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Review Article

An overview of different chemical fertilizers' applications on the agronomic performance (growth and yield) and quality parameters of rice (*Oryza sativa*) crop

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Abstract
Excessive use of nitrogen fertilizers causes leaching, denitrification, runoff, and volatilization, among other issues. However, nanotechnology, which releases nutrients through nanoparticles, solves these issues. It is the most economical and successful. With the use of nanotechnology, plants can receive nutrients in a regulated way. Nutrients are essential for plants' growth and development. There are seventeen essential nutrients in all, which were divided into two groups: macronutrients and micronutrients. These were divided into three "R" concepts, i.e., right dose, right place, and right way of application. The administration of balanced nutrients is essential for the best possible growth, development, and yield from plants. The three main nutrients that plants need are N, P, and K, but overuse of fertilizers too quickly depletes soil fertility and pollutes the environment. It lessens the plants' requirement for nutrients, reduces pollution in the environment, and reduces the issues brought on by the conventional use of fertilizers. Rice is the primary energy source for 60% of the world's population. Since 2017, rice output has increased rapidly and is significant in nutrition and food security sources. The present review discusses the effect of different nutrients on the agronomic performance of rice in various studies.

Keywords: Consumption and production, Food security, Life on land, Poverty, Nano N, Zinc pollution

INTRODUCTION

Around the world, 114 countries grow rice (*Oryza sativa*). Together with wheat and maize, it is the world's most important cereal crop. Half the world's population depends on rice, making it the staple food globally (Mohidem, 2022). It is from Southeast Asia and is a member of the Poaceous family. Usually, it is grown in fields that have flooded. Rice needs a warm, humid atmosphere to flourish to its full potential (Tahir *et al.,* 2023). It has significant social, cultural, and economic implications for the world's populace. *Oryza sativa* is a plant that grows in moist, humid climates; it is not a tropical plant (Al-hashimi, 2023). India is the world's second-largest producer of rice after China. In comparison to 2017, the country's rice production is expected to rise in 2023 (Srivastava *et al.,* 2023). The incorrect and imbalanced use of fertilizers and nutrient application techniques has resulted in nutrient loss and low fertilizer usage efficiency (Arivelarasan *et al.,* 2023). Understanding each nutrient's influence on crop growth and development is essential for preserving appropriate nitrogen use efficiency.

Plants require 17 different essential mineral nutrients. Micronutrients and macronutrients make up the two divisions. The macronutrients are magnesium (Mg), sulphur (S), calcium (Ca), hydrogen (H), carbon (C), nitrogen (N), phosphorous (P), potassium (K), iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), molybdenum (Mb), nickel (Ni), boron (B), and zinc (Zn) are micronutrients. N, P, and K are the three main nutrients that the crop needs (Gush *et al.,* 2021). Chlorophyll activity, crop yield, and photosynthesis are all impacted by nitrogen. It contains both an amino acid and a chlorophyll component. It contributes to the growth of rice plants in terms of height, tiller count, panicle count, internode elongation, metabolism, and panicle length. So, adding too much nitrogen could stop some production and make it harder for spikelets that grow to move from the leaves to the plant's stems. This could lead to unfilled grains and reduced grain yield. Phosphorous is more important for plants' root and reproductive growth than nitrogen. Biomolecules such as ATP, nucleic acid such as RNA, DNA, and phospholipids are found in phosphorous (Nath, 2023). K^+ is very important for making rice crops resistant to pests and diseases. Potassium helps to lessen the effects of lodging and abiotic stress. It helps the plant control the amount of water in the stomatal cavity by opening and closing it. For plants to grow and develop, zinc is an important element that they need (Zhang *et al.,* 2023).

Instead of conventional fertilizer treatments, nanotechnology improves soil health, plant mineral nutrition, and interaction with soil microflora geared towards sustainable solutions. With its unique qualities, nanotechnology in agriculture can be used for precision farming and improving crop growth and quality, soil health, crop protection, and stress situations. Due to their unique qualities, nanoparticles will aid in lowering bioavailability and mineral uptake difficulties, increase agricultural productivity, and lower fertilizer waste and pollution in the environment (Chhipa *et al.,* 2019). According to several studies, the size, composition, concentration, and application method of essential and non-essential element nanoparticles have unique effects on crop physiology, growth, and development due to larger surface area, nanoparticles can hold onto nutrients and release them gradually over time to meet crop needs. Slow-release and super sorbent nitrogenous and phosphate fertilizers are in great demand in the agricultural sector (Alvarez *et al.,* 2019). Neem-coated urea and sulfur-coated urea are used to limit nitrogen release and prevent runoff, denitrification, volatilization, and other issues related to using nitrogen fertilizers. Compared to commercial nitrogen applications, nano N applications are the best option because they eliminate the losses by nitrogen and have a slow-release procedure. The conventional fertilizers could only sustain for 300 hours, nano fertilizers could release nutrients for up to 1200 hours. Zeolites contain a nano fertilizer that regulates the efficiency of nitrogen consumption (Singh *et al.,* 2019). Adding zeolites to the fertilizer and controlling the release and retention of NH_4^+ can also minimize N losses. Micronutrients are not as necessary for crop growth as they are for healthy plant growth and lucrative agricultural output. Due to factors such high bicarbonate concentration in irrigation water, drying overtime, low organic matter, high soil pH, and uneven NPK fertilizer application, micronutrient deficiencies are common in several Asian nations (Preetha and Balakrishnan, 2017). Crop output and plant morphological structures are affected, disease and pest assault are on the rise, and fertilizer use efficiency is decreased because of this micronutrient deficit. Zinc and iron are thus absorbed and released by zeolites and bentonite. The minerals bentonite and zeolite have a high capacity for slow-release fertilizer and a significant potential for sorption of zinc and iron (Cataldo *et al.,*2021)

Nutrients and their role in rice

Nitrogen (N), Phosphorous (P), Potassium (K) and Zinc (Zn)

According to Rathnayaka,2018, nitrogen is essential for crop growth and has a chlorophyll concentration that aids in photosynthetic processes. Additionally, nitrogen catalysis the production of proteins and the growth of plants. N fertilization has an impact on biomass and crop yield. Different forms of nitrogen are applied, such as nitrate (NO_3^-) and ammonium (NH_4^+). Available Nitrogen use efficiency decreased in soil due to leaching and denitrification. The soil's N concentration is declining because of processes including leaching and denitrification. Thus, higher nitrogen application is required for crops. An excessive amount of nitrogen can be hazardous to persons and the environment. Moreover, reduced growth and production may result from low nitrogen dosages. Therefore, to improve yield, we should maintain optimal nitrogen efficiency. Maintaining appropriate soil and water management techniques will prevent runoff, leaching, and volatilization from reducing the nitrogen concentration, and by doing so, we can lower environmental pollution (Singh *et al.,* 2018). Phosphorus (P) is an important element for plant growth and output. It is one of the most important plant nutrients and affects all biological systems in some way. Because P is fixed in the soil, there is not always enough of it for plants to grow and develop properly. P is an important part of the structure of nucleic acids, sugars, and lipids. Potassium is plants' third most crucial nutrient, after N and P. More than N and P, the high concentration of K is removed from modern high-yielding rice cultivars. It facilitates the translocation of carbohydrates and sugar. The pore known as stomata, which is present in leaves, stems, and other organs, is opened and closed in large part by K. Stomate facilitates the exchange of gases. K supports crops under abiotic stress situations. As a result, it raises yield and boosts crop output. After NPK, zinc is the fourth major yielding nutrient. The accessible critical limit of zinc in soil for rice crops is 0.3 mg kg^{-1} (Apoorva 2017). It is essential for protein synthesis and functions as a cofactor for antioxidant enzymes like peroxidase and catalase, which protect plants and increase yield. Zinc improves the plant parts' absorption of other nutrients such as phosphorus, potassium, and iron (Kheyri, 2018). The functions of the Macro and micronutrients are mentioned in Table 1.

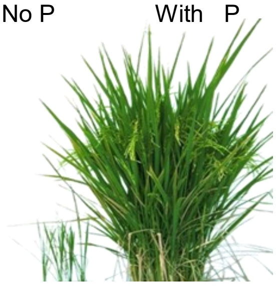
Impact of nutrient uptake on the morphology of rice

Plants need the right amount of nutrients for healthy growth and development; even a small variation in the amount might result in toxicity or deficiency. Crops primarily need macronutrients and have unique roles in plants' internal and external structure. Plant nutrients interact with one another to provide both antagonistic and synergistic effects when used efficiently. The relationship of each specific nutrient regulates the intake of that nutrient (Thakur *et al.*,2020).

Uptake of nitrogen (N)

Following carbon, hydrogen, and oxygen, nitrogen is essential for synthesising chlorophyll and photosynthesis since it participates in catalysis and regulation of plant growth and development. Grain yield can be directly correlated with nitrogen uptake. While nitrate is a

Table 1. Nutrients and their functions in rice

Nutrients	Images with and without nutrients	Functions	References
Nitrogen (N)	N+ N- 	It has a significant impact on how plants grow and develop. Additionally, it is essential for chlorophyll that supports photosynthesis, increases plant height, the number of tillers, and the length of the panicle.	Leghari et al., 2016
Phosphorous (P)	No P With P 	Phosphorous is plants' second most significant element during their reproductive stage after nitrogen. Additionally, it includes crucial elements including co-enzymes, nucleotides, and phospholipids.	Malhotra et al.,2018
Potassium (K)	Without Potassium 	In terms of disease and pest resistance, K is crucial. It enhances the crop's abiotic stress conditions and aidsin the stomatal body's opening and closing.	Pandey et al., 2020
Zinc (Zn)	Zinc deficiency 	A crucial micronutrient is zinc. It contributes to raising crop yields and productivity. Additionally, it is crucial to absorb other minerals like potassium and phosphorus.	Vadlamudi et al.,2020

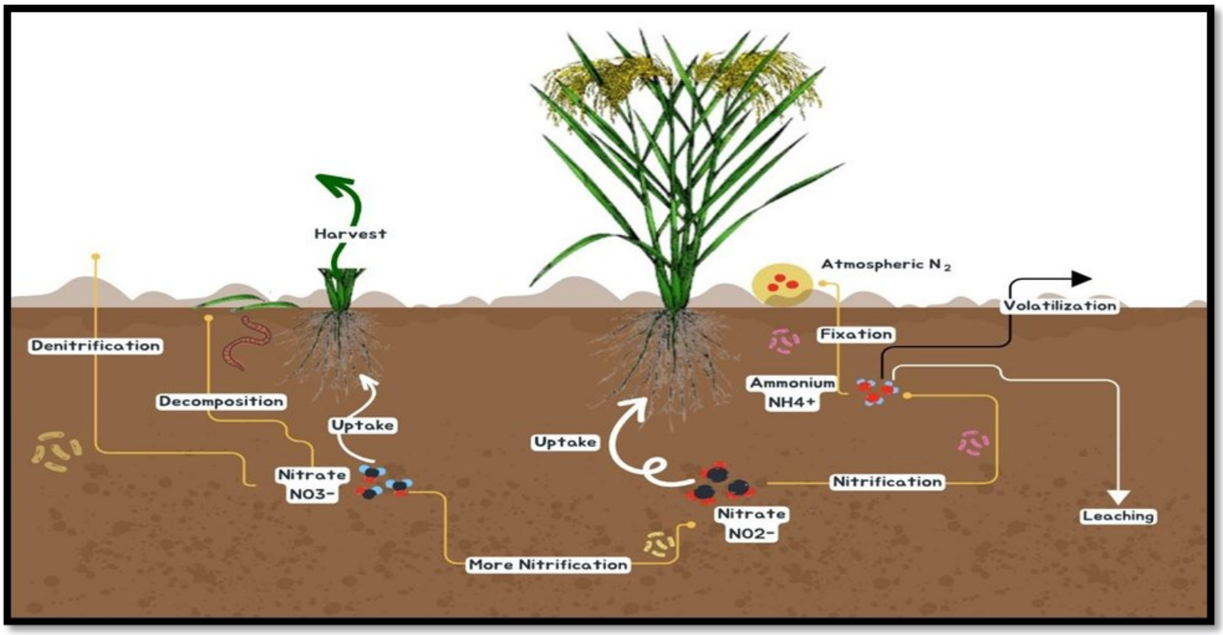


Fig. 1. *Nitrogen uptake in rice*

key absorption technique, it also plays a significant signal role in a fibrous system like rice and strongly develops lateral roots (Belete *et al.,* 2018). NO_3^- is taken up by the roots, switches to the shoots, and eventually reaches the grains. Plants can absorb both types of nitrogen in flooded rice, and the atmosphere reduces nitrate (NO_3^-) to ammonia by reduction. These move to the shoots after being absorbed by the roots. It absorbs more nitrogen than in the solution (Islam, 2019). The higher quantity needed from the panicle initiation stage to the panicle formation stage, in this case, the higher quantity of nitrogen presents more in spikelets. Since nitrogen is a mobile component of the plant body, older leaves exhibit a nitrogen deficit before younger leaves as represented in Fig. 1.

Ammonium (NH_4^+) is produced from atmospheric nitrogen gas (N_2) through biological fixation. This is typically caused by soil bacteria or certain plants' root nodules, such as legumes. These bacteria can convert atmospheric nitrogen into a form that plants can use because they possess nitrogenase enzymes (Gu and Yang, 2022). The ammonium produced during fixation is converted into nitrate (NO_3^-) using a two-step nitrification procedure. Ammonium is first converted to nitrite (NO_2^-) by bacteria such as Nitrosomonas species, and nitrite is subsequently converted to nitrate by bacteria such as Nitrobacter species (Fu *et al.,* 2021). Plants absorb nitrate and ammonium from the soil through their roots. Nitrogen is essential for plant development because it is a part of proteins, nucleic acids, and amino acids. Organic debris left behind by deceased plants and animals is broken down by decomposers like fungi and bacteria, which replenishes the soil with ammonium (Manivannan *et al.,* 2020).

Uptake of phosphorus (P)

Plants require more phosphorus than nitrogen. Phosphorus is a mobile macronutrient inside plants and can remobilize if its early stages include a higher phosphorus concentration. 0.2% of the dry weight of plants is phosphorous. Grain phosphorus is very high in *indica* and *japonica* varieties (Rawat *et al.,*2022). The amount of phosphorus in dry matter reduces as phosphorus intake rises. It oversees root development, early flowering, ripening, and some biotic and abiotic stresses. Dry matter builds up during rice tillering because phosphorus is crucial to this process and even a small alteration might cause stunting and physiological alterations in the plants Fig. 2. The presence of phosphorus in the soil is essential, and plants primarily absorb it as inorganic phosphate. Soil microorganisms produce organic phosphate with the assistance of various bacteria and fungi. The organic phosphate found in plant leftovers, organic matter content, etc., is subsequently broken down by enzymatic activity and transformed into inorganic phosphate in the soil. Because the rice plant absorbs phosphorus through its roots, it needs energy to do so because it is an active process (Yang *et al.,* 2020). Through the xylem and phloem, the plant receives the phosphorus that the root has absorbed. Additionally, phosphorus transported to xylem travels from root to shoot and continuously gives the plant nutrients. The surplus phosphorus is then stored in the different plant tissue sections after leaving the phloem and moving to other plant components including leaves, stems, and eventually the forming grains (Wang *et al.,*2021). The elevated nutritional demand during the grain-filling stage causes the phosphorus that has been accumulated in the various tissues to be moved from older tissues

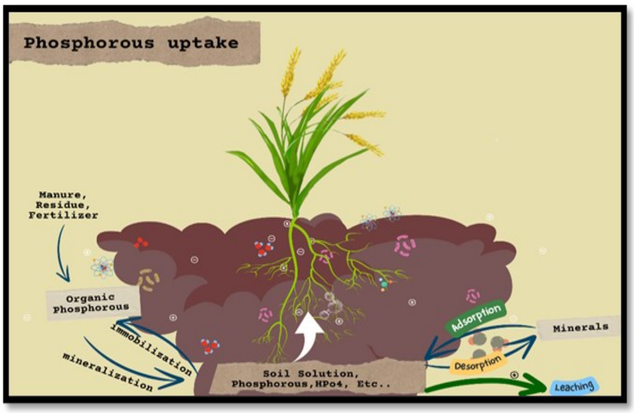


Fig. 2. *Pathway of phosphorous uptake in rice*

to the newly forming tissues. Additionally, phosphorus in the soil is constantly changing through enzymatic processes such mineralization, immobilization, and microbial absorption into organic and inorganic forms.

Uptake of potassium (K)

One macronutrient that is crucial for crops is potassium. Potassium raises grain output, and fertilizer helps crops grow sustainably. Numerous tests demonstrate that K deficiency occurs in farms with high rice and maize yields. Folds in rice shoots are visible. The K content was associated with root dry matter, shoot dry matter and overall biomass. The symptoms of a K shortage are like those of the "Tungro" virus. As a result, whole rice is more resistant to adverse weather, pest attacks, etc. (Sharma and Singh 2021). Another name for potassium is "Chemical Policeman." Growth is slowed in cases of nutrient deficit, usually within two to three weeks of transplantation. In cases where it is more severe, leaves develop uneven patches, tillering is decreased, and the ripening period is prolonged (Fig. 3). Potassium is essential for photosynthesis, respiration, and the management of water in plants, among other vital physiological processes. Potassium is a cofactor for many of the enzymatic actions involved in metabolic processes. The root hairs absorb most of the potassium, transferring it to the entire plant body through the xylem and phloem. Additionally, potassium absorption by the root hairs increases the root cells' capacity to absorb nutrients. The rice plant absorbs more magnesium and calcium because of the uptake of potassium ions. Potassium ions control the opening and closing of stomata, which controls water absorption. They operate as an activator to preserve the structure and function of several enzymes.

Impact of nano fertilizers on rice crop

Well-developed and existing at the nanoscale are nano fertilizers. It is more reactive, has a larger surface area, and is more mobile. These characteristics make nano fertilizers more effective for plants, resulting in appropriate nutrient utilization, control over nutrient leaching, and decreased environmental hazards (Kumar *et al.,*2023). Additionally, it facilitates photosynthesis by enhancing pigments like chlorophyll and enhancing the absorption of CO_2. In addition, the resilience of rice plants to both biotic and abiotic stress conditions is enhanced (Midde *et al.,* 2021). Increased cell division promotes greater growth of the shoots and roots, elongation, and differentiation. Because of their larger surface area, nano fertilizers have a greater nutrient utilization efficiency of up to 20–30% when compared to regular fertilizers. Targeted applications and a controlled release of nutrients are also included. Better crop yields range from 10% to 20%. Up to 50% more nitrogen is used efficiently. Additionally, the increased nutritious content of the grain results in superior quality Al-Khuzai *et al.* (2020).

Role of nano N and nano Zn in rice

Nitrogen is essential for enhancing and expanding crop yield. Moreover, overutilization of nitrogen can result in

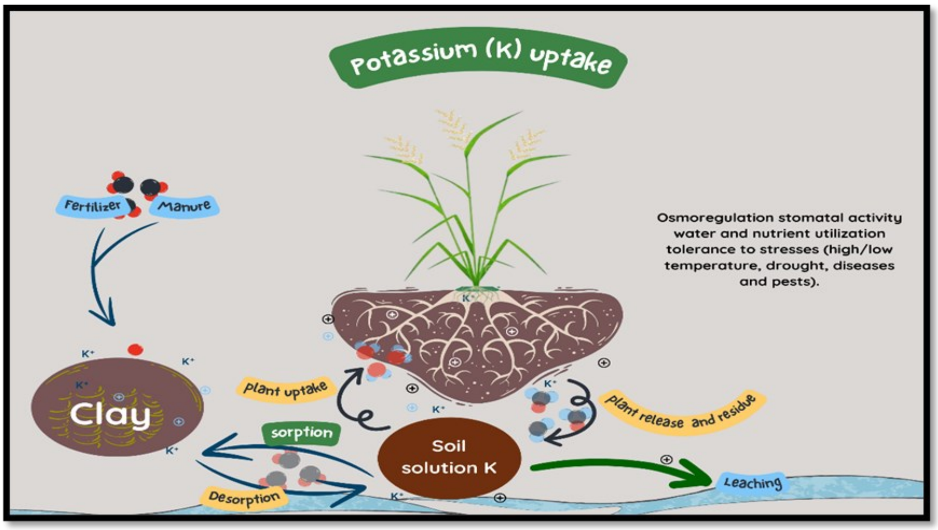


Fig. 3. *Potassium uptake in rice*

problems such as leaching and volatilization. Nitrogen can also be utilized for an alternative application called Nano N. It mitigates the problems associated with excessive nitrogen, such as runoff, volatilization, and leaching. It enhances both the chlorophyll content and the photosynthesis process. Zinc (Zn) is an essential element that is crucial for the regular growth and development of plants (Wang *et al.,*2018). Zinc plays a crucial function in various processes as it is an essential component of numerous enzymes and proteins. It is particularly important for the generation of growth hormones and the elongation of internodes. Although only needed in minute quantities, this substance is essential for the growth and progress of plants. Zinc is a crucial micronutrient that is necessary for improving crop productivity. Zinc is essential for the synthesis of chlorophyll, the functioning of pollen, the process of fertilization, and the initiation of germination. Zinc exhibits moderate mobility and is capable of being transported through the phloem and transported from leaves to roots, stems, and growing grains, as well as from one root to another (Dimkpa *et al*.,2020).

Nano-nitrogen particles may affect enzymatic processes related to nitrogen metabolism and absorption. Enhanced nitrogen consumption efficiency and elevated enzyme activity may promote better plant growth and development. The most crucial micronutrient for plant growth and development is zinc. It is an important structural and enzymatic regulatory component of many proteins and enzymes. It improves the binding of proteins. Additionally, excessive Zn use has an impact on the health of the soil and plants. Researchers have looked into ZnO nanoparticles to improve rice crop growth and zinc uptake relative to traditional zinc fertilizer (Zhang *et al*., 2021). Nano Zn is the most popular type of nano fertilizer. Nano-zinc oxide (ZnO) has been widely utilized in several industries for many years. However, implementing this technology in the agricultural sector is currently insufficiently important and is not widely implemented to enhance fertilizer usage efficiency. Zinc inadequacy is a well-acknowledged worldwide issue, including a lack of essential nutrients in agricultural soils, which leads to below-optimal crop output. Additionally, it affects human populations and contributes to poor human health. Most Zn in soils is insoluble, making it inaccessible to plants. This accounts for almost 90% of the total Zinc content (Wang *et al*., 2018). Approximately 95% of rice cultivation occurs in Asia, where most of the crop is also consumed. Zinc deficiency is the most prevalent illness related to micronutrients in rice. Significant advancements have been achieved in the field of nanotechnology in recent years. This field also offers the means and technological frameworks to study its impact on biological systems. Furthermore, these small particles exhibit significant surface areas, high aspect ratios, and unique surface characteristics (Zhang *et al*., 2018). In addition, nanotechnology is currently seeing significant progress in other areas, including creating nano-particles, comprehending their fundamental physical and chemical properties, and arranging complex nano-scale matter through weak non-covalent interactions. Recently, a specific focus has been on engineered nano-materials due to their beneficial effects on enhancing agricultural output. These materials are now being manufactured more frequently for various purposes. Nanoparticles smaller than 100 nm exist in the intermediate region between individual molecules and the larger bulk materials. Only a few researches indicate the beneficial or no negative impacts of nanoparticles (NPs) on higher plants.

Effect of ZnO nano particles on rice growth, yield components and quality parameters

Applying zinc fertilizer to both leaves and soil can enhance the uptake and conversion of zinc into the edible parts of plants. Applying fertilizers directly to the leaves of crops, known as foliar fertilization, is an effective and safe way to enhance the levels of zinc in crops. Substances applied to the leaf can enter through either the cuticle or the stomatal route. Fang *et al.,* 2008 found that applying zinc foliar fertilizer during the flowering stage significantly enhances the zinc content of rice. Nevertheless, the capacity of Zn ions to remain attached to the surface of rice leaves is extremely difficult to maintain, and zinc solutions sprayed over the leaves tend to drip off or get washed away by rain, impacting the absorption of Zn by the leaves. Significantly, the application of Zn fertilizer to the soil enhances the Zn concentration in grains, as well as boosting the yield of grains. Multiple research studies on the fortification of rice with Zn indicate that applying Zn fertilizer promotes rice growth, and an optimal dosage of Zn enhances rice output (Dou *et al.*, 2021). Regrettably, the presence of iron and Aluminium oxides, clay minerals, and humus in the soil can absorb and immobilize Zn ions, diminishing the efficacy of Zn fertilizers. Furthermore, unabsorbed Zn fertilizer can build in the agricultural soil, potentially causing negative effects on the agricultural environment. Hence, exploring a novel fertilizer that incorporates Zn, exhibiting superior efficacy while minimizing adverse ecological consequences, and capable of replacing traditional Zn fertilizers is imperative.

Research on the use of nanotechnology in agriculture has been rapidly expanding in recent decades. Researchers have recently assessed the ability of nano-zinc to be absorbed and utilized by crops, resulting in increased grain yields and zinc content. For example, Dimkpa *et al*., 2020 found that when using a low NPK fertilization method, the application of Zn oxide nano-

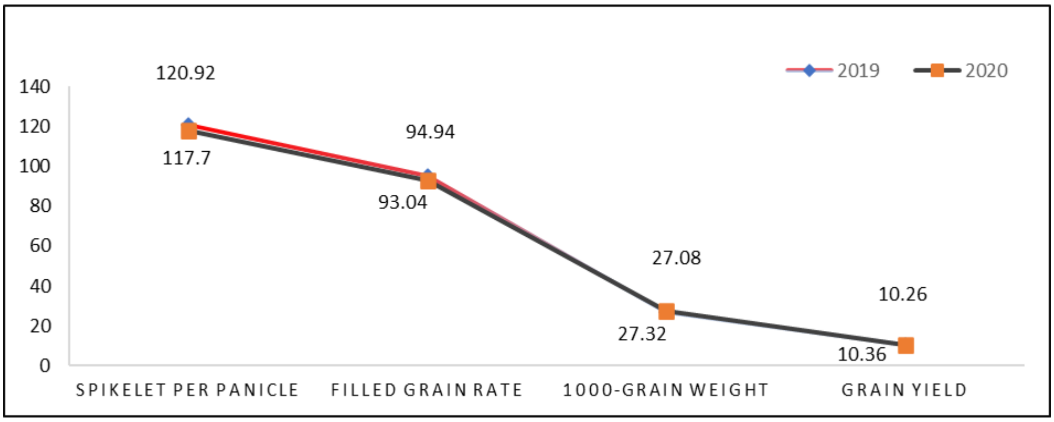


Fig. 4. *Average yield parameter of rice (Wang et al., 2023)*

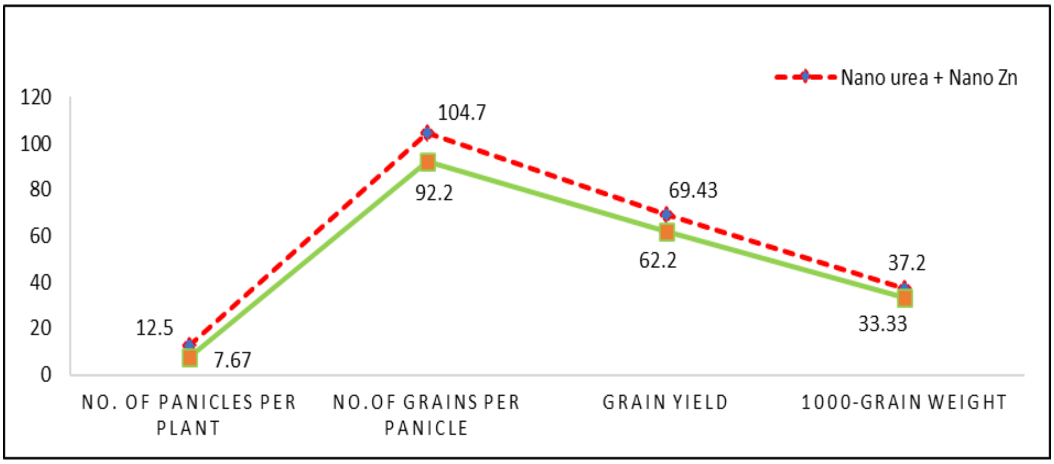


Fig. 5. *Yield parameter of rice (Kumar et al., 2022)*

particles resulted in enhanced growth, improved nutrient absorption, and increased zinc content in sorghum crops. Applying nano-zinc fertilizer can enhance the Zn concentration in grains and stimulate root growth, hence enhancing rice growth.

Several plant species have reported favorable effects of ZnO NPs in reducing Cd levels. Zinc oxide nanoparticles (ZnO NPs) have a non-saturable nature and can be combined with other atoms to form stable compounds, demonstrating significant chemical reactivity (Kheyri *et al.,* 2019). As the size of the particles reduces, the surface area, surface energy, and surface binding energy of ZnO NPs particles experience a significant increase. Hence, in contrast to conventional fertilisers, nano-zinc fertilisers exhibit reduced susceptibility to soil texture, structure, and colloidal concentration variations. Additionally, plants readily assimilated and utilized them. Zinc oxide nanoparticles (ZnO NPs) have numerous beneficial effects on enhancing the zinc levels in grains, especially cereal grains (Kheyri *et al.,* 2019). Moreover, most ZnO nanoparticles are used with conventional fertilizers to create novel fertilizers or employed as agents for seed dressing. Nevertheless, limited studies have investigated the effects of applied ZnO NPs on rice yield formation or the Zn concentration in grains. Based on Liu's 1994 classification of zinc fertilizer application to soil and crops, the tested soil comes within the effective range for zinc fertilizer (0.5-1.0 mg kg^{-1}). Applying zinc fertilizer to soils that lack sufficient zinc can enhance crop productivity. The application of ZnO nanoparticles enhanced the yield of rice panicles and the number of spikelets per panicle. Consequently, the augmented spikelet counts in rice harvests resulted in a consistent full-grain rate and stable 1000-grain weight. The findings of Zhang *et al.,* 2021 reveal that applying ZnO NPs throughout the jointing, heading, and mature stages might lead to higher collection of dry substances, hence indicating that ZnO NPs may enhance final yield increases. Zinc has a crucial role in the functioning of numerous plant enzymes involved in synthesising chlorophyll, auxin, and carbohydrates. Elevated concentrations of zinc in rice will enhance the process of photosynthesis and improve its efficiency. According to Dou *et al.* (2021), there is a consensus among experts that getting a high grain yield relies heavily on the abundant production of photosynthetic chemicals. The study conducted by Zhang *et al*. (2021) found that utilising ZnO nanoparticles resulted in a substantial enhancement in the zinc content of the grains. Increased zinc concentration led to elevated photosynthetic capacity and greater accumulation of photosynthetic compounds. Moreover, applying

ZnO nanoparticles resulted in a substantial rise in the Leaf Area Index of rice during its whole growth cycle. The attenuation rate of leaf area index was reduced throughout the grain-filling stage, indicating a higher transfer of photosynthetic chemicals from leaves to grains. These mechanisms directly influence the development of ZnO NPs and contribute to the resulting results. The maximum grain yield was obtained when the application level of ZnO nanoparticles was 2.4 grams of zinc per pot (equivalent to 60 kg per hectare). The yield of this specific application dosage of ZnO NPs was 7.55% greater compared to the treatment without ZnO NP (Kheyri *et al.,* 2019).

Moreover, the application of ZnO NPs impacts the quality of rice. Zinc can stimulate flavor enzymes, which break down sugar, fat, and protein in rice. The presence of flavor compounds such as fatty acids, aldehydes, and ketones is enhanced, resulting in an overall improvement in rice taste (Kheyri *et al.,* 2019). Applying the optimal quantity of ZnO NPs at the base of the rice plants enhanced the growth rate of brown rice, milled rice, and head rice, improving the quality of rice processing. Furthermore, the application of ZnO NPs increased the size of chalkiness, grain rate of chalkiness, degree of chalkiness, amylose content, and protein content (Yang *et al.,* 2021) These results could be attributed to the significant leaf area index, photosynthetic capacity, dry matter accumulation, and slow decline in leaf area during the grain-filling stage. Research has also demonstrated that zinc fertilizers can enhance the movement of photosynthetic products to the grains and boost the activity of rice protein synthase (Dimkpa *et al.,* 2020). The application of ZnO NPs primarily raised the Zn content of edible polished rice, facilitating the movement of Zn from the aleurone layer. This finding was reported by Yin *et al.,* 2016. Additional zinc-rich supplements for the human body are highly significant in enhancing the nutritional content of rice.

Zinc's efficacy in ZnO NPs has been proposed as a key factor in how nanomaterials impact plant growth. Due to the small size of the nanoparticles, ZnO NPs cannot stick to the soil particles, leading to the loss of Zn components (Zhang *et al.,* 2018). In addition, ZnO nanoparticles can gradually and consistently release Zn (Samart *et al.,* 2019), providing a continuous and sufficient supply of Zn to fulfil the plants' requirements. Rice roots absorbed enough zinc during the growth phase, which stimulated the growth and development of the rice, particularly at the heading-mature stage. In addition, ZnO nanoparticles with strong free radicals exhibit enhanced chemical reactivity and interact with organic compounds in the soil, facilitating the breakdown of organic molecules and the liberation of soil nutrients (Sun *et al.,* 2020). For instance, when ZnO NPs release Zn ions, these ions combine with phosphate to produce Zn phosphate agglomerates. This process enhances the root system's absorption and utilization of nutrient components, fulfilling the rice growth requirements (Siddiqui *et al.,* 2021). Multiple studies have demonstrated that nanomaterials substantially impact the nutritional levels of nitrogen, phosphorous, and potassium in the soil by influencing the activity of microorganisms involved in these processes (Sun *et al.,* 2020). Significantly, the presence of ZnO nanoparticles in rice plants can directly enhance the peroxidase activity and aid in the elimination of active oxygen, so successfully enhancing the resistance of rice (Wang *et al.,* 2018). In addition, ZnO nanoparticles (NPs) positively influenced the process of chlorophyll synthesis in leaves by modulating the functions of glutamyl-tRNA reductase and protoporphyrinogen oxidase (Siddiqui *et al.,*2021). The increased SPAD values, photosynthesis, and photosynthetic efficiency found during the grain-filling period in ZnO NPs treatments may be the reason for the greater grain yields and improved rice quality compared to treatments lacking ZnO NPs.

The use of ZnO nanoparticles could have a greater impact on grain accumulation and Zn content. Nano Zn and ultrasound dosages were used for up to 30 minutes to make a therapeutic solution of nanometric Zn of various weights in one litre of pure water. According to the data, the application of ZnO NPs by foliar spray significantly increased grain yield by 2.3% to 4.1% compared to the control. Therefore, the influence of "N-Zn" mutual promotion throughout the late nutrient transport pathway is responsible for this development (Wang *et al.,* 2023). Zinc oxide nanoparticles (ZnO-NPs) application causes plants to translocate nitrogen more often, increasing the amount of nitrogen in grains as indicated in Fig. 4. Applying 2% of Nano N and 2% of Nano Zn increased the number of panicles per plant, the number of grains per panicle, the grain yield, and the straw yield. This is a result of the ZnO nanoparticles' substantial impact on plants' increased NPK content, which raises the number of panicles and spikelet's as well as yield. By storing nitrogen in plant cells and releasing it gradually, nano urea protects plants from biotic and abiotic stressors and boosts grain yield. Plant growth is aided by the regulated release of nutrients by the nano urea Fig. 5. Yang, *et al.* (2021) investigated the impact of ZnO nanoparticles on rice at different stages-basal, tillering, and panicle. When ZnO is applied during the early phases of the crop, such as the basal and tillering stages, as opposed to the panicle stage, grain production is considerably increased. As a result, using ZnO nanoparticles has increased panicle number, spikelet number, and total biomass, increasing grain production. Furthermore, when compared to traditional fertilizer, applying zinc salt and zinc oxide nanoparticles improves the uptake of NPK and raises its N content. In addition, compared to traditional fertilizer, ZnO NPs and Zn salt improve biomass accumulation because they boost rice's intake of nitrogen and chlorophyll Fig. 6.

Effect of doses and sources of nutrients on growth, yield, and nutrient uptake in paddy

Ujjwal *et al.* (2023) stated that applying nano zinc, NPK consortia, and bio stimulant together with micronutrients significantly increases the length of the panicle and the number of grains filled per panicle by increasing cell elongation and multiplication. Additionally, nanozinc, NPK consortiums, and biostimulant spray increase the amount of nutrients available to plants and increase the 1000-grain weight. Because of the gradual release of nutrients and effective utilization of macro and micronutrients, applying various micronutrients of nano zinc with NPK also boosts grain yield. As a result, adding nano zinc to grains improves their N, P, and K contents and increases their Zn concentration. Additionally, adding micronutrients in addition to regular NPK fertilizer preserves the soil's fertility. Mohapatra *et al.* (2023) stated that different nutrient treatments dramatically altered soil fertility, absorption, and content. Compared to 100% NPK, Zn, Fe, Zn+ Fe, and Zn+ Fe+ VAM improved nutrient content, absorption, and soil fertility. The crop treated with 100% NPK + 0.5% $ZnSO_4$ + 0.5% $FeSO_4$ had the highest grain nutrient content (N-1.33%, P-0.43%, K-0.39%, Zn-36.5 mg kg^{-1} and Fe-127.31 mg kg^{-1}), grain nutrient uptake (N-57.5 kg ha^{-1}, P-18.6 kg ha^{-1}, K-16.8 kg ha-^{1}, Zn-157.7 g ha^{-1} and Fe-550.0 g ha^{-1}), and residual soil nutrient status. Paramasivan *et al.* (2016) resulted that compared to control, 200:75:75 kg NPK ha^{-1} produced the highest plant height (95.7 cm), number of productive tillers (18.3), panicle length (27.2), number of grains (212), 1000 grain weight (26.0 g), grain yield (7.04 t ha^{-1}), straw yield (8.58 t ha^{-1}), net return (52,576 ha^{-1}), B:C ratio (1.65), N, P, and K (171.9, 28.6, and 185.2 kg ha^{-1}, respectively) and uptake. Applying 200:75:75 kg NPK ha^{-1} increased organic carbon (1.24%), accessible N (326.7 kg ha^{-1}), P (21.4 kg ha^{-1}), and K (362.7 kg ha^{-1}). This treatment also had the highest N, P, and K balances (50.7, 5.6, and 74.0 kg ha^{-1}).

Evaluation of nano urea on growth and yield attributes of rice

Midde *et al.* (2021) assessed the impact of nanonitrogen on rice development and yield parameters. This experiment added urea and nano urea to the nitrogen concentration at varying rates. When administering 50% N through urea + 50% N through nano urea, growth characteristics like plant height and the number of tillers and yield qualities like panicles, full grains, and grain yield have a greater impact. Because the nanoparticles are so small, they will cover a larger area and contain more particles per fertilizer. Additionally, the slow release of nitrogen by the nano urea increases nitrogen uptake and improves nitrogen utilisation efficiency. Combining traditional urea fertilizer and nano urea causes the plant cells to store nitrogen. Additionally, it can gradually release extra nitrogen when the plant experiences biotic and abiotic stressors, boosting grain output (Fig. 7). According to Rathnayaka *et al.* (2018), nitrogen increases plant height. Increased cell development under nitrogen may contribute to plant height gain. Studies show that exogenous nanoparticle application enhances plant growth (Salam *et al.,*2020*)*. Mixing nano fertilizer with traditional fertilizers increased plant height, even at lower application rates (Lemraski *et al.,* 2017). Nitrogen fertilizer increased tiller number. The quantity of effective tillers produced is a valuable indicator because it determines yield. Nitrogen increases tiller number (Lemraski *et al.,* 2017).

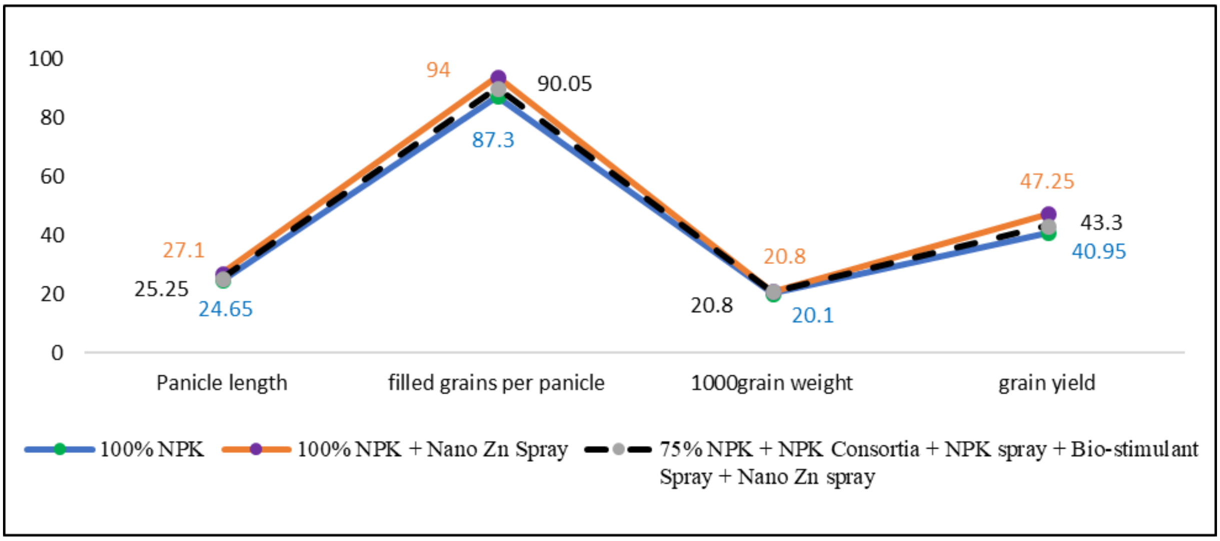


Fig. 6. *Average k growth and yield parameter of rice (Yang et al.,2022)*

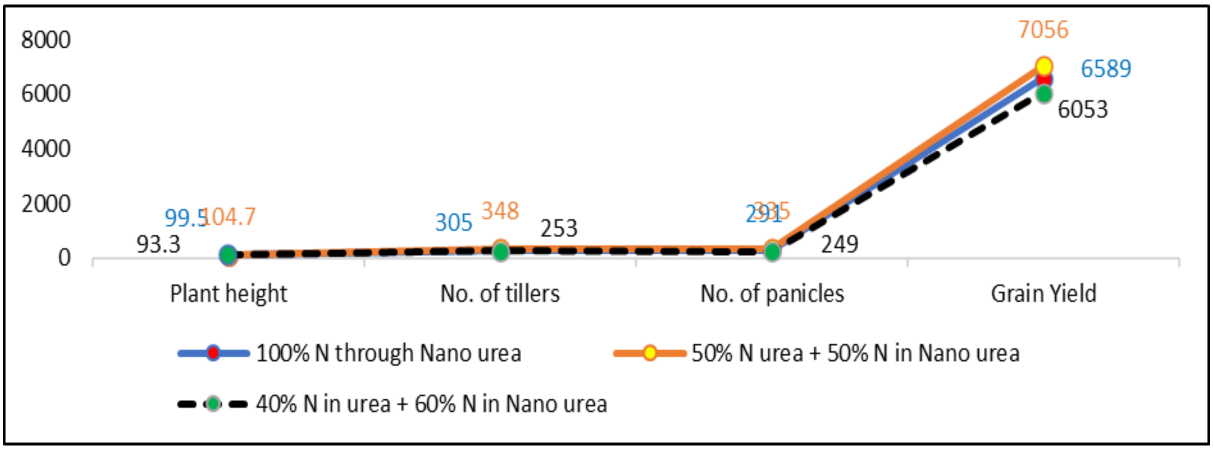


Fig. 7. *Growth and yield of parameter of rice* (Jiang *et al.,* 2021)

Conventional fertilizer and Nano-fertilizer dramatically reduced reproductive tillers. According to Manikandan and Subramanian (2016), nanozeourea-treated soil yields the highest dry matter yield in maize due to enhanced N availability via reduced ammonia loss. Similar results were obtained by Lakshman *et al.,* 2022 who showed that nanomaterials boosted water activity and N, P, and K absorption into plants, increasing dry matter production. According to the study, nano-fertilizers significantly affected straw and grain yield. Nano-fertilizers were proven important
by several researchers. Samui *et al.* (2022) observed increased rice crop production with nano fertilizer.

Future aspects

Researchers in agriculture aim for sustainable agriculture with increased output and societal health. Chemical fertilizers have been mocked for harming the environment and agricultural products, prompting experts to seek alternatives.Nano-material studies have increased rice yield, although only two or three are documented. Nano-fertilizers and slowly-released fertilizers are suitable alternatives for controlled soil nutrient supply. Nano chelate with chemical fertilizers reduces pollution and is cost-effective. Effective nitrogen management procedures must consider cultivar variability and important crop growth stages for fertilization to prevent yield loss. Managing rice crop nitrogen nutrition is challenging due to nitrogen losses from ammonia volatilization, nitrification, denitrification, leaching, and runoff, reducing nitrogen availability for rice plants. Additional research is needed to assess the impact of nitrogen nano fertilizers on rice cultivar growth and yield.

Conclusion

The nutrients determine the growth and development of rice crop output, with N, P & K, and Zn being the three main nutrients needed. The improved development and output of rice are significantly attributed to these nutrients. Because of their smaller particle size, nano fertilizers have demonstrated superior growth and development in rice crops when combined with standard fertilizer combinations. Its slower release of nutrients ensures that they reach their intended location with maximum efficiency. Additionally, its improved surface area contributes to improved soil fertility. Utilizing a 100% Nano fertilizer has resulted in the most significant growth performance compared to the other treatments. Nitrogen losses can result via denitrification, volatilization, and leaching, leading to air and water pollution. It can be inferred that substituting urea with nano nitrogen fertilizer has enhanced the development and productivity of the rice cultivar. The utilization of Nano-N fertilizer can mitigate the adverse impacts of nitrogen on the ecosystem by decreasing the introduction of detrimental nitrogen inputs.

Conflict of interest

The authors declare that they have no conflict of interest.

REFERENCES

1. Adhikari, T. & Ramana, S. (2019). Nano fertilizer: its impact on crop growth and soil health. 1-11.
2. Srivastava, P., Das, A., Gupta, K., Muthukumaran, M., Kurdekar, A. K., Sharma, U. & Zaman, M. I. (2023). Impact of Nano and Non-nano Fertilizers on Rice Quality and Productivity: A Review. *International Journal of Environment and Climate Change*, *13*(8), 973-987. https://doi.org/10.9734/ijecc/2023/v13i82035
3. AL Aasmi, A., Li, J., Hamoud, Y. A., Lan, Y., Alordzinu, K. E., Appiah, S. A. & Yu, C. (2022). Impacts of slow-release nitrogen fertilizer rates on the morpho-physiological traits, yield, and nitrogen use efficiency of rice under different water regimes. *Agriculture*, *12*(1), 86. https://doi.org/10.3390/agriculture12010086
4. Al-hashimi, A. M. (2023). A Review: Growing Rice in the Controlled Environments. *Biosciences Biotechnology Research Asia*, *20*(1), 13-28. http://dx.doi.org/10.13005/bbra/3064

5. Al-Khuzai, A. H. G. & Al-Juthery, H. W. A. (2020). Effect of DAP fertilizer source and nano fertilizers (silicon and complete) spray on some growth and yield indicators of rice (Oryza sativa L. cv. Anber 33). In *IOP Conference Series: Earth and Environmental Science* (Vol. 553, No. 1, p. 012008). IOP Publishing. https://doi.org/10.1088/1755-1315/553/1/012008
6. Alvarez, R. C. F., Prado, R. M., Souza Júnior, J. P., Oliveira, R. L. L., Felisberto, G., Deus, A. C. F. & Cruz, F. J. R. (2019). Effects of foliar spraying with new zinc sources on rice seed enrichment, nutrition, and productivity. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science, 69(6), 511-515. https://doi.org/10.1080/09064710.2019.1612939
7. Apoorva, M. R., Rao, P. C. & Padmaja, G. (2017). Effect of zinc with special reference to nano zinc carrier on yield, nutrient content, and uptake by rice (*Oryza sativa* L.). Int J Curr Microbiol App Sci, 6(8), 1057-1063. http://dx.doi.org/10.20546/ijcmas.2017.602.131
8. Arivelarasan, T., Manivasagam, V. S., Geethalakshmi, V., Bhuvaneswari, K., Natarajan, K., Balasubramanian, M., ... & Muthurajan, R. (2023). How Far Will Climate Change Affect Future Food Security? An Inquiry into the Irrigated Rice System of Peninsular India. *Agriculture*, *13*(3), 551. https://doi.org/10.3390/agriculture13030551
9. Belete, F., Dechassa, N., Molla, A. & Tana, T. (2018). Effect of split application of different N rates on productivity and nitrogen use efficiency of bread wheat (Triticum aestivum L.). *Agriculture & Food Security*, *7*, 1-10. https://doi.org/10.1186/s40066-018-0242-9
10. Cataldo, E., Salvi, L., Paoli, F., Fucile, M., Masciandaro, G., Manzi, D. & Mattii, G. B. (2021). Application of zeolites in agriculture and other potential uses: A review. *Agronomy*, *11*(8), 1547. https://doi.org/10.3390/agronomy11081547
11. Chhipa, H. (2019). Applications of nanotechnology in agriculture. In *Methods in microbiology* (Vol. 46, pp. 115-142). Academic Press. https://doi.org/10.1016/bs.mim.2019.01.002
12. Dimkpa, C. O., Andrews, J., Fugice, J., Singh, U., Bindraban, P. S., Elmer, W. H. & White, J. C. (2020). Facile coating of urea with low-dose ZnO nanoparticles promotes wheat performance and enhances Zn uptake under drought stress. *Frontiers in plant science*, *11*, 168. https://doi.org/10.3389/fpls.2020.00168
13. Dou, Z., Li, Y., Guo, H., Chen, L., Jiang, J., Zhou, Y. & Zhang, H. (2021). Effects of mechanically transplanting methods and planting densities on yield and quality of Nanjing 2728 under rice-crayfish continuous production system. *Agronomy*, *11*(3), 488. https://doi.org/10.3390/agronomy11030488
14. Fang, Y., Wang, L., Xin, Z., Zhao, L., An, X. & Hu, Q. (2008). Effect of foliar application of zinc, selenium, and iron fertilizers on nutrients concentration and yield of rice grain in China. *Journal of agricultural and food chemistry*, *56*(6), 2079-2084. https://doi.org/10.1021/jf800150z
15. Fu, H., Cui, D. & Shen, H. (2021). Effects of nitrogen forms and application rates on nitrogen uptake, photosynthetic characteristics and yield of double-cropping rice in south China. *Agronomy*, *11*(1), 158. https://doi.org/10.3390/agronomy11010158
16. Godebo T, Laekemariam F. & Loha G. (2021). Nutrient uptake, use efficiency and productivity of bread rice (Oryza sativa L.) as affected by nitrogen and potassium fertilizer in Keddida Gamela Woreda, Southern Ethiopia. *Environmental Systems Research.* 10(1),1-16. https://doi.org/10.1186/s40068-020-00210-4
17. Gush, L., Shah, S. & Gilani, F. (2021). Macronutrients and micronutrients. In *A prescription for healthy living* (pp. 255-273). Academic Press. https://doi.org/ 10.1016/B978-0-12-821573-9.00023-0
18. Islam, M. S. (2019). Sensing and uptake of nitrogen in rice plant: a molecular view. *Rice Science*, *26*(6), 343-355. https://doi.org/10.1016/j.rsci.2018.12.007
19. Jiang, B., Jianlin, S. H. E. N., Minghong, S. U. N., Yajun, H. U., Jiang, W., Juan, W. A. N. G. & Jinshui, W. U. (2021). Soil phosphorus availability and rice phosphorus uptake in paddy fields under various agronomic practices. *Pedosphere*, *31*(1), 103-115. https://doi.org/10.1016/S1002-0160(20)60053-4
20. Kheyri, N., Norouzi, A. H., Mobasser, H. R., & Torabi, B. (2018). Effect of different resources and methods of silicon and zinc application on agronomic traits, nutrient uptake, and grain yield of rice (Oryza sativa L.). Applied Ecology & Environmental Research, 16(5). http://dx.doi.org/10.15666/aeer/1605_57815798
21. Kheyri, N., Norouzi, H. A., Mobasser, H. R. & Torabi, B. (2019). Effects of silicon and zinc nanoparticles on growth, yield, and biochemical characteristics of rice. Agronomy Journal, 111(6), 3084-3090. https://doi.org/10.2134/agronj2019.04.0304
22. Kumar, M., Singh, Y. K., Maurya, S. K., Maurya, S. K., Maurya, D. K., Sachan, R. & Tiwari, A. (2023). Efficient use of nano-fertilizer for increasing productivity and profitability along with maintain sustainability in rice crop: a review. *International Journal of Environment and Climate Change*, *13*(10), 1358-1368. https://doi.org/10.9734/ijecc/2023/v13i102788
23. Kumar, S. A., Chhabra, V., Sreethu, S. & Kaur, G. (2022). Response of rice cultivars to conventional and nano fertilizers on yield and yield attributes in the central plain zone of Punjab. Pharm. Innovation. J, 11, 1320-1323.
24. Lakshman, K., Chandrakala, M., Prasad, P. S., Babu, G. P., Srinivas, T., Naik, N. R., & Korah, A. (2022). Liquid nano-urea: an emerging nano fertilizer substitute for conventional urea. *Chronicle of Bioresource Management*, *6* (Jun, 2), 054-059.
25. Leghari, S. J., Wahocho, N. A., Laghari, G. M., HafeezLaghari, A., MustafaBhabhan, G., HussainTalpur, K. & Lashari, A. A. (2016). Role of nitrogen for plant growth and development: A review. *Advances in Environmental Biology*, *10*(9), 209-219.
26. Lemraski, M. G., Normohamadi, G., Madani, H., Abad, H. H. S., & Mobasser, H. R. (2017). Two Iranian rice cultivars' response to nitrogen and nano-fertilizer. *Open journal of Ecology*, *7*(10), 591-603. https://doi.org/10.4236/oje.2017.710040
27. Malhotra, H., Vandana, Sharma, S. & Pandey, R. (2018). Phosphorus nutrition: plant growth in response to deficiency and excess. *Plant nutrients and abiotic stress tolerance*, 171-190. https://doi.org/10.1007/978-981-10-9044-8_7

28. Manikandan, A. & Subramanian, K. S. (2017). Study on mitigation of ammonia volatilization loss in urea through adsorbents. *Journal of Applied and Natural Science*, *9*(2), 688-692. https://doi.org/10.31018/jans.v9i2.1258
29. Manivannan, R., Sriram Chandrasekharan, M. V. & Senthil valavan, P. (2020). Nutrient uptake, nitrogen use efficiency and yield of rice as influenced by organics and fertilizer nitrogen in lowland rice soils. *Plant Arch*, *20*, 3713-3717.
30. Midde, S. K., Perumal, M. S., Murugan, G., Sudhagar, R., Mattepally, V. S. & Bada, M. R. (2021). Evaluation of nano urea on growth and yield attributes of rice (Oryza Sativa L.). Chemical Science Review and Letters, 11(42), 211-214. https://doi.org/10.37273/chesci.cs205301427
31. Mohapatra, S., Ujjwal, A., Gurjar, T., Mishra, J., Das, T. P., Pattnaik, S. & Pradhan, J. (2023). Influence of Micronutrient Application on Nutrient Content, Uptake and Residual Soil Nutrient Status in Rice (Oryza sativa L.) in Western Uttar Pradesh Condition. *International Journal of Plant & Soil Science*, *35*(20), 253-259. https://doi.org/10.9734/ijpss/2023/v35i203805
32. Mohidem, N. A., Hashim, N., Shamsudin, R. & Che Man, H. (2022). Rice for food security: Revisiting its production, diversity, rice milling process and nutrient content. *Agriculture*, *12*(6), 741. https://doi.org/10.3390/agriculture12060741
33. Nath, S. (2023). Phosphorus Chemistry at the Roots of Bioenergetics: Ligand Permutation as the Molecular Basis of the Mechanism of ATP Synthesis/Hydrolysis by FOF1-ATP Synthase. *Molecules*, *28* (22), 7486. https://doi.org/10.3390/molecules28227486
34. Pandey, G. K. & Mahiwal, S. (2020). *Role of potassium in plants* (Vol. 49). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-45953-6
35. Paramasivan, M., Arunkumar, V. & Senthilkumar, N. (2016). Effect of nutrient levels on productivity, profitability and soil fertility in rice (Oryza sativa) in alfisols of Tambiraparani tract. 103(1), 31-34
36. Preetha, P. S. & Balakrishnan, N. (2017). A review of nano fertilizers and their use and functions in soil. Int. J. Curr. Microbiol. Appl. Sci, 6(12), 3117-3133. https://doi.org/10.20546/ijcmas.2017.612.364
37. Rathnayaka, R. M. N. N., Mahendran, S., Iqbal, Y. B. & Rifnas, L. M. (2018). Influence of urea and nano-nitrogen fertilizers on the growth and yield of rice (Oryza sativa L.) cultivar Bg 250. *International Journal of Research Publications*. https://hal.science/hal-04194488
38. Rawat, P., Sharma, A., Shankhdhar, D., & Shankhdhar, S. C. (2022). Improvement of phosphorus uptake, phosphorus use efficiency, and grain yield of upland rice (Oryza sativa L.) in response to phosphate-solubilizing bacteria blended with phosphorus fertilizer. *Pedosphere*, *32*(5), 752-763. https://doi.org/10.1016/j.pedsph.2022.06.005
39. Samart, S., & Chutipaijit, S. (2019). Growth of pigmented rice (Oryza sativa L. cv. Riceberry) exposed to ZnO nanoparticles. *Materials Today: Proceedings*, *17*, 1987-1994. https://doi.org/10.1016/j.matpr.2019.06.246
40. Samui, S., Sagar, L., Sankar, T., Manohar, A., Adhikary, R., Maitra, S. & Praharaj, S. (2022). Growth and productivity of rabi maize as influenced by foliar application of urea and nano-urea. *Crop Research*, *57*(3), 136-140. https://doi.org/10.31830/2454-1761.2022.019
41. Sharma, S. N., Prasad, R., Shivay, Y. S., Dwivedi, M. K., Kumar, S. & Kumar, D. (2009). Effect of rates and sources of phosphorus on productivity and economics of rice (Oryza sativa) as influenced by crop-residue incorporation. *Indian Journal of Agronomy*, 54(1), 42-46.
42. Sharma, S. & Singh, J. (2021). Split application of potassium improves yield and potassium uptake of rice under deficient soils. *Journal of Soil and Water Conservation*, *20* (2), 213-220. https://doi.org/10.5958/2455-7145.2021.00027.8
43. Siddiqui, Z. A., Parveen, A., Ahmad, L. & Hashem, A. (2019). Effects of graphene oxide and zinc oxide nanoparticles on growth, chlorophyll, carotenoids, proline contents and diseases of carrot. *Scientia Horticulturae*, *249*, 374-382. https://doi.org/10.1016/j.scienta.2019.01.054
44. Singh, A., Jaswal, A. & Singh, M. (2019). Enhancing nutrients use efficiency in crops by different approaches-A review. *Agricultural Reviews,* 40(1), 65-69. https://doi.org/10.18805/ag. R-1815
45. Singh, A., Jaswal, A. & Singh, M. (2019). Impact of neem coated urea on rice yield and nutrient use efficiency (NUE). *Agricultural Reviews*, *40*(1), 70-74. https://doi.org/10.18805/ag. R-1817
46. Singh, A., Kumar, A., Jaswal, A., Singh, M. & Gaikwad, D. S. (2018). Nutrient use efficiency concept and interventions for improving nitrogen use efficiency. Plant Arch, 18 (1), 1015-1023.
47. Singh, A., Mehta, C. M., Seddique, A., Jaswal, A. & Sarkar, S. (2019). Impact of Various sources of Zinc on Growth, Production and Nutrient Uptake of Rice Crop. Think India Journal, 22(16), 1621-1634.
48. Sun, H., Du, W., Peng, Q., Lv, Z., Mao, H. & Kopittke, P. M. (2020). Development of ZnO nanoparticles as an efficient Zn fertilizer: Using synchrotron-based techniques and laser ablation to examine elemental distribution in wheat grain. *Journal of agricultural and food chemistry*, *68* (18), 5068-5075. https://doi.org/10.1021/acs.jafc.0c00084
49. Tahir, Z., Anjum, S., Masood, A. & Ismial, T. (2023). Elemental Composition of Rice Varieties and Their Importance to Human Health. *Pakistan's Multidisciplinary Journal for Arts & Science*, 20-26. https://doi.org/10.5281/zenodo.10043885
50. Thakur, A. K., Mandal, K. G., & Raychaudhuri, S. (2020). Impact of crop and nutrient management on crop growth and yield, nutrient uptake and content in rice. *Paddy and Water Environment*, *18*(1), 139-151. https://doi.org/10.1007/s10333-019-00770-x
51. Ujjwal, A., Vivek, B. P., Kumar, M. & Singh, A. (2023). Effect of doses and sources of nutrients on growth, yield, and nutrient uptake in paddy (Oryza sativa L.). Pharma Innovation 2023, 12(5), 2519-2526.
52. Vadlamudi, K., Upadhyay, H., Singh, A. & Reddy, M. (2020). Influence of zinc application in plant growth: an overview. *Eur. J. Mol. Clin. Med*, *7*(7), 2321-2327.
53. Velmurugan, A., Subramanil, T., Bommayasamy, N., Ramakrishna, M. K. & Swaranam, T. P. (2021). The effect of foliar application of nano urea (liquid) on rice (Oryza sativa L.). J. Andaman Sci. Assoc, 26, 76-81.
54. Wang, R., Mi, K., Yuan, X., Chen, J., Pu, J., Shi, X. & Zhang, H. (2023). Zinc Oxide Nanoparticles Foliar Application Effectively Enhanced Zinc and Aroma Content in

Rice (Oryza sativa L.) Grains. *Rice*, *16*(1), 36. https://doi.org/10.1186/s12284-023-00653-0

55. Wang, X. P., Li, Q. Q., Pei, Z. M. & Wang, S. C. (2018). Effects of zinc oxide nanoparticles on the growth, photosynthetic traits, and antioxidative enzymes in tomato plants. *Biologia plantarum*, *62*, 801-808. https://doi.org/10.1007/s10535-018-0813-4
56. Wang, Y., Wang, F., Lu, H., Liu, Y. & Mao, C. (2021). Phosphate uptake and transport in plants: an elaborate regulatory system. *Plant and Cell Physiology*, *62*(4), 564-572. https://doi.org/10.1093/pcp/pcab011
57. Yang, G., Yuan, H., Ji, H., Liu, H., Zhang, Y., Wang, G. & Guo, Z. (2021). Effect of ZnO nanoparticles on the productivity, Zn biofortification, and nutritional quality of rice in a life cycle study. *Plant Physiology and Biochemistry*, *163*, 87-94. https://doi.org/10.1016/j.plaphy.2021.03.053
58. Yang, Y., Hu, H., Fu, Q., Zhu, J., Zhang, X. & Xi, R. (2020). Phosphorus regulates As uptake by rice via releasing As into soil porewater and sequestrating it on Fe plaque. *Science of the Total Environment*, *738*, 139869. https://doi.org/10.1016/j.scitotenv.2020.139869
59. Yin, H., Gao, X., Stomph, T., Li, L., Zhang, F. & Zou, C. (2016). Zinc concentration in rice (Oryza sativa L.) grains and allocation in plants as affected by different zinc fertilization strategies. *Communications in Soil Science and Plant Analysis*, *47*(6), 761-768. https://doi.org/10.1080/00103624.2016.1146891
60. Zhang, H., Wang, R., Chen, Z., Cui, P., Lu, H., Yang, Y. & Zhang, H. (2021). The effect of zinc oxide nanoparticles for enhancing rice (*Oryza sativa* L.) yield and quality. *Agriculture,* 11(12), 1247. https://doi.org/10.3390/agriculture11121247
61. Zhang, T., Sun, H., Lv, Z., Cui, L., Mao, H. & Kopittke, P. M. (2017). Using synchrotron-based approaches to examine the foliar application of ZnSO4 and ZnO nanoparticles for field-grown winter wheat. *Journal of Agricultural and Food Chemistry*, *66*(11), 2572-2579. https://doi.org/10.1021/acs.jafc.7b04153