

Exploring the Effects and Consequences of Nano Fertilizer Application on Plant Wellness- A Review

Abstract

Nano fertilizers have emerged as a cutting-edge innovation in agricultural practices, poised to redefine nutrient delivery and management at the plant-soil interface. This review provides a comprehensive overview of the effects and consequences of nano fertilizer application on plant wellness. The inherent properties of nanoparticles allow for enhanced nutrient absorption, precise delivery, and increased bioavailability, potentially revolutionizing traditional fertilization methods. The results, as evidenced by multiple studies, indicate significant improvements in growth parameters, seed production, and overall plant health. Moreover, plants treated with nano fertilizers have shown heightened resistance to both biotic and abiotic stresses. However, while the benefits are promising, concerns arise regarding the ecological persistence of nanoparticles, potential bio-magnification, and implications for human health. A comparative analysis with conventional fertilizers revealed nano fertilizers' superior efficiency, but also brought forth economic considerations and environmental footprints. The current regulatory landscape is dynamic, with policies adapting to the rapid advancements of nanotechnology in agriculture. As research continues to bridge existing gaps, technological advancements are concurrently shaping the future prospects of nano fertilizer application. This review underscores the need for a balanced understanding of the potential and challenges, emphasizing collaborative efforts to harness nano fertilizers' full potential while ensuring ecological and human health safety.

Keywords: *Nanogrowth, Nanonutrients, Nanoagriculture, Nanoplants, Nanosoil*

Introduction

The fertilization of crops has been an essential practice since the advent of agriculture, a testament to humanity's constant endeavor to enhance the yield and quality of crops. Traditional fertilizers, stemming from both organic and inorganic origins, have played a pivotal role in modern agriculture, enabling the production of food at a scale that sustains the global population [1]. These fertilizers, while effective, often come with a set of challenges, including nutrient runoff, inefficiencies in nutrient uptake, and potential environmental repercussions. Enter the era of nanotechnology: a field that has impacted multiple domains, from medicine to electronics. The agricultural sector, not one to lag, has begun to harness the potential of nanotechnology, leading to the emergence of nano fertilizers. At their core, nano fertilizers are essentially nutrient particles that have been reduced to the nanoscale, thereby increasing their surface area and reactivity. This new formulation and the size change of these nutrients allow for enhanced uptake, reduced wastage, and potential benefits not previously observed with conventional

fertilizers [2]. But what sets nano fertilizers apart from their traditional counterparts? It's primarily their size and mode of action. Nano fertilizers can permeate the plant cells more effectively, releasing nutrients in a controlled manner, reducing wastage, and promoting efficient nutrient use [3]. Their potential to deliver nutrients directly to the target site can lead to reduced nutrient runoff, a major environmental concern with conventional fertilizers. The rise of nano fertilizers in agriculture promises a range of benefits, including increased yields, improved plant health, and better ecological outcomes. Yet, as with any new technological advancement, it is crucial to understand its impact thoroughly, not only on the crops but on the broader ecosystem. It is within this context that this review seeks to elucidate the scope and significance of nano fertilizer applications, focusing on its effects on plant wellness. The transition from traditional to nano-enhanced agricultural practices isn't just a mere switch in fertilizer type. It's an evolution in the way we understand and approach crop nourishment. The nuances of this transition are manifold. While conventional fertilizers often release nutrients either too quickly, leading to wastage, or too slowly, impeding plant growth, nano fertilizers, with their controlled release mechanisms, aim to strike the right balance. Their size allows for a more intimate interaction with plant cells, facilitating better nutrient absorption and, consequently, better plant health [4]. Plant wellness isn't restricted to just growth and yield. It extends to the plant's ability to combat stress, its nutritional profile, and its overall vigor. Nano fertilizers, with their precision delivery, hold the potential to address these facets of plant health in a more targeted manner than traditional fertilizers ever could. While the prospects sound promising, it is equally essential to consider any unintended consequences. The nanoscale realm behaves differently, and while certain effects are beneficial, there could be unknown ramifications to plant health and the surrounding environment. This review, therefore, aims not only to shine a light on the evident benefits of nano fertilizers but also to probe into areas that require investigation.

Methods

The methodology employed in this review is crucial for ensuring that the information gathered on the effects and consequences of nano fertilizer application on plant wellness is reliable, pertinent, and rigorous. The primary focus was on how studies were selected, ensuring that the breadth and depth of research in this domain were covered. Once the relevant studies were identified, a systematic data extraction process was conducted to categorize, collate, and evaluate the information found in these studies. This methodological approach was designed not just for comprehensiveness, but also for transparency, allowing readers to understand and, if necessary, replicate the research process. Determining which studies to include was both a rigorous and meticulous process. Given the significance of the topic, it was essential to ensure that the studies selected for review were not only relevant but also of high academic and scientific quality. **Relevance:** The first and most fundamental criterion was the relevance of the study to the topic. Only studies that directly investigated the effects and consequences of nano fertilizers on plant wellness were considered. **Date of Publication:** Due to the rapidly evolving nature of nanotechnology and its applications in agriculture, priority was given to more recent

studies. This ensured that the findings were contemporary and aligned with the latest technological advancements. Studies from the last decade were primarily considered, with a few seminal works from before this period included for foundational understanding [5]. Research Design: Studies that employed robust research methodologies were prioritized. This included experimental studies, longitudinal studies, and comprehensive reviews. While observational studies and case reports provided valuable insights, they were weighed against more rigorous research designs. Peer-Reviewed: Only studies that had undergone the peer-review process were considered. This acted as a quality check, ensuring that the research methodologies and findings had been vetted by experts in the field. Geographic Distribution: To ensure a holistic understanding, studies from various geographical regions were considered. This allowed for insights into how nano fertilizers' effects might vary depending on soil types, climates, and specific crop varieties. Multiple academic databases were used to ensure a comprehensive search. These included: PubMed: A leading source for life science and biomedical literature. It provided studies that investigated the biochemical and physiological effects of nano fertilizers on plants. Web of Science: An interdisciplinary database, it offered research articles that spanned the gamut from the fundamental science behind nano fertilizers to their practical applications. Scopus: Given its vast repository of scientific literature, Scopus was instrumental in identifying both primary research articles and review papers on the topic. AGRIS: As a specialized database focusing on agricultural science, AGRIS was invaluable in pinpointing research specifically geared towards the application of nanotechnology in agriculture [6]. Once the studies were selected based on the criteria mentioned above, the next challenge was extracting relevant data from them. This step was pivotal, as it determined the quality and relevance of the information that would be discussed in the review. Approach to Collate, Categorize, and Evaluate Pertinent Data: Data Compilation: Initial efforts were focused on compiling all the relevant data from the selected studies. This involved summarizing key findings, noting down methodologies used, and recording results and conclusions. Categorization: Once compiled, the data was grouped under broad themes for clarity and coherence. These themes revolved around the effects of nano fertilizers on plant growth, their biochemical implications, environmental consequences, and economic considerations. Cross-Validation: It was essential to ensure the reliability of the data. This involved cross-referencing findings across multiple studies to identify consistent trends, discrepancies, or anomalies. Quantitative Analysis: For studies that provided quantitative data, statistical analyses were undertaken to discern patterns, significance levels, and correlations. This ensured that the review wasn't just qualitative but had a firm grounding in empirical evidence. Qualitative Analysis: Apart from numeric data, many studies provided qualitative insights. These were analyzed using thematic analysis, helping identify overarching themes, concerns, and implications related to nano fertilizers in agriculture [7]. Interpretation: After the extraction and categorization, the data was then interpreted in the context of the broader scientific and agricultural landscape. This was crucial in determining the real-world implications of the findings.

Nano Fertilizers

Agriculture, as one of the pillars of human civilization, has consistently evolved, adapting to the needs of an expanding global population and the pressures of a changing environment. The introduction of nano fertilizers represents one of the most recent evolutions, promising to revolutionize the way we nourish our crops. But to appreciate their potential and address associated challenges, a foundational understanding of what nano fertilizers are and how they are categorized is essential. At its core, a nano fertilizer is not drastically different from a traditional fertilizer. Both supply plants with essential nutrients to promote growth, yield, and overall health. The distinction lies in the scale and delivery mechanism. Nano fertilizers are essentially fertilizers that have been engineered to the nanoscale, typically between 1 and 100 nanometers in at least one dimension [8]. This nano-scale restructuring offers a significant increase in surface area relative to volume, enhancing reactivity and allowing for unique interactions with plant tissues that are not achievable with bulkier, traditional fertilizer particles. The composition of nano fertilizers is where science and nature intertwine. They contain essential nutrients like nitrogen, phosphorus, potassium, and various micro-nutrients. However, these nutrients are encapsulated, embedded, or coated in nanoparticles, which can be of various types: lipid-based, polymer-based, or even inorganic like silica or metal-based nanoparticles. The nano-scale delivery system ensures a more controlled release of nutrients, allowing plants to absorb them more efficiently, thereby reducing wastage and potential environmental pollution [9]. It's also worth noting that the reduced size doesn't just change the physical properties of the fertilizers, but can also alter their chemical and biological properties. Nanoparticles can penetrate plant cells and tissues more easily, allowing for targeted delivery of nutrients directly to cellular sites where they are most needed [10]. Diving deeper into the world of nano fertilizers, we uncover a landscape rich in diversity. This variety is not just essential for catering to different crops and soils but also crucial in optimizing the benefits of nanotechnology for agriculture.

Organic Nano Fertilizers: These are derived from biological materials, like proteins or lipids, and are engineered to provide nutrients in an organic matrix. For instance, lipid-based nanoparticles can be loaded with nutrients, ensuring a slow and steady release.

Inorganic Nano Fertilizers: These consist of inorganic nanoparticles like silica, zinc oxide, or even gold nanoparticles. They are often used to deliver specific micro-nutrients to plants, leveraging their unique properties, like high stability or specific interactions with plant tissues [11].

Bio-derived Nano Fertilizers: These are synthesized using biological processes. For instance, certain fungi and bacteria can produce nanoparticles when supplied with metal ions. Such bio-derived nanoparticles can then be loaded with nutrients and used as fertilizers.

Chemically Synthesized Nano Fertilizers: These are produced using chemical reactions and processes, often in laboratories. The advantage here is precision, as chemists can control the size, shape, and properties of the nanoparticles with great accuracy [12].

Slow-release Nano Fertilizers: These are designed to release nutrients over an extended period, reducing the need for frequent fertilization and ensuring steady nutrition for the plant.

Targeted Nano Fertilizers: Leveraging the unique properties of nanoparticles, these fertilizers can deliver nutrients to specific parts of the plant, like roots or specific cellular organelles. This can be particularly useful when addressing specific nutrient deficiencies or

aiming to stimulate certain physiological processes. Multifunctional Nano Fertilizers: These are the epitome of nanotechnological advancement in agriculture. They don't just supply nutrients but can also offer protection against pests, improve soil health, or even monitor plant health by including sensing elements [13].

Table 1: Impact of NFs on productivity of different crops plants. [14]

Nanofertilizers	Crops	Yield increment (%)
Nanofertilizer + urea	Rice	10.2
	Rice	8.5
	Wheat	6.5
	Wheat	7.3
Nano-encapsulated phosphorous	Maize	10.9
	Soybean	16.7
	Wheat	28.8
	Vegetables	12.0–19.7
Nano chitosan-NPK fertilizers	Wheat	14.6
	Tomato	20.0
	Cucumber	9.3
	Capsicum	11.5
	Beet-root	8.4
	Pea	20.0
Nanopowder of cotton seed and ammonium fertilizer	Nanopowder of cotton seed and ammonium fertilizer	16.0
Aqueous solution on nanoiron	Cereals	8–17
Nanoparticles of ZnO	Cucumber	6.3
	Peanut	4.8
	Cabbage	9.1
	Cauliflower	8.3
	Chickpea	14.9
Rare earth oxides nanoparticles	Vegetables	7–45
Nanosilver + allicin	Cereals	4–8.5
Iron oxide nanoparticles + calcium carbonate nanoparticles + peat	Cereals	14.8–23.1
Sulfur nanoparticles + silicon dioxide nanoparticles + synthetic fertilizer	Cereals	3.4–45

Mechanism of Action

Modern agriculture sits at the intersection of science and nature, always striving for efficient ways to harness the bounty of the soil. Within this dynamic, nano fertilizers emerge as both an evolution and revolution, redefining the traditional paradigms of plant nutrition. Their efficacy, however, is rooted in their underlying mechanisms of action, which redefine how plants access and utilize essential nutrients. The essence of a fertilizer's effectiveness rests not just in its

nutrient content but in how effectively these nutrients are absorbed by plants. Traditional fertilizers, although beneficial, often face challenges in ensuring that a maximum portion of their nutrient content is taken up by the plants. Nutrient losses due to leaching, evaporation, or microbial action are common issues. Nano fertilizers, by virtue of their size and design, are poised to overcome these challenges. At the nanoscale, the interactions between matter change profoundly. These tiny particles can more easily penetrate the protective barriers of plant roots, ensuring a direct pathway for nutrient delivery [15]. Their large surface area relative to volume means that a greater portion of the nutrient-loaded particle interacts directly with plant tissues, facilitating a more efficient transfer. Additionally, the nanostructure can protect the nutrients from external environmental factors. For instance, nano-encapsulated nitrogen can be shielded from microbial action in the soil, ensuring that more of it remains available for the plant. This efficient delivery system means that even at reduced application rates, nano fertilizers can achieve, or even surpass, the effectiveness of their traditional counterparts [16]. One of the most groundbreaking attributes of nano fertilizers is their ability for targeted delivery. In traditional fertilization, nutrients are distributed somewhat indiscriminately, relying on the plant's root system to locate and absorb them. Nano fertilizers, however, can be engineered to deliver their nutrient content directly to specific parts of the plant. This precision is achieved through various mechanisms. Some nano fertilizers are designed to be attracted to specific cellular components in the root system, ensuring that they release their nutrients right where they're most needed [17]. Others can be triggered to release their nutrient content in response to specific environmental or physiological cues, such as changes in soil pH, moisture levels, or even the presence of certain enzymes in the plant tissue. This targeted approach not only ensures efficient nutrient use but can also mitigate potential environmental impacts. For instance, phosphorus, when applied in excess, can run off into water systems and cause issues like algal blooms. By ensuring a targeted and efficient delivery of phosphorus right to the plant roots, nano fertilizers can significantly reduce such environmental risks [17].

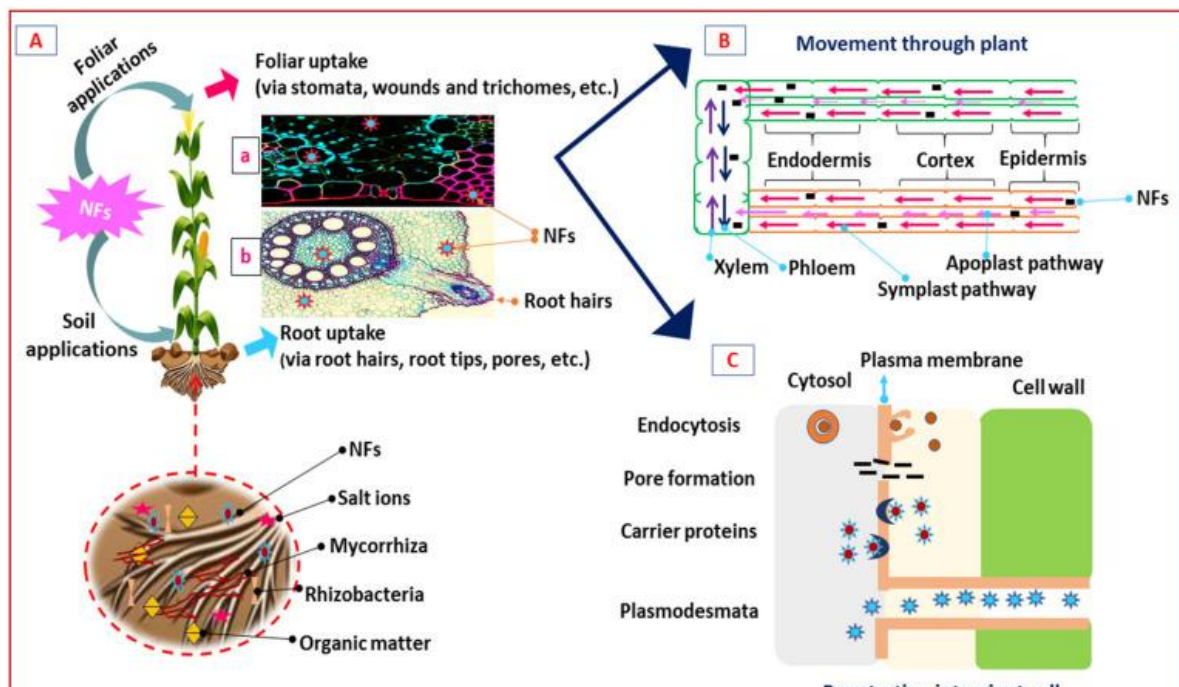


Image 1: Uptake of NFs via various channels and their translocation paths across multiple plant sections are depicted schematically. (Source: <https://www.ncbi.nlm.nih.gov/>)

Bioavailability refers to the proportion of a substance that enters the organism's system and is actively used. In the context of fertilizers, it represents the fraction of applied nutrients that plants can effectively absorb and utilize. Nano fertilizers have shown a marked increase in the bioavailability of nutrients, a phenomenon rooted in several reasons. Firstly, the nanoscale structure of these fertilizers ensures a higher surface contact with plant tissues. This direct interaction facilitates an enhanced dissolution of nutrients in the plant's internal aqueous environment, making them more readily available for cellular processes. The protective attributes of many nanostructures mean that nutrients are shielded from interactions that might render them unavailable. For instance, certain soil compositions can bind with nutrients like phosphorus, preventing plants from accessing them. Nano-encapsulation can shield phosphorus from such interactions, ensuring that a greater portion remains bioavailable [19]. Lastly, there's the potential for synergy. Some nano fertilizers can deliver not just nutrients but also other compounds that enhance the plant's ability to absorb and utilize these nutrients. For instance, certain nanoparticles can stimulate root growth or enhance cellular permeability, ensuring that the accompanying nutrients are more effectively utilized [20].

Effects of Nano Fertilizer Application

The convergence of nanotechnology and agriculture has garnered significant attention in recent years. As humanity grapples with challenges like population growth, climate change, and dwindling arable land, innovative solutions like nano fertilizers offer a beacon of hope. But what

are the tangible benefits of nano fertilizers when applied to crops? To truly understand their potential, we need to delve deep into the observed effects of their application on plant growth, yield, nutritional quality, and resilience. The primary goal of any fertilizer is to promote growth, and nano fertilizers excel in this arena. Numerous studies have documented significant enhancements in growth parameters upon nano fertilizer application. Shoot and root lengths have been observed to increase significantly in plants treated with nano fertilizers compared to those treated with traditional fertilizers [21]. This not only ensures a robust above-ground plant structure but also a well-established root system capable of accessing water and nutrients effectively. There's a marked increase in plant biomass, signifying a more efficient conversion of nutrients into plant tissues. Leaf area, a critical parameter influencing photosynthesis and, by extension, overall plant health, has also been reported to improve. The enhanced nutrient uptake facilitated by the nanoscale delivery mechanisms ensures that plants receive optimal nourishment, translating into robust growth and development [22]. Beyond growth, the true metric of a fertilizer's success is the yield it facilitates. In the realm of nano fertilizers, the results are promising. Enhanced seed production has been documented in several crops, indicating a direct impact on reproductive success. The quality of the produce is of paramount importance. Fruits treated with nano fertilizers not only tend to be larger but also exhibit better texture, color, and overall appearance. This can be attributed to the balanced and efficient nutrient supply that these fertilizers offer [23]. Most significantly, the overall yield, be it grain, fruit, or vegetable, has been reported to increase by notable margins upon nano fertilizer application. For farmers and agricultural stakeholders, this translates to better returns and the potential for more sustainable agricultural practices. Beyond quantity, quality matters. The nutritional profile of the produce is a critical concern, especially in regions grappling with malnutrition. Nano fertilizers have shown potential in not just increasing yield but also enhancing the nutritional quality of the produce.

There's documented evidence of increased concentrations of essential nutrients like vitamins, minerals, and proteins in crops treated with nano fertilizers. The phytochemical composition, which includes antioxidants and other beneficial compounds, is also positively influenced. This means that the produce is not just more abundant, but also richer in nutrients that are vital for human health [24]. Every plant, regardless of its location or species, faces a multitude of stresses. From pests and diseases to drought and extreme temperatures, these challenges can significantly impact growth and yield. Nano fertilizers, intriguingly, have been observed to play a role in bolstering plant defenses against such stresses. For biotic stresses, such as pests and pathogens, certain nano fertilizers can deliver nutrients in tandem with compounds that deter these threats. For abiotic stresses, the story is even more compelling. Plants fortified with nano fertilizers exhibit better resilience against environmental challenges. Nano-fertilized plants have shown better drought resistance, attributed to a more robust root system and efficient nutrient utilization that promotes water conservation within the plant tissues [25].

Consequences of Nano Fertilizer Application

The marriage of nanotechnology and agriculture, particularly in the form of nano fertilizers, has elicited both awe and concern. While the benefits of these novel fertilization methods, as covered previously, are numerous, it is equally essential to critically assess the potential consequences. Like all technologies, nano fertilizers come with their own set of challenges and uncertainties, especially in terms of ecological impacts, potential bioaccumulation, and implications for human health. While nano fertilizers present revolutionary potential for crop production, the environmental repercussions of introducing nanoparticles into ecosystems require thoughtful consideration. Nanoparticles, due to their minuscule size, exhibit unique behaviors when released into the environment. Their mobility, for instance, is of significant concern. Unlike larger particles, which might settle rapidly, nanoparticles can be more easily dispersed, carried away by water currents or even wind, and can penetrate deeper into soil profiles or aquatic systems [26]. Such mobility can lead to unintended dissemination across ecosystems, potentially impacting organisms not targeted by the initial application. Another aspect is the persistence of nanoparticles. While some may degrade over time, others can persist in the environment for extended periods, providing a continuous potential source of exposure for flora and fauna. This persistence can lead to chronic exposure for certain organisms, the effects of which are not fully understood. Interactions of nanoparticles with existing environmental components might lead to unforeseen consequences. For instance, certain nanoparticles might bind with naturally occurring toxins, enhancing their uptake by plants or aquatic organisms, thereby exacerbating their harmful effects [27]. One of the significant challenges posed by nanoparticles is their propensity for bioaccumulation. Certain nanoparticles, when taken up by plants, can accumulate within plant tissues rather than being metabolized or excreted. Over time, especially with continuous application of nano fertilizers, this can lead to significant concentrations within plants. While this accumulation might not always be harmful to the plants themselves, it presents potential challenges as we move up the food chain. Herbivorous organisms consuming these plants will intake these nanoparticles, and if they too accumulate these particles, it sets the stage for biomagnification. As one moves up the trophic levels, the concentrations can magnify, potentially reaching harmful levels for apex predators, including humans in some cases [28].

Comparison with Conventional Fertilizers

Agriculture's relentless pursuit of maximizing crop yields to meet the global demand for food has witnessed a plethora of innovations. The advent of nanotechnology in the agricultural sector brought forth nano fertilizers, presenting new avenues to enhance crop productivity and nutrition. Yet, a pertinent question lingers: How do nano fertilizers measure up against their conventional counterparts? To elucidate this comparison, we delve into various aspects, ranging from efficiency to the economic and environmental implications. One of the paramount factors in agriculture is the effective utilization of inputs to achieve optimal outcomes. Conventional fertilizers have, for long, been the mainstay in achieving this. Inefficiencies have been observed, mainly owing to nutrient runoff, leaching, volatilization, and in some instances, poor uptake by plants [29]. Nano fertilizers, on the other hand, tout a revolutionary edge. Their minuscule size

and unique physicochemical properties confer them the ability to enhance nutrient utilization. A significant merit of nano fertilizers lies in their ability to target specific plant structures, ensuring a more direct and efficient nutrient delivery. The outcome? A marked reduction in the quantities required to achieve similar or even superior results compared to conventional fertilizers. Studies have demonstrated that plants can absorb and utilize nutrients from nano fertilizers more effectively, thereby reducing wastage and ensuring that the majority of the applied nutrient reaches its intended target [30]. An effective agricultural practice is not solely gauged by its agronomic efficiency but also its economic viability. Traditional fertilizers, given their long-standing history and established manufacturing processes, often come at a lower initial cost. Their widespread use and production on a large scale have led to economies of scale, making them relatively affordable. Nano fertilizers, while promising superior efficiency, come with a steeper price tag, predominantly due to the intricacies involved in their production. Nanotechnological processes, sophisticated equipment, and quality control measures elevate their production costs [31]. This narrative is gradually shifting. With advancements in nanotechnology and increasing production capacities, costs are expected to decline over time. Beyond production costs, a holistic economic evaluation must factor in long-term returns. Given the efficiency of nano fertilizers, their prolonged effects, and potential to reduce the frequency of application, they might present more sustainable economic advantages in the long run. The potential to produce better quality crops could translate to higher market values, offsetting the initial investment in nano fertilizers. Perhaps the most critical comparison metric in our era of heightened environmental consciousness is the ecological impact. Traditional fertilizers, while pivotal in the Green Revolution and subsequent agricultural advancements, have been linked to various environmental concerns. Nutrient runoffs from fields have led to phenomena such as eutrophication, leading to algal blooms in water bodies, which subsequently result in 'dead zones'—regions with reduced oxygen that cannot support aquatic life [32]. Additionally, the production of these fertilizers, especially nitrogenous ones, has been associated with significant greenhouse gas emissions. Nano fertilizers, at first glance, seem to offer a greener alternative. Their enhanced efficiency means reduced application rates, which can curtail nutrient runoffs. Additionally, their targeted delivery mechanisms could minimize unintended environmental exposures.

Current Challenges and Future Prospects

As we tread into the era of nano-enhanced agriculture, it is crucial to demystify the underlying challenges and recognize the boundless possibilities that the future holds. The canvas of nano fertilizers, while colored with promises of efficiency and sustainability, also bears patches of uncertainties. A balanced understanding of the potential bottlenecks, gaps, and forward-looking trajectories will better equip us for a future where technology and agriculture coalesce seamlessly. At the crux of any scientific innovation lies the robustness of the research underpinning it. With nano fertilizers, while substantial strides have been made, there are glaring gaps that must be addressed. Firstly, much of the current knowledge on nano fertilizers is

empirical. While these insights provide a basis for applications, they lack a thorough mechanistic understanding. Knowing *how* a phenomenon occurs is just as important as knowing *that* it occurs. Such knowledge can aid in refining products, predicting outcomes, and ensuring safety [33]. Another predominant gap is the long-term impact of nano fertilizers. Most studies are relatively short-term, not exceeding a few crop cycles. The perennial nature of soil and perennial crops demands an understanding that spans years, if not decades. Assessing the long-term accumulation, interaction with soil microbiota, and potential degradation pathways of nanoparticles is crucial. Lastly, much of the existing research operates in controlled environments – greenhouses, labs, and simulation chambers. While these provide controlled conditions, they often do not truly represent the complexity and variability of open-field conditions.

Conclusion

Nano fertilizers represent a revolutionary stride in sustainable agriculture, promising enhanced nutrient utilization, crop yield, and overall plant wellness. While they herald numerous benefits, from targeted nutrient delivery to stress resistance in plants, they also come with potential ecological and health ramifications. The juxtaposition of nano fertilizers with conventional counterparts underscores their superior efficiency but also highlights economic and environmental challenges. As we tread forward, addressing research gaps, harnessing technological advancements, and establishing robust regulatory frameworks become imperative. Collaborative efforts between scientists, policymakers, and stakeholders will be pivotal in ensuring that nano fertilizers fulfill their potential in shaping a sustainable and food-secure future.

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