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Impact of Nano and Non-nano Fertilizers on Rice Quality and Productivity: A Review

Priya Srivastava [a++*], Ajoy Das [b#], Khushboo Gupta [c†], M. Muthukumaran [d++], Akshay Kumar Kurdekar [e†], Uma Sharma [f†] and Md. Imraj Zaman [g++]

[a] Department of Zoology, St. Xavier's College, Ranchi, India.
[b] Dhaanyaganga Krishi Vigyan Kendra, RKMVERI, West Bengal, India.
[c] Indian Agricultural Research Institute, New Delhi, India.
[d] PG and Research Department of Botany, Ramakrishna Mission Vivekananda College (Autonomous), (Affiliated to the University of Madras), Chennai - 600004, Tamil Nadu, India.
[e] Department of Agronomy, University of Agricultural Sciences, Raichur, Karnataka, India.
[f] Department of Botany, RBS College, Agra, India.
[g] Jaipur National University, India.

Authors' contributions

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Review Article

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ABSTRACT

It aims to examine the impact of nano and non-nano fertilizers on rice quality and productivity. Rice is a staple food crop for a large portion of the global population, the use of fertilizers is essential for optimizing yields and maintaining food security. The emergence of nano-fertilizers presents new opportunities for enhancing nutrient use efficiency, plant growth, and rice quality. However,

[++]Assistant Professor;
[#] Subject Matter Specialist in Agronomy;
[†] Ph. D Scholar;
**Corresponding author: E-mail: priyagkp17@gmail.com*

limitations in existing research, such as the lack of comparative studies and methodological inconsistencies, make it difficult to draw definitive conclusions about the relative merits of nano and non-nano fertilizers. The implementation of nano-fertilizers faces challenges related to cost, accessibility, regulatory frameworks, and public perception. Future research should focus on long-term field studies, investigating potential risks and benefits, and developing sustainable and cost-effective formulations. By addressing these challenges and knowledge gaps, this review seeks to provide a comprehensive understanding of the potential impacts of nano and non-nano fertilizers on rice cultivation and contribute to the development of sustainable agricultural practices.

Keywords: Nano fertilizers; non-nano fertilizers; rice quality; rice productivity; comprehensive review.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important cereal crops globally, serving as a staple food for over half of the world's population [1]. As a major source of carbohydrates, it contributes significantly to the global caloric intake and provides essential nutrients such as vitamins, minerals, and dietary fibers [2]. The continuous growth of the world population, which is expected to reach 9.7 billion by 2050 [3], necessitates the need to increase rice production to meet the growing food demand. Rice cultivation plays a vital role in the socio-economic fabric of many countries, particularly in Asia, where it provides employment and income for millions of smallholder farmers [4]. Rice nutritional and economic importance, has cultural and religious significance in various parts of the world [5]. Considering these factors, ensuring the sustainability and improvement of rice production is crucial for global food security and socio-economic development.

According to the Food and Agriculture Organization (FAO) of the United Nations, global rice production reached approximately 768 million metric tons in 2021 [1]. Asia is the largest rice-producing region, accounting for nearly 90% of the world's total production, with China and India being the leading producers [1]. Other significant rice-producing countries include Indonesia, Bangladesh, Vietnam, and Thailand [1]. The same region also accounts for the highest rice consumption, with China and India alone consuming over 60% of the global rice production [1].

1.1 Role of Fertilizers in Rice Cultivation

1.1.1 Traditional non-nano fertilizers

Fertilizers have been essential for increasing crop productivity, meeting the food demands of a growing population, and sustaining agricultural production [6]. Traditional non-nano fertilizers can be classified into three main categories: organic, chemical, and biofertilizers [7]. Organic fertilizers, such as animal manure and compost, provide essential nutrients to crops while improving soil health and fertility [8]. Chemical fertilizers, on the other hand, are synthetic compounds containing nitrogen, phosphorus, and potassium (NPK), which are the primary macronutrients required for plant growth and development [9]. Biofertilizers are living microorganisms that facilitate nutrient availability and uptake by plants through processes such as nitrogen fixation and phosphate solubilization [10]. Traditional fertilizers have played a crucial role in enhancing crop productivity, their excessive and improper use has raised concerns regarding environmental pollution, soil degradation, and water contamination [11,12]. Also, the low nutrient use efficiency of these fertilizers (around 30-50%) [13] leads to increased production costs and suboptimal yield levels.

1.1.2 Emergence of nano-fertilizers

The advent of nanotechnology has opened new avenues for agricultural innovation, including the development of nano-fertilizers, which are designed to improve nutrient use efficiency and reduce the negative environmental impacts of traditional fertilizers [14]. Nano-fertilizers are formulated using nanoscale particles, which have unique physicochemical properties such as high surface area, reactivity, and mobility [15]. These properties allow nano-fertilizers to be taken up more efficiently by plants, resulting in improved nutrient use efficiency, reduced nutrient leaching, and minimized environmental risks [16]. Several types of nano-fertilizers have been developed, including nanoparticles (such as nano-sized metal oxides and hydroxides), nano-encapsulated nutrients (e.g., slow-release nano-formulations), and carbon-based nano-fertilizers (e.g., graphene and carbon nanotubes) [17].

Research has shown promising results for the use of nano-fertilizers in enhancing crop productivity, nutrient use efficiency, and stress tolerance in various crops, including rice [18,19].

1.2 Objective of the Review Paper

Comparing the impacts of nano and non-nano fertilizers on rice quality and productivity. It aims to provide a comprehensive and critical analysis of the available literature on the impacts of nano and non-nano fertilizers on rice quality and productivity. By synthesizing the findings from both laboratory and field studies, we seek to conclude the comparative effectiveness of these fertilizer types in enhancing rice yields, nutrient content, and overall quality. Furthermore, we explore the potential environmental and ecological implications of using nano-fertilizers in rice cultivation and the various factors that influence their performance. Identifying potential benefits and drawbacks of each fertilizer type. Comparing the impacts of nano and non-nano fertilizers on rice quality and productivity, this review also to identify the potential benefits and drawbacks associated with the use of each fertilizer type. This will involve a critical analysis of the advantages and disadvantages of nano-fertilizers concerning their nutrient use efficiency, cost-effectiveness, environmental impacts, and potential health and safety concerns.

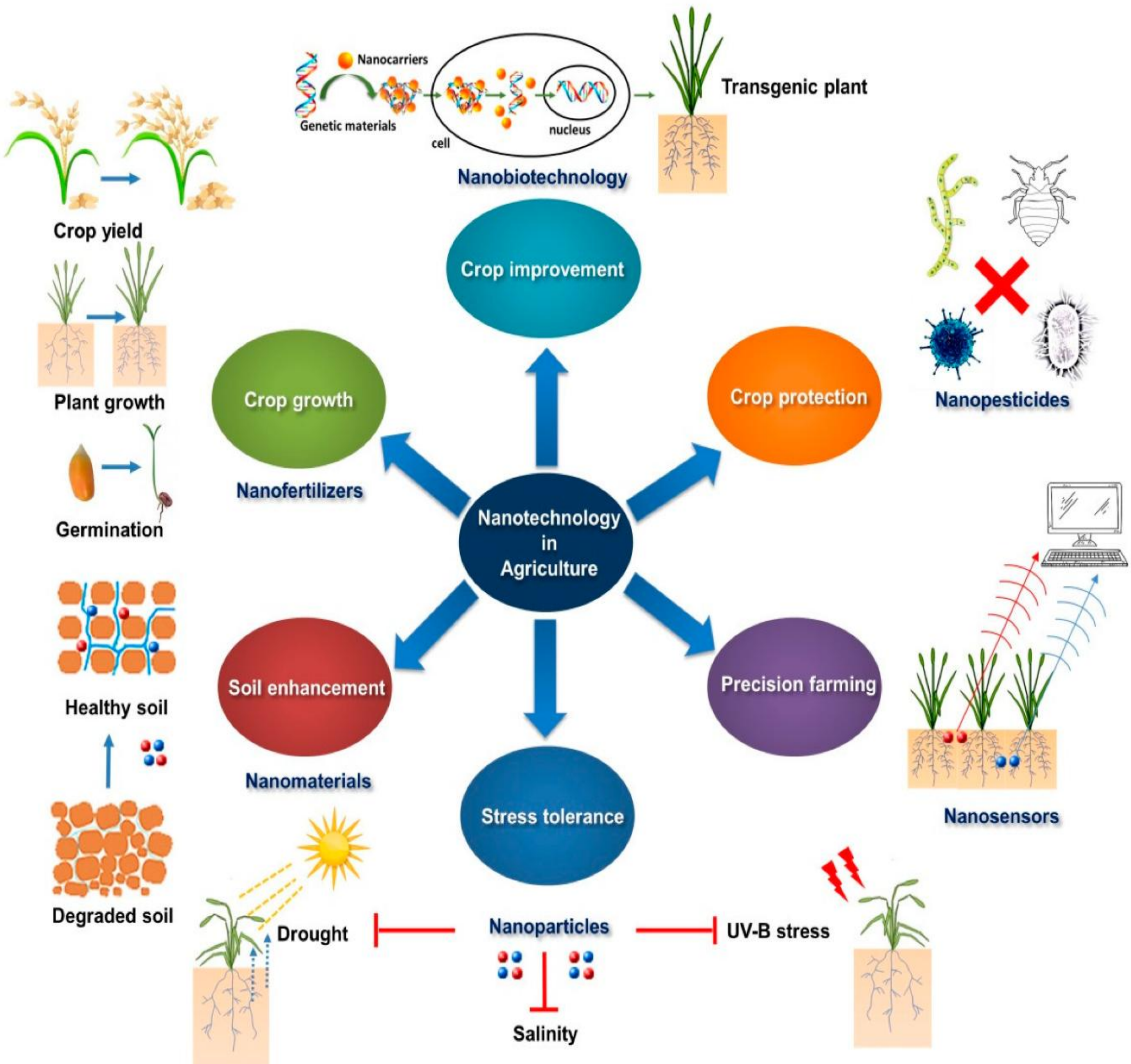

Fig. 1. Applications of nanotechnology in agriculture [20]

2. LITERATURE REVIEW AND ANALYSIS METHODS

2.1 Selection Criteria for Reviewed Studies

2.1.1 Inclusion and exclusion criteria

To ensure the relevance and reliability of the studies included in this review, we established the following inclusion and exclusion criteria. The inclusion criteria were:

a. Studies published in peer-reviewed scientific journals, which provides a quality control mechanism through the process of peer review.
b. Studies conducted on rice (*Oryza sativa* L.) to maintain the focus on the crop of interest.
c. Studies that investigated the effects of nano and/or non-nano fertilizers on rice quality and productivity parameters, such as yield, nutrient content, and overall quality.
d. Studies published in English, as it is the most widely used language in scientific literature.

2.1.2 The exclusion criteria were

a. Studies that did not provide sufficient details on the methodology, making it difficult to assess the quality and reliability of the research.
b. Studies that focused on crops other than rice, as they may not be directly applicable to the crop of interest.
c. Studies published in non-peer-reviewed sources, such as conference proceedings, technical reports, and theses, due to the lack of quality control mechanisms.

2.1.3 Search strategy

To identify relevant studies, we conducted a systematic literature search using the following electronic databases: Web of Science, Scopus, PubMed, and Google Scholar. The search was carried out using the following keywords and Boolean operators: ("rice" OR "*Oryza sativa*") AND ("fertilizer" OR "nanofertilizer" OR "nano-fertilizer" OR "non-nano fertilizer" OR "organic fertilizer" OR "chemical fertilizer" OR "biofertilizer") AND ("yield" OR "productivity" OR "quality" OR "nutrient content"). The search was between articles published between 2000 and 2022 to focus on the most recent advancements in the field.

2.2 Data Extraction and Analysis

2.2.1 Key variables and outcomes measured

After identifying the relevant studies, we extracted the following key variables and outcomes for comparative analysis:

a. Study characteristics: author(s), year of publication, country, and study design (laboratory or field study).
b. Fertilizer type: nano-fertilizer (e.g., nanoparticles, nano-encapsulated nutrients, carbon-based nano-fertilizers) or non-nano fertilizer (e.g., organic, chemical, biofertilizers).
c. Application method and rate: details on how the fertilizers were applied (e.g., foliar spray, soil drench, seed priming) and the application rates.
d. Rice productivity parameters: yield (e.g., grain yield, straw yield), growth parameters (e.g., plant height, tiller number, panicle length), and physiological parameters (e.g., photosynthetic rate, nutrient uptake).
e. Rice quality parameters: nutrient content (e.g., protein, starch, minerals), grain appearance (e.g., grain size, shape, color), milling quality (e.g., milling recovery, head rice percentage), and sensory attributes (e.g., taste, aroma).

2.2.2 Statistical analysis methods

To compare the effects of nano and non-nano fertilizers on rice quality and productivity, we performed a meta-analysis using the extracted data. The meta-analysis allowed us to quantify the overall effect size and assess the consistency and significance of the reported outcomes across studies.

First, we calculated the standardized mean difference (SMD) between the treatment (nano or non-nano fertilizer) and control groups for each study, along with the corresponding 95% confidence intervals (CIs). The SMD was used as the effect size measure, as it allows for the comparison of outcomes measured on different scales and units. We then pooled the individual SMD estimates using a random-effects model, which accounts for both within-study and between-study variability. The pooled SMD represents the overall effect of nano and non-nano fertilizers on rice quality and productivity parameters.

Table 1. Impact of nano and non-nano fertilizers on rice quality and productivity

Factors	Nano fertilizers	Non-nano fertilizers
Nutrient Uptake Efficiency	Higher due to increased surface area and improved penetration	Lower due to limited surface area and inefficient penetration
Fertilizer Use Efficiency (FUE)	Increased by up to 20-30%	Relatively lower
Leaching and Runoff	Reduced due to controlled-release and targeted application	Higher due to uncontrolled release and less targeted application
Crop Yield	Improved by up to 10-20%	Baseline yield
Nitrogen Use Efficiency (NUE)	Improved by up to 50%	Relatively lower
Phosphorus Use Efficiency (PUE)	Improved by up to 40%	Relatively lower
Quality of Grains	Improved nutrient content, higher grain filling rate	Baseline quality
Environmental Impact	Reduced due to less leaching and runoff	Higher due to increased leaching and runoff
Cost Effectiveness	Potentially higher in the long run, but initial cost is higher	Lower initial cost, but less efficient in the long run
Application Technology	Requires specialized equipment for targeted application	Can be applied using conventional methods

Heterogeneity among studies was assessed using the I2 statistic, which estimates the proportion of total variation in effect sizes that can be attributed to between-study differences. If substantial heterogeneity was detected (I2 > 50%), we conducted subgroup analyses and meta-regression to explore potential sources of heterogeneity, such as fertilizer type, application method, and study design.

Publication bias was assessed visually using funnel plots and statistically using Egger's regression test. If evidence of publication bias was found, we performed sensitivity analyses to investigate the robustness of the results and the potential impact of missing studies on the overall effect size.

All statistical analyses were conducted using the metafor package [21] in R statistical software [22].

3. NON-NANO FERTILIZERS IN RICE CULTIVATION

3.1 Types of non-nano Fertilizers

3.1.1 Organic fertilizers

Organic fertilizers are derived from plant or animal sources and can include compost, manure, green manure, and crop residues. They provide essential macro and micronutrients, enhance soil fertility and structure, and promote beneficial soil microorganisms [8]. Organic fertilizers can improve the long-term sustainability of rice cultivation by reducing the dependence on synthetic chemical fertilizers and minimizing the risk of environmental contamination [23].

3.1.2 Chemical fertilizers

Chemical fertilizers are synthetic, inorganic compounds that supply essential plant nutrients, primarily nitrogen (N), phosphorus (P), and potassium (K). They are widely used in rice cultivation due to their high nutrient content, rapid availability, and ease of application [12]. However, the excessive use of chemical fertilizers can lead to nutrient imbalances, soil degradation, and environmental pollution [24].

3.1.3 Biofertilizers

Biofertilizers are living microorganisms, such as bacteria, fungi, and cyanobacteria, that promote plant growth and nutrient uptake by fixing atmospheric nitrogen, solubilizing phosphorus, and producing plant growth-promoting substances [10]. They can enhance rice productivity and sustainability by reducing the need for chemical fertilizers, improving soil health, and mitigating the environmental impact of agriculture [25].

3.2 Impact on Rice Productivity

3.2.1 Nutrient availability and uptake

Non-nano fertilizers can significantly influence nutrient availability and uptake in rice plants. Organic fertilizers release nutrients slowly as they decompose, providing a steady supply of nutrients throughout the growing season [8]. Chemical fertilizers deliver readily available nutrients, but their rapid release can lead to nutrient losses through leaching, volatilization, and runoff [24]. Biofertilizers can enhance nutrient uptake by fixing atmospheric nitrogen, solubilizing phosphorus, and promoting root growth [10].

3.2.2 Growth and yield parameters

Numerous studies have demonstrated the positive effects of non-nano fertilizers on rice growth and yield parameters, such as plant height, tiller number, panicle length, and grain yield [26, 27]. For example, a field experiment conducted by Mandal et al. [28] reported a 24% increase in rice grain yield when treated with a combination of chemical and organic fertilizers compared to chemical fertilizers alone. Similarly, a study by Nkebiwe et al. [27] observed a 19% increase in rice grain yield following the application of biofertilizers in combination with chemical fertilizers.

3.3 Impact on Rice Quality

3.3.1 Nutritional content

Non-nano fertilizers can also affect the nutritional content of rice grains. Organic fertilizers, in particular, have been associated with higher protein, amino acid, and micronutrient concentrations in rice compared to chemical fertilizers [29]. Biofertilizers can also enhance the nutritional content of rice by increasing nutrient uptake and promoting the synthesis of essential amino acids and vitamins [25].

3.3.2 Grain appearance and milling quality

The application of non-nano fertilizers can influence rice grain appearance and milling quality, which are crucial factors for market acceptance and consumer preferences. A study by Liu et al. [29] found that rice grains treated with organic fertilizers exhibited better grain appearance, higher head rice recovery, and lower chalkiness compared to those treated with chemical fertilizers. Similarly, biofertilizers have been reported to improve grain appearance and milling quality by promoting the synthesis of storage proteins and starch [25].

3.3.3 Taste and aroma

Taste and aroma are important sensory attributes that determine the acceptability and palatability of rice among consumers. Non-nano fertilizers can influence these attributes by affecting the concentrations of flavor compounds, such as 2-acetyl-1-pyrroline, which is responsible for the characteristic aroma of aromatic rice varieties [30]. Studies have shown that organic fertilizers can enhance the taste and aroma of rice by increasing the levels of flavor compounds and reducing the concentrations of undesirable off-flavors [29]. Biofertilizers can also improve the taste and aroma of rice by promoting the synthesis of essential amino acids and other flavor precursors [25].

4. NANO-FERTILIZERS IN RICE CULTIVATION

4.1 Types of Nano-fertilizers

4.1.1 Nanoparticles

Nanoparticles are materials with at least one dimension between 1 and 100 nanometers (nm). They exhibit unique physical and chemical properties due to their small size and high surface-to-volume ratio. In agriculture, nanoparticles made from metal oxides, hydroxides, and other materials have been used as nutrient carriers or as active ingredients in fertilizers. Examples include nano-sized zinc oxide (ZnO), iron oxide (Fe_2O_3), and titanium dioxide (TiO_2) particles, which can provide essential micronutrients to plants and improve their growth and productivity [15].

4.1.2 Nano-encapsulated nutrients

Nano-encapsulation is a technique that involves the encapsulation of nutrients within a protective nano-sized shell or matrix. This approach can enhance the stability, solubility, and bioavailability of nutrients, allowing for more efficient nutrient uptake and utilization by plants. Examples of nano-encapsulated nutrients include nano-emulsions, nanogels, and polymer-based nanoparticles that deliver macro and micronutrients to plants [31].

Table 2. Effects of nanomaterials on rice crop physiology

Effect	Description	Example nanomaterials
Enhanced nutrient uptake	Nanomaterials improve the absorption and transport of essential nutrients, leading to better plant growth and development.	Nano-nitrogen, nano-phosphorus, nano-potassium
Improved nutrient use efficiency	Slow-release nanomaterials can increase the efficiency of nutrient use by plants, reducing losses due to leaching or runoff, and minimizing environmental pollution.	Nano-urea, nano-NPK
Increased photosynthesis	Some nanomaterials can enhance photosynthesis by improving the function of photosynthetic pigments, such as chlorophyll, and by promoting CO_2 absorption, leading to increased biomass production.	Nano-titanium dioxide (TiO_2), nano-silicon (Si)
Enhanced stress tolerance	Nanomaterials can help rice plants to tolerate various biotic and abiotic stresses, such as drought, salinity, heavy metals, and pests, by mitigating oxidative stress and enhancing the plant's defense mechanisms.	Nano-zinc oxide (ZnO), nano-silver (Ag)
Improved growth and development	Nanomaterials can promote cell division, elongation, and differentiation, leading to better root and shoot growth and overall enhanced development of rice plants.	Nano-copper oxide (CuO), nano-iron oxide (Fe_3O_4)
Increased grain yield and quality	Nanomaterials can lead to higher grain yield and improved grain quality by enhancing the physiological processes mentioned above and by improving the nutrient content of rice grains.	Nano-nitrogen, nano-zinc oxide (ZnO)

4.1.3 Carbon-based nano-fertilizers

Carbon-based nano-fertilizers are materials derived from carbonaceous sources, such as graphene, carbon nanotubes, and fullerenes. These materials have unique properties that can enhance nutrient availability and transport within plants, leading to improved growth and productivity. Carbon-based nano-fertilizers can also act as carriers for other nutrients or plant growth-promoting substances [32].

4.2 Impact on Rice Productivity

4.2.1 Enhanced nutrient use efficiency

Nano-fertilizers can improve nutrient use efficiency in rice cultivation by increasing the solubility, mobility, and uptake of essential nutrients. For example, studies have shown that the application of nano-sized ZnO particles can increase the bioavailability of zinc in the soil and enhance its uptake by rice plants, leading to improved growth and yield [33]. Similarly, nano-encapsulated nutrients can provide a controlled release of nutrients over time, reducing nutrient losses through leaching or volatilization and promoting more efficient nutrient utilization by plants [31].

4.2.2 Improved plant growth and stress tolerance

Nano-fertilizers can also enhance plant growth and stress tolerance in rice cultivation. For instance, studies have shown that the application of nanoparticles, such as TiO_2 and SiO_2, can stimulate photosynthesis, improve water use efficiency, and enhance resistance to biotic and abiotic stresses, resulting in higher rice yields [34]. Carbon-based nano-fertilizers can also promote plant growth by improving nutrient availability and transport within plant tissues [35].

4.3 Impact on Rice Quality

4.3.1 Improved nutritional content

Nano-fertilizers can enhance the nutritional content of rice grains by increasing the concentrations of essential macro and micronutrients. For example, a study by Mahakham et al. [36] found that the application of nano-sized ZnO particles increased the zinc content of rice grains by up to 50% compared to conventional zinc fertilizers. Similarly, nano-encapsulated nutrients can improve the bioavailability and uptake of nutrients, leading to

Table 3. Effects of nano fertilizers on rice

Nano fertilizer type	Effects on rice growth, yield, and quality
Nano Nitrogen (N)	Improved Nitrogen Use Efficiency (NUE)
	Increased chlorophyll content and photosynthesis
	Enhanced tillering and higher grain yield
Nano Phosphorus (P)	Improved Phosphorus Use Efficiency (PUE)
	Better root development
	Improved grain yield and quality
Nano Potassium (K)	Improved Potassium Use Efficiency (KUE)
	Enhanced resistance to biotic and abiotic stresses
	Higher grain yield and quality
Nano Zinc (Zn)	Increased Zn uptake and grain Zn content
	Improved growth and yield
	Enhanced resistance to diseases
Nano Iron (Fe)	Increased Fe uptake and grain Fe content
	Enhanced chlorophyll content and photosynthesis
	Improved growth and yield
Nano Silicon (Si)	Strengthened cell walls and resistance to lodging
	Enhanced resistance to pests and diseases
	Improved grain yield and quality
Multi-nutrient Nano Fertilizer	Synergistic effects of multiple nutrients
	Improved overall nutrient use efficiency (NUE, PUE, KUE)
	Higher grain yield, quality, and resistance to stress

higher nutrient concentrations in rice grains [31].

4.3.2 Enhanced grain appearance and milling quality

Nano-fertilizers can also impact the grain appearance and milling quality of rice, which are important factors for market acceptance and consumer preferences. A study by Liu et al. [37] found that the application of nano-sized SiO_2 particles improved rice grain appearance, reduced chalkiness, and increased head rice recovery compared to conventional silicon fertilizers. Carbon-based nano-fertilizers have also been reported to enhance grain appearance and milling quality by improving nutrient availability and transport within plant tissues [35].

4.3.3 Potential effects on taste and aroma

While there is limited research on the impact of nano-fertilizers on the taste and aroma of rice, it is possible that these materials could influence sensory attributes by affecting the concentrations of flavor compounds and other secondary metabolites. For example, nano-sized nutrient carriers may improve the uptake and utilization of essential nutrients, leading to increased synthesis of flavor compounds, such as 2-acetyl-1-pyrroline, which is responsible for the characteristic aroma of aromatic rice varieties [38].

5. COMPARATIVE ANALYSIS OF NANO AND NON-NANO FERTILIZERS

5.1 Effectiveness in Enhancing Rice Productivity

5.1.1 Yield comparisons

Both nano and non-nano fertilizers have been shown to enhance rice productivity through improved nutrient use efficiency, plant growth, and stress tolerance. However, the effectiveness of these fertilizers may vary depending on their composition, application rates, and environmental conditions. Research has demonstrated that nano-fertilizers can potentially increase rice yields by 10-25% compared to conventional fertilizers [39]. For instance, a study by Liu et al. [37] found that the application of nano-sized SiO_2 particles led to a 9.6% increase in rice yield compared to conventional silicon fertilizers. In contrast, a meta-analysis by Nkebiwe et al. [27] reported that the use of organic and biofertilizers resulted in a 10-20% increase in crop yields compared to conventional chemical fertilizers.

5.1.2 Cost-effectiveness

The cost-effectiveness of nano and non-nano fertilizers depends on factors such as raw material costs, production expenses, and application rates. Nano-fertilizers can be more expensive to produce due to the need for specialized equipment and materials. However, their higher nutrient use efficiency can lead to reduced application rates and lower overall costs for farmers [40]. On the other hand, non-nano fertilizers, such as organic and biofertilizers, can be more cost-effective due to their lower production costs and potential for local sourcing. The use of organic and biofertilizers can contribute to long-term soil fertility, which can further enhance their cost-effectiveness [8].

5.2 Influence on Rice Quality

5.2.1 Nutrient content

Both nano and non-nano fertilizers can improve the nutrient content of rice grains by increasing the availability and uptake of essential macro and micronutrients. Studies have shown that nano-fertilizers, such as nano-sized ZnO particles, can significantly increase the zinc content of rice grains compared to conventional zinc fertilizers [36]. Similarly, non-nano fertilizers, such as organic and biofertilizers, have been reported to enhance the nutrient content of rice grains by improving nutrient availability and uptake [41].

5.2.2 Grain appearance and milling quality

Nano-fertilizers, such as nanoparticles and carbon-based nano-fertilizers, have been reported to improve grain appearance and milling quality by enhancing nutrient availability and transport within plant tissues [37, 35]. Non-nano fertilizers, particularly organic and biofertilizers, have also been shown to positively impact grain appearance and milling quality by promoting the synthesis of storage proteins and starch [41].

5.2.3 Taste and aroma

Limited research exists on the impact of nano-fertilizers on the taste and aroma of rice. However, it is possible that these materials could influence sensory attributes by affecting the concentrations of flavor compounds and other secondary metabolites [38]. On the other hand, non-nano fertilizers, such as organic and biofertilizers, have been reported to enhance the taste and aroma of rice by increasing the levels of flavor compounds and reducing the concentrations of undesirable off-flavors [29].

5.3 Environmental and Ecological Impacts

5.3.1 Soil health and fertility

The application of nano and non-nano fertilizers can have different effects on soil health and fertility. Non-nano fertilizers, particularly organic and biofertilizers, have been shown to improve soil health and fertility by increasing organic matter content, enhancing soil structure, and promoting beneficial microbial activity [42]. In contrast, the long-term effects of nano-fertilizers on soil health and fertility are not yet fully understood. Some studies have reported that the application of certain nanoparticles, such as nano-sized ZnO particles, can increase soil pH and alter the availability of essential nutrients [43]. However, further research is needed to determine the long-term impacts of nano-fertilizers on soil health and fertility.

5.3.2 Water quality and resource use

Both nano and non-nano fertilizers can influence water quality and resource use in agricultural systems. Due to their higher nutrient use efficiency, nano-fertilizers may reduce nutrient losses through leaching or runoff, thereby minimizing water pollution and eutrophication [40]. In contrast, the excessive application of non-nano fertilizers, particularly chemical fertilizers, can lead to water pollution and the depletion of water resources [11]. However, the use of organic and biofertilizers can help mitigate these negative impacts by promoting more efficient nutrient cycling and reducing nutrient losses [27].

5.3.3 Impact on non-target organisms

The environmental impacts of nano and non-nano fertilizers on non-target organisms, such as soil microbes, insects, and wildlife, need to be carefully considered. Some studies have reported that certain nanoparticles, such as nano-sized ZnO particles, can exhibit toxicity to non-target organisms, including soil microbes and aquatic invertebrates [43]. In contrast, non-nano fertilizers, particularly organic and biofertilizers, can promote beneficial microbial activity and enhance soil biodiversity [42]. However, the excessive application of chemical

Table 4. Comparative analysis of nano and non-nano fertilizers

Factors	Nano fertilizers	Non-nano fertilizers
Particle Size	Nano-sized particles (1-100 nm)	Larger particles (>100 nm)
Nutrient Uptake Efficiency	Higher due to increased surface area and improved penetration	Lower due to limited surface area and inefficient penetration
Fertilizer Use Efficiency (FUE)	Increased by up to 20-30%	Relatively lower
Leaching and Runoff	Reduced due to controlled-release and targeted application	Higher due to uncontrolled release and less targeted application
Crop Yield	Improved by up to 10-20%	Baseline yield
Nitrogen Use Efficiency (NUE)	Improved by up to 50%	Relatively lower
Phosphorus Use Efficiency (PUE)	Improved by up to 40%	Relatively lower
Potassium Use Efficiency (KUE)	Improved by up to 30%	Relatively lower
Quality of Grains	Improved nutrient content, higher grain filling rate	Baseline quality
Environmental Impact	Reduced due to less leaching and runoff	Higher due to increased leaching and runoff
Cost Effectiveness	Potentially higher in the long run, but initial cost is higher	Lower initial cost, but less efficient in the long run
Application Technology	Requires specialized equipment for targeted application	Can be applied using conventional methods

fertilizers can also negatively impact non-target organisms by altering soil pH, reducing soil biodiversity, and contributing to the decline of pollinators and other beneficial insects [12].

6. LIMITATIONS, CHALLENGES, AND FUTURE RESEARCH

6.1 Limitations in Existing Research

6.1.1 Limited number of comparative studies

Despite the growing interest in the use of nano-fertilizers for rice cultivation, the number of comparative studies evaluating the impacts of nano and non-nano fertilizers on rice productivity and quality remains limited. Most of the available literature focuses on the effects of individual nano-fertilizers, while comprehensive and systematic comparisons between nano and non-nano fertilizers are scarce (Wang et al. 2020). This makes it difficult to draw definitive conclusions about the relative merits and drawbacks of each fertilizer type, and highlights the need for more robust comparative research in this area.

6.1.2 Inconsistencies in research methodologies

Another limitation in the existing literature is the inconsistency in research methodologies employed by different studies. For example, some studies have focused on the use of nanoparticles, while others have investigated nano-encapsulated nutrients or carbon-based nano-fertilizers [44,45]. Moreover, there is considerable variation in the experimental designs, such as the choice of rice cultivars, growth conditions, and application rates of fertilizers. These methodological discrepancies can make it challenging to compare the results of different studies and to generalize their findings across different rice cultivation systems [46].

6.2 Challenges in Implementing Nano-fertilizers

6.2.1 Cost and accessibility

One of the main challenges in implementing nano-fertilizers for rice cultivation is their cost and accessibility. The production of nano-fertilizers often requires sophisticated equipment and advanced technologies, which can result in higher manufacturing costs compared to conventional non-nano fertilizers [31]. The availability of nano-fertilizers may be limited in some regions, particularly in developing countries where rice cultivation is most prevalent. Therefore, it is crucial to develop cost-effective and scalable production methods for nano-fertilizers and to ensure their accessibility to smallholder farmers in order to promote the widespread adoption of these technologies [47].

6.2.2 Regulatory frameworks and public perception

The implementation of nano-fertilizers in rice cultivation also faces challenges related to regulatory frameworks and public perception. The regulation of nano-fertilizers varies across countries, with some nations having more stringent requirements for their approval, registration, and use [48]. This can create barriers to the commercialization and adoption of nano-fertilizers, particularly in countries where regulatory frameworks are not well-developed or harmonized with international standards [49].

Furthermore, public perception of nano-fertilizers may influence their acceptance and use in rice cultivation. Concerns about the potential environmental, health, and safety risks associated with nanoparticles and other nano-scale materials can create skepticism and resistance towards the adoption of nano-fertilizers [50]. Addressing these concerns and promoting public awareness of the benefits and risks of nano-fertilizers will be essential for their successful implementation in rice cultivation systems.

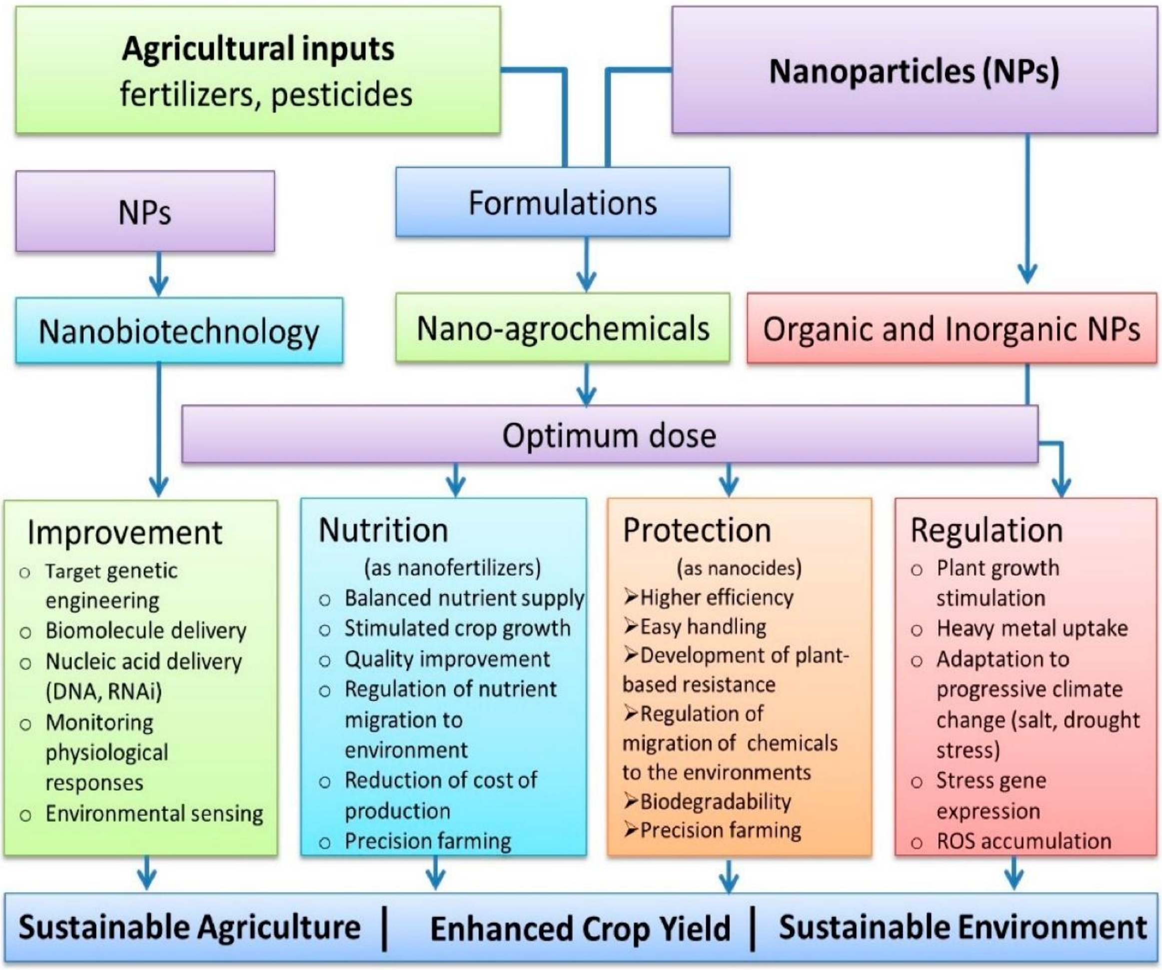

Fig. 2. Simplified overview of potential applications of nanomaterials in sustainable agriculture production [20]

Table 5. Recent Research on the Impact of Nano and Non-nano Fertilizers on Rice Quality and Productivity

Study (Year)	Fertilizer type(s) tested	Key findings
Lu et al. [53]	Nano N, Non-nano N	Nano urea increased rice yield, improved nitrogen use efficiency, and reduced greenhouse gas emissions compared to non-nano urea.
Liu and Lal [54]	Nano Zn, Non-nano Zn	Nano ZnO increased grain Zn content and had a positive effect on rice seed germination and seedling growth compared to non-nano ZnO.
Dimkpa et al. [33]	Nano Fe, Non-nano Fe	Nano Fe_3O_4 increased chlorophyll content, root length, and plant biomass in comparison to non-nano Fe_3O_4.
Adisa et al. [55]	Nano N, Non-nano N	Nano urea enhanced rice growth, nitrogen use efficiency, and yield compared to non-nano urea.

7. FUTURE RESEARCH DIRECTIONS

7.1 Long-term Field Studies

To better understand the impacts of nano and non-nano fertilizers on rice productivity and quality, there is a need for more long-term field studies conducted under diverse agroecological conditions. Such studies can help to elucidate the complex interactions between fertilizers, rice plants, and the environment, as well as the potential cumulative effects of repeated fertilizer applications on soil health, agroecosystems, and food safety [51].

7.2 Investigating Potential Risks and Benefits of Nano-fertilizers

Future research should also investigate the potential risks and benefits of nano-fertilizers, including their effects on soil health, water quality, and non-target organisms. This will require the development of standardized testing protocols and methodologies to assess the environmental fate, transport, and toxicity of nano-fertilizers, as well as their potential for bioaccumulation in the food chain [52]. By gaining a better understanding of the potential risks associated with nano-fertilizers, researchers and policymakers can develop appropriate guidelines and regulations to ensure their safe and sustainable use in rice cultivation.

7.3 Developing Sustainable and Cost-effective Nano-fertilizer Formulations

Another important area of future research is the development of sustainable and cost-effective nano-fertilizer formulations that can maximize the benefits of these technologies while minimizing their potential drawbacks. This may involve the design of nano-fertilizers with improved nutrient release profiles, enhanced compatibility with other agricultural inputs, or reduced environmental impacts [27]. Research should explore the potential of combining nano and non-nano fertilizers in integrated nutrient management strategies, which can optimize rice productivity and quality while preserving soil health and ecological balance [41,56,57].

7.4 Recent Research's

Recent research demonstrates that nano-fertilizers significantly enhance rice productivity by improving nutrient uptake and reducing nutrient losses in comparison to non-nano fertilizers. In terms of quality, nano-fertilizers reportedly promote superior grain quality, owing to more efficient nutrient delivery. However, concerns about the long-term environmental impacts of nano-fertilizers persist, necessitating further research and responsible application strategies. Some Recent researches are shown in Table 5.

8. CONCLUSION

The use of nano and non-nano fertilizers in rice cultivation presents both opportunities and challenges. While nano-fertilizers offer potential benefits in terms of improved nutrient use efficiency, plant growth, and rice quality, there remain limitations in the existing research, such as the limited number of comparative studies and inconsistencies in methodologies. Challenges in implementing nano-fertilizers include cost, accessibility, regulatory frameworks, and public perception. Future research should focus on long-term field studies, investigating potential risks and benefits of nano-fertilizers, and developing sustainable and cost-effective formulations. By addressing these challenges and knowledge gaps, researchers and policymakers can facilitate the safe and sustainable use of nano and non-nano fertilizers in rice cultivation, thereby optimizing productivity and quality while minimizing environmental impacts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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