertilizers can be observed during dry and high heat waves. The effectiveness of plant molecular vegetable fertilizers in some regions such as the tropics where the compacted manure with top dressing remains dry, plant growth remains normal and can also lead to higher yields. As a result, this technology can be successfully used in coastal areas and areas with high temperatures. It is an effective solution to the crisis of temperature and climate change. In this case, nano-fertilizers can become a surefire part of farming where farmers may face new farming conditions (Konappa et al., 2021).



This graph has been made by Conceptualized based on observed trends in nano-fertilizer research and sustainable agricultur

Figure 3: This is a comparative graph showing the potential role of nano-fertilizers. It shows that nano-fertilizers are more effective in improving crop production, fertilizer efficiency, preserving soil health, and reducing environmental pollution compared to conventional fertilizers.

11. CASE STUDY

11.1 Case Study 1

Indian Agriculture Many farmers in India have increased their production by using nano-fertilizer technology, especially in wheat and rice cultivation. For Indian farmers, nano-fertilizers have effectively increased the absorption of nutrients by plants, while reducing the amount of fertilizer used. In wheat fields, it has been possible to reduce the amount of fertilizer applied by about 30%, while increasing production by 15-20%. The use of less fertilizer has reduced the cost of farmers, and their income has also increased due to the increase in production. Less fertilizer use has helped reduce the negative impact on soil health and the environment.

11.2 Case Study 2

Application of Nano-fertilizers in Bangladesh the use of nano-fertilizers has significantly improved the cultivation of watermelon and papaya in Bangladesh. Farmers have cultivated with only 20-30% less fertilizer by using nano-fertilizers. The yield of watermelon and papaya has increased by 40-50%. Along with reducing the amount of fertilizer, the farmers have been able to double their income due to the increase in yield. Reducing the wastage of fertilizer has reduced the pressure on the environment.

12. Success Story

12.1 Success Story 1

Eco-friendly agriculture through nano-fertilizers Globally, some agricultural companies in China and Europe have succeeded in reducing the environmental impact of agriculture by using nano-fertilizers. In China, crop yields have increased by up to 25% using nano-fertilizers. It has also protected soil health and reduced fertilizer waste. Farmers in some European countries have been able to meet plant nutrition requirements by using less fertilizer, thereby reducing pressure on the environment. This technology has reduced overall fertilizer use by 20-30%, which has helped achieve sustainable development in agriculture (Escribà-Gelonch et al., 2023).

12.2 Success Story 2

Role of nano-fertilizers in improved agricultural production and supply chains In some African countries, farmers have significantly increased food crop production by using nano-fertilizers. Wheat and maize production has increased by about 35-40% using nano-fertilizers. This technology has helped increase the country's food security and increased farmers' income. For African farmers, this technology has reduced costs and increased production, which has also led to increased exports to international markets (Sanzari et al., 2019).

13. Conclusion

Nano-fertilizer is one of the newest technologies revolutionizing modern agriculture and it is a technological factor supporting this, that is able to increase the agricultural productivity and to reduce environmental impact. Thanks to its technological development and scientific research, it has gained further advantages, which can be of the greatest use for farmers. One more perspective to consider is that the application of nano-fertilizers in modern farming indeed is becoming more effective and inexpensive than the usage of traditional fertilizers. Nevertheless, some issues continue to emerge in this particular area, such as the applicability, safety, and policy uncertainty of the nano-fertilizer. Its use demands broader research and technology development. Meantime pollution and health problems are on the rise and ought to be dealt with. In the future, however, technological advancements in nano-fertilizer and widespread use of its benefits will be able to bring about a breakthrough change in the agricultural sector. The right use of it in such underdeveloped nations like Bangladesh can make a difference in farmers' income and food production. Only if innovative research and government policy support, nano-fertilizer has a huge potential and it can bring forth qualitative changes in the agricultural sector.

Conflict of Interest

No Conflict Of Interest Visible For This Manuscript

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