



Nano-fertilizers: The future of nutrient approaches for cereals

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ABSTRACT

Nanotechnology offers a promising solution to address the nutrient demands of cereals, which are nutrient-intensive crops typically reliant on large amounts of inorganic fertilizers. These large quantities of nutrients are supplied to the crop by applying a huge amount of inorganic fertilizer as a soil application led to a decline in environmental systems, particularly affecting the soil health, lesser use efficiency of fertilizers and water resources contamination. In this context, nanotechnology serves as a potential solution. The huge demand for nutrients in cereal crops is met by nano-fertilizers. The nano-fertilizers are now playing a promising role in fulfilling the nutrient requirement of the crops by replacing the normal conventional fertilizers not only for cereals but also for other agricultural crops. The mechanism of action of nano-fertilizers is that they are smaller than the pore size of plant cell walls, allowing them to easily enter and reach the plasma membrane. Nano-fertilizers have 100 times greater surface area than conventional fertilizers, allowing them to easily interact with plant surfaces and increase the absorption of nutrients. Therefore, the nutrient-use efficiency of the crop is increased and shown a positive effect on the physiological and growth parameters of cereal crops, resulting in enhanced yield and improved drought tolerance. This review discussed, the effects and efficiency of nano-fertilizers on cereal crop growth and the correlation between physiological, qualitative, quantitative traits with nano-form of application in detailed manner. This review concludes that nano-fertilizers are the potential nutrient source for cereal crops like rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays*) etc. and they are going to be a promising resource for nutrient management in agricultural crops.

Keywords: Conventional fertilizers, Foliar application, Nano-carriers, Nano-nutrients, Nano-particles, Nanotechnology, Nutrient-use efficiency, Smart fertilizers

The growth in global population over the past decade has led to increased crop output to meet the demands of billions, particularly in developing countries. Agriculture is under pressure to increase food production efficiency as a result of a growing population and dwindling arable land and water supplies. India is dealing with issues related to lower organic matter, imbalanced fertilization and poor fertilizer reactivity, which have led to a plateau in crop yields. Fertilizers improve soil fertility and crop productivity, irrespective of cropping sequence or environmental conditions. Fertilizers play a significant role in crop productivity and agri-input efficiency. However, plants cannot fully access available nutrients in bulk chemical forms. Furthermore, the majority of macronutrients are underutilized because they are converted to insoluble forms in soil. Crop plants generally use less

than half of the chemical fertilizers applied. Minerals may become entrenched in soil and causing air pollution. Using chemical fertilizers on a big scale to boost crop output is not sustainable since it can disrupt soil mineral balance and reduce fertility. Excessive use of chemical fertilizers harms soil structure, mineral cycles, microbial flora, plants, and food chains, perhaps causing heritable mutations in future generations (Rai *et al.* 2015).

Cereals are annual grasses that are part of the Poaceae family, typically featuring long, narrow stalks. Examples of these include rice (*Oryza sativa* L.), wheat (*Triticum aestivum*), sorghum (*Sorghum bicolor*), barley (*Hordeum vulgare*), millets and rye (*Secale cereale*), all of which produce starchy grains used for food. All cereal grains are rich in energy, primarily due to their starch content, but they also derive significant energy from their fat and protein components. Cereal grains are a key part of the human diet and significantly influenced the development of human civilization for thousands of years. The use of chemical fertilizers in agriculture has risen in recent decades to boost crop yields, with cereal crops consuming the largest share

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of these fertilizers (Halli *et al.* 2016). Rice is one of the world's most significant cereal crops. At present, nearly 90% of rice production and consumption is in Asia. India is the second-largest producer of rice in the world, behind China, with 22% of global rice output (Kothari *et al.* 2023). India cultivates 44.1 million hectares of rice, producing around 105.5 million tonnes each year (Kumar *et al.* 2019). Over 2 billion people in Asia rely on rice and its derivatives for 60–70% of their energy needs (Aasif *et al.* 2018). It is rich in nutrients like carbohydrates, vitamins, proteins, dietary fiber and minerals, and also contains biologically active phytochemicals and phenolic substances. Rice requires large amounts of inorganic fertilizers for optimal growth and yield. Rice yield is determined by soil conditions and the availability of nutrients such as nitrogen, phosphorus, potassium, sulphur and zinc (Ghasemi *et al.* 2017). Therefore, fertilizers play an important role in improving food productivity and quality and are an essential part of any agricultural production system (Manikandan and Subramanian 2016). Applying nutrients to the soil can also help faster seedlings development (Bharathi *et al.* 2020). Crop growth, development and yield are determined by their nutrient intake pattern (Prakash *et al.* 2018).

The average percentage of the yield attributed to N, P and K fertilizers in rice is around 38, 12 and 8%, respectively. N, P and K fertilizers have been administered with an overall efficiency of around or less than 50%, 10%, and 40%, respectively, over the last few decades. For production of 1 tonne rice crop requires around 17 kg of nitrogen (Saud *et al.* 2022). Lack or excess of essential nutrients can negatively impact crop development and output (Bharathi *et al.* 2018). Due to the lower use efficiencies of these conventional fertilizers yield reduction occurs in major cereal crops. Therefore, slow-release, effective fertilizers could be created by employing nanotechnology (Manikandan and Subramanian 2016). It would be really beneficial if we could utilize nano-fertilizer on certain crops, such as rice to reduce the potential negative effects brought about by the significant use of chemical inputs without compromising productivity and nutritional benefits (Benzon *et al.* 2015).

Nanotechnology

Conventional fertilizers are typically applied to crops by spraying or broadcasting. However, one of the most important aspects influencing the technique of administration is the final concentration of fertilizers reaching the plant. Chemical leaching, runoff, drift, hydrolysis, evaporation by soil moisture, photolytic and microbiological degradation result in significantly lower concentrations reaching the target site. Nanotechnology focuses on particles with dimensions of one billionth of a meter. This allows for atom-by-atom manipulation, resulting in nanotechnology processes or products that are extremely accurate and difficult to create with traditional methods. Using nanotechnology in fertilizer products can increase release profiles and absorption efficiency, providing considerable environmental and economic benefits. Nanoscale fertilizer

inputs include particles and emulsions. In general, it is claimed that lowering the size of the input leads to improved absorption and higher total release efficiency, delivering better efficacy with a smaller amount required. This category encompasses nano-objects made from traditional fertilizers such as urea, ammonium salts, and peat (Rai *et al.* 2015).

Nano-particles

Urea nano-particles can be prepared using both chemical and physical methods. A chemical technique was employed to deposit urea on calcium cyanamide cores, resulting in a nano-particle fertilizer formulation. A new patent has been issued for a nano-particle composition made from urea, bacteria, plant antibiotics, and an NPK composite fertilizer. In some cases, a combination of physical, chemical, or biochemical techniques is utilized to create the nanomaterial. Biochemical fermentation yields the final nanoscale product. For instance, peat, ammonium humate and other additions are milled to micron size, then subjected to biochemical reactions, and finally ground to produce a nanoscale product and also nano-particles containing micronutrients have been developed to enhance absorption. Nano-particles may enter the food chain through farm crops, making it important to study their effects on plants. Limited research exists on the potential for nano-particles to bioaccumulate in plants and eventually reach higher-level creatures. Nano-fertilizers are nutrient transporters with nano-dimensions ranging in size from 30–40 nm (10^{-9} m). Their high surface area allows them to retain a large number of nutrient ions and release them gradually and steadily to meet crop demand. Nano-fertilizers are very efficient and easily distributed to rhizosphere targets. Nitrogenous and phosphatic fertilizers are available in both slow-release and super sorbent forms. Recent research suggests that there is still much work to be done before nano-fertilizers are widely used in agriculture. Almost every critical nutrient has been attempted to be given using nano adsorbents. The plant cell wall serves as a barrier to external stimuli, including nano-particles. Sieving qualities are governed by the pore diameter of the cell wall, which ranges from 5–20 nm. Hence, Nano-particles with a diameter smaller than the cell wall's pore diameter can easily pass through to the plasma membrane. Nano-fertilizer formulations should have desired properties, including high solubility, stability, effectiveness, target activity, time-controlled release, low eco-toxicity, and easy delivery and disposal (Rai *et al.* 2015)

Foliar application of nano-fertilizers

Fertilizers play an important role in plant growth and development, but are often ineffective due to several causes such as leaching, photolysis, hydrolysis, and decomposition. Micronutrients, found in small concentrations in soil and plants, play an equally significant role as major and secondary nutrients. Although soil application of fertilizers is the predominant approach, it has limitations in terms of plant nutrient availability. The reason is that inorganic nutrients are soluble in soil and probably leached by rain or

irrigation water results in nutrient deficiency (Alshaal and El-Ramady 2017). Some, inorganic fertilizers after application into the soil get fix and availability is reduced resulting into decreased nutrient-use efficiency. Foliar application helps circumvent these constraints. Foliar spraying can ensure the availability of nutrients to crops, resulting in increased yield. The application of macro and micronutrient fertilizers in the cultivation zone may not meet crop root growth and nutritional requirements. Foliar treatments involve spraying liquid fertilizers, chemicals, or natural products directly onto plant leaves to increase output and minimize nutrient losses. Foliar feeding is the fastest approach to overcome nutrient shortages, increase crop output, and improve product quality by using less fertilizer on the soil, it also reduces pollution to the environment and enhances nutrient utilization (Abou El-Nour 2002). Applying foliar nutrition to hydroponic maize fodders significantly increased the root length, shoot length, seedling vigour, and green fodder output (Manikkavasakam *et al.* 2022). Foliar application of nano-fertilizers boosted nitrogen absorption through leaves, which may have resulted to higher mobilization of produced carbohydrates into amino acids and protein, stimulating fast cell division and cell elongation (Song *et al.* 2013). Similar results were observed in rice by Rathnayaka *et al.* (2018). Nano-carriers supply nutrients to plants at the optimal time and place, reducing the need for additional chemicals and increasing nutrient efficiency as foliar spray. Foliar fertilizers face structural hurdles due to their salt-based nutrients, which may not reach plant tissue cells. This is because of the cell wall's pore size, which ranges between 5–20 nm (Benzon *et al.* 2015). Nano coated substances improve stomatal penetration by excluding particles larger than 10 nm. The diameter of the aggregated nano-particles is smaller than the plant cell walls pore size, allowing them to easily enter and reach the plasma membrane (Navarro *et al.* 2008). Nano-particles applied to the foliar surface are transferred to heterotrophic cells via phloem vessels through plasmodesmata (40 nm diameter) (Knoblauch and Oparka 2012). By this way nano-particles can be introduced into the plant system and travel through the vascular system. Polymer-coated nano-fertilizers can release nutrients in a controlled manner, creating them a potential smart fertilizer option for the nutrient supply of plants. The most often used synthetic polymers include polylactide, polyacrylates polylactide-polyglycolide copolymers and polycaprolactones. Foliar application of nitrogen, phosphorus, and potassium is proven to improve carbon balance, leaf nutrition and photosynthetic capacity. Therefore, by applying nano-fertilizer as a foliar spray is a promising and effective way to transfer nutrients to the desired plant parts (Deepa *et al.* 2015).

Nano-N, P and K

Nitrogen is an essential component of numerous structural, genetic, and metabolic components in plant cells. It is a key component of chlorophyll, which helps plants use sunlight to convert water and carbon dioxide into sugars through photosynthesis. It is a major component of amino

acids, which serve as the base for proteins. Proteins play several roles in plant cells, including structural units and enzymes that enable biochemical reactions necessary for life (Alshaal and El-Ramady 2017). Nitrogen, a component of energy-transfer chemicals like ATP (adenosine triphosphate), helps cell preserve and utilize energy generated during metabolism. Nitrogen is a key component of nucleic acids like DNA. Liquid nano-N fertilizer is now the greatest alternative option to traditional urea fertilizers. The 500 ml bottle of nano urea is equal to a bag of urea fertilizer (45 kg), which costs 10% less than conventional urea. Nano urea liquid particles are 30 nm in diameter and have 10,000 times more surface area per volume than regular granular urea (Sahu *et al.* 2022). Nano urea comprises of 4% N and has a storage life of approximately two years. Nano urea (liquid) is sprayed at the rate of 4 ml/litre of H₂O, depends upon crop nitrogen requirements, crop canopy growth, and the amount of water needed for the growing crop. It is sprayed during critical crop growth phases when the crop canopy has sufficiently developed to allow for effective foliar nutrient absorption. The number and concentration of sprays were coordinated to meet the crop's nitrogen requirements. Spraying nano urea-liquid (Nano N) provides the crops 100 ppm N requirement at crucial growth stages and prompts favourable crop response, fulfils its nutritional need, and enhances nutrient availability in the rhizosphere (Kumar *et al.* 2021). Phosphorus is key nutrient that plays a role in plant structure and conversion and it is the primary nutrient responsible for energy transport and storage in plants. The application of nano-phosphorus improved grain quality attributes as well as phosphorus and nitrogen levels in milled grains. Nano-DAP (di-ammonium phosphate) has greater agronomic efficiency over conventional DAP. Nano DAP supplemented seedlings contribute to the enhanced agronomic efficiency of the developed nano-P fertilizer. The usage of nano DAP in reduced quantities while satisfying the plants' optimal P requirement is advocated for greater soil health and agricultural sustainability. Nano potassium fertilizers application enhance the qualitative and quantitative parameters in rice and wheat. Potassium is essential for several plant activities and plays a key role in plant development and reproduction. Potassium is not found in plant structures or molecules, yet it plays a crucial function in regulatory processes. Potassium is essential for photosynthesis, protein synthesis, photosynthate translocation, ionic balancing, stomatal regulation, water usage, enzyme activation, and other functions. It activates at least 60 enzymes involved in plant development. Potassium deficiency can make plants more vulnerable to drought, excess water, and extreme heat. Natural zeolites with high exchangeable K⁺ levels can promote plant development in potting soil. Zeolite has the capability to absorb potassium from chemical fertilizer and prevent leaking. Natural zeolites are more selective for K⁺ than sodium or divalent cations (e.g. calcium and magnesium) due to the negative charge's position and density within the internal channels (Noaema *et al.* 2020).

Nano-fertilizer use efficiency

Nano-fertilizers contains nano-materials have small particle size and a more surface area, resulting in a more particles per unit of weight and specific surface area, as well as high reactivity, which enhances fertilizer contact with the plant, increasing nutrient absorption and fertilizer use efficiency (Herrera *et al.* 2016). The nano-fertilizers may enter the plant cells straight through the sieve like cell wall structures of pores (sizes ranging from 5–20 nm) as the particle sizes are lesser than the cell wall diameters. To put it another way, nano-fertilizers dissolve in solution and deliver the nutrients as soluble ions. The pace and extent of dissolution of nano-fertilizers in soil/water solution should be greater than that of similar bulk materials due of the former's substantially smaller particle sizes and larger specific surface areas (Liu and Lal 2015). There are several possible mechanisms for nano-particle absorption by plant cells. Nano-particles can enter the plant through interactions with transport proteins, aquaporins, or ionic channels, or by the formation of new pores or endocytosis. Here some of the advantages of nano-fertilizers include increased fertilizer usage efficiency, higher yield, and reduced soil contamination (Naderi and Danesh Shahraki 2013).

Nano-formulations can release phosphate for 40–50 days, but conventional fertilizers release nutrients only for a period of 10–12 days. A study reveals that surface-modified zeolite could improve phosphorus use efficiency, which currently hovers around 18–20% in conventional systems (Preetha and Balakrishnan 2017).

A study by Jhanzab *et al.* (2015) shows that highest nitrogen usage efficiency (74.3%) in wheat was seen at 25 ppm SNPs (silver nano particles). The increased concentration of SNPs was followed by a considerable decline in nitrogen utilization efficiency. It appears that lower concentrations of SNPs at 25 ppm greatly increased NUE (Fig. 1). Further boosting the concentration of SNPs from 50–150 ppm results in a decrease in wheat's phosphorus use efficiency (Jhanzab *et al.* 2015). Nano mixed fertilizers were also observed to improve nitrogen use efficiency. Slow and controlled release fertilizers coated and combined with

nanomaterials greatly boosted nitrogen use efficiency and wheat yield (Zhang *et al.* 2006).

Effect of nano-fertilizers on cereal crops

Wheat: Wheat is India's second most important staple food, accounting for around 61% of its protein requirements (Benzon *et al.* 2015). Improved wheat seeds, chemical fertilizers, and irrigation all contribute to significant wheat productivity enhancement. Fertilizer recommendations in south Asian countries for wheat are typically prepared by agricultural departments to attain maximum yields in wide areas with comparable climate and landforms. Fertilizer recommendations for nitrogen, phosphorus, and potassium for wheat vary widely throughout south Asian states and areas. Nano-fertilizers are easily absorbed by the epidermis of leaves and transferred to stems, resulting in increased growth and production of wheat. The nano-fertilizer utilized in the experiment by Benzon *et al.* (2015) in previously established cv. Ilpum rice seedlings (10–15 days old) were transplanted into pots and allowed to mature. The outcomes of his research showed that other than treatments administered with nano-fertilizer alone, every treatment saw a significant increase above the control. Nano-fertilizers may have a synergistic impact with traditional conventional fertilizers, resulting in improved nutrient uptake by plant cells results optimal growth. The application of HRR-NF (half recommended rate of nano-fertilizers) yielded the higher total phenolic content when compared to black and red rice cultivars studied by Ham *et al.* (2013). The administration of the entire recommended rate of nano-fertilizers at 15 and 30 DAT increased plant height. As the plant matured, the fully recommended rate of nano-fertilizers treatment dramatically increased plant height compared to control. Except for HRR-NF, all treatments were able to significantly improve plant height, according to general observations. Overall, the FRR-CF + FRR-NF (Fully recommended rate of conventional fertilizers + Fully recommended rate of nano-fertilizers) outperformed the others. These findings imply that nano-fertilizers can either deliver nutrients to plants or aid in the transportation or absorption of available nutrients, resulting in improved crop development (Benzon *et al.* 2015). A related study found similar outcomes in soybean by Liu and Lal (2014). They developed a new form of 16 nm hydroxyapatite phosphorus nano-particles (NPs) and assessed the fertilizer effect on soybean. The research showed that utilizing phosphorus NPs increased growth rate by 33%.

Silver nano-particles (SNPs) have a significant influence on plant growth in terms of germination, seedling growth, root growth, root elongation, root-shoot ratio, and senescence suppression. In wheat, the concentration of SNPs increased as applied by foliar spray, reducing the leaf area. SNPs content increased considerably lowered wheat plant shoot dry weight and fresh weight (Jhanzab *et al.* 2015). Mirzajani *et al.* (2013) found similar results in rice with the application of SNPs. It may have increased yield due to the growth-stimulating action of silver. Applying Nano-

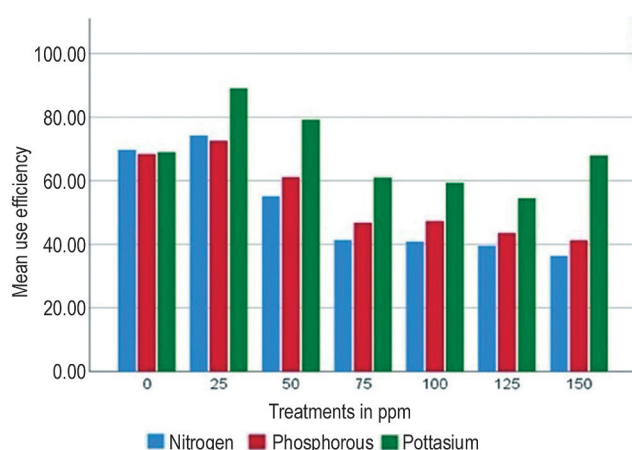


Fig. 1 Nitrogen, phosphorus and potassium use efficiency of silver nano particles (SNPs) on wheat.

Fe fertilizer during tillering and stem elongation increased the quantity of seeds per spike, but early application of Fe fertilizer lowered the no. of seeds in wheat. Fe availability can boost leaf area duration, leaf area index, and reduce leaf senescence, leading to increased economic yield in wheat (Armin *et al.* 2014).

Rice: Rice production is crucial for addressing the global food issue and may be cultivated utilizing numerous techniques (Gunalarasi *et al.* 2022). Rice is essential for ensuring food security for the continuously growing population (Baby *et al.* 2021). Nano-fertilizers significantly increased all growth parameters in rice. Nano-N fertilizer can be used instead of urea to promote rice growth with lower nitrogen pressure on the ground. Combining conventional fertilizers with nano-fertilizers increased the no. of spikelets, panicles, and reproductive tillers in rice. Furthermore, the FRR-NF (Full recommended dose of nano-fertilizers) treatment resulted in increased plant height compared to control group (Ham *et al.* 2013). They reported that the recommended amount of nano-fertilizers at 15 and 30 days after transplanting resulted in increased plant height in rice. Zinc nano-particles increased root and shoot length in rice seedlings. The length of the shoot and root increases gradually as the concentration of Zn nano-particles solution increases (Upadhyaya *et al.* 2015). Under zinc shortage, stomatal conductance and transpiration rates both decreased. Zinc's potential responsibilities in protecting plant cells against reactive oxygen species (ROS) damage, as well as its effect on plant metabolism, have been thoroughly examined by Cakmak (2008).

Maize: Maize is becoming a major cereal in India due to its rising market price and great production potential. It is a significant cereal crop in global agriculture, serving as a food, feed, and industrial raw material. It ranks third in cereal production behind rice and wheat. Poor fertilizer management is an important contributor to low productivity of maize. Effective fertilizer management significantly impacts maize crop growth and output as it is the most exhausting crop after sugarcane, requires both micro and macro nutrients for optimal growth and yield potential. India cultivates 9.38 million hectares of maize, yielding 28.75 million tonnes (Kumar *et al.* 2020). Corn is one of the plants that is most vulnerable to zinc deficiency. Zinc, along with N, P, and K, is regarded the most important nutrient globally (Prakash *et al.* 2017). Zinc is important in growth and metabolism, including metabolism of carbohydrates, nucleic acids, lipids, gene expression and control, enzyme activation, protein synthesis and plant reproductive development (Prakashya *et al.* 2019). Zinc deficiency reduces the amount of growth regulator, which leads to shorter internodes on the stem. According to the findings, each zinc oxide treatment increased leaf area (Taheri *et al.* 2016). As per some research, zinc shortage and a decrease in photosynthetic active radiation might impact the rate at which leaves develop and grow. Irrigation with zinc oxide nano-particles increased growth, leaf area, and leaf dry weight as per findings of Taheri *et al.* (2016). The

increased surface area resulted in improved contact between Zinc Oxide and soil components. To explain further, zinc oxide nano-particles were more efficiently absorbed and were most likely the source of improved plant development (Taheri *et al.* 2016). Similarly, applying zinc nano-fertilizer to pearl millet resulted in enhanced root length, root area, shoot length and plant dry biomass. Iron Nano-particles treatments increased shoot length in maize plants at Fe concentration of 27 and 54 μM (Elanchezhian *et al.* 2017).

Barley and other crops: Barley is the cereal crop with the most diverse production locations in the world. Compared to other cereals, barley ranks fourth in global production, trailing maize, wheat and rice. Janmohammadi *et al.* (2016) found that foliar spraying of nano TiO_2 improves barely yield and growth components and nano-fertilizers boosted fertilizer use efficiency. The likely rationale for such a favourable role is owing to an increase in photosynthetic activity by increasing cyclic and linear phosphorylation by nano TiO_2 spraying. Finger millet is a major grain and fodder crop in India (Ashokh Aravind *et al.* 2020). Spraying 40 kg N/ha + nano urea at 4 ml/litre resulted in maximum plant height (104.9 cm), dry matter (406.2 g/m²), and LAI (4.8) values in finger millet (Samanta *et al.* 2022). The presence of ZnO nano particles significantly decreased the biomass of rye grass (Lin and Xing 2008). SNPs resulted in lower root growth, root length, and biomass in mungbean, jowar, and Italian ryegrass (Lee *et al.* 2012). Iron oxide improved soybean production substantially (Sheykhabglou *et al.* 2010). In cotton crop, improved physiological processes, including antioxidant activity and chlorophyll content, resulting in higher dry and fresh weight (Rezaei and Abbasi 2014).

Effect of nano fertilization on soil health

Silver, in both its ionic (Ag^+) and nano forms, has been shown to be hazardous to soil microbes and other soil dwelling creatures. Many researches have been conducted on the microbiological toxicity of AgNPs, and several hypotheses have been established as a result of these findings. The suggested mechanisms of antibacterial activities of AgNPs have primarily been attributed to the dissolved silver ions (Ag^+) from AgNPs. AgNPs have an impact on soil microbial endpoints such as enzyme activity, biological nitrification, and microbial diversity. Chavan *et al.* (2023) discussed the non-significant effect of nano-fertilizer on soil parameters such as available nutrient content (N, P, and K), soil organic carbon (%) and pH after harvesting little millet (Fig. 2 A, B and C).

Effect of nano-fertilization on qualitative traits of cereals

Antioxidants are secondary metabolites produced by plants under unfavourable conditions such water stress, salt, and restricted nutrients. Numerous studies have revealed that the presence of one or more aromatic rings with one or more hydroxyl groups gives the phenolic compounds present in grains their potent antioxidant properties. The availability of essential macronutrients during plant growth has the potential to significantly influence phenolic buildup

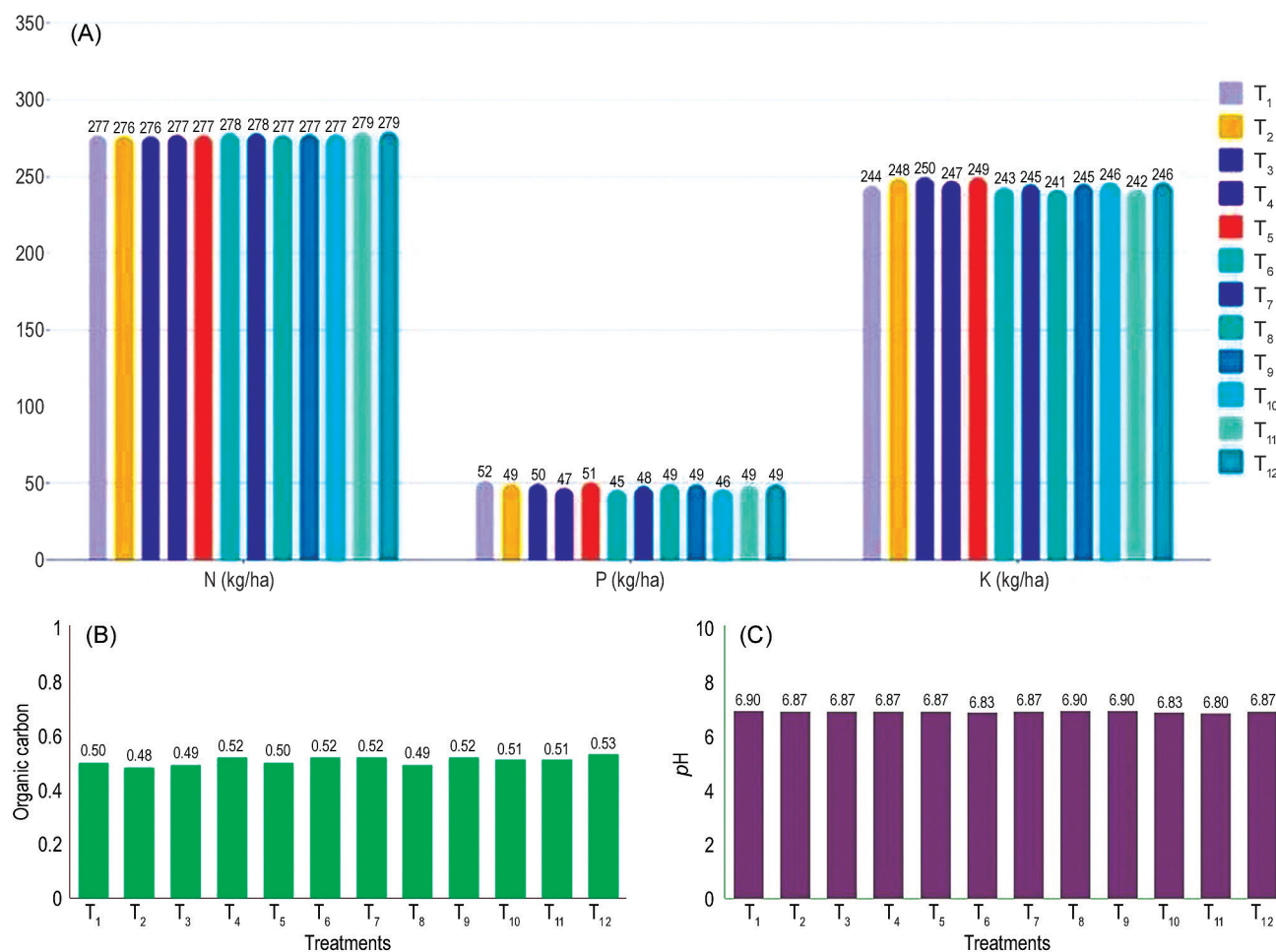


Fig. 2 (A) Mean soil N, P and K; (B) Mean soil organic carbon (SOC); (C) Mean soil pH in the soil after little millet harvest as impacted by nano-fertilizers.

T₁, Recommended dose of fertilizer (60:30:30 kg/ha NPK); T₂, T₁ without nitrogen application; T₃, 50% recommended dose of nitrogen + seed treatment with 1% nano-fertilizers; T₄, 50% recommended dose of nitrogen + foliar spray of nano-fertilizers @0.4% at active tillering stage; T₅, 50% recommended dose of nitrogen + foliar spray of nano-fertilizers @0.4% at 7–10 days before flowering; T₆, 50% recommended dose of nitrogen + foliar spray of nano-fertilizers @0.4% at active tillering stage and at 7–10 days before flowering; T₇, T₃ + foliar spray of nano-fertilizers @0.4% at active tillering stage and at 7–10 days before flowering; T₈, 75% recommended dose of nitrogen + seed treatment with 1% nano-fertilizer; T₉, 75% recommended dose of nitrogen + foliar spray of nano-fertilizers @0.4% at active tillering stage; T₁₀, 75% recommended dose of nitrogen + foliar spray of nano-fertilizers @0.4% at 7–10 days before flowering; T₁₁, 75% recommended dose of nitrogen + foliar spray of nano-fertilizers @0.4% at active tillering stage and at 7–10 days before flowering; T₁₂, T₈ + foliar spray of nano-fertilizers @0.4% at active tillering stage and at 7–10 days before flowering.

(Parr and Bolwell 2000). Nano-fertilizers were used as a supplement, allowing for greater nutrient absorption through plant cells and thereby improving antioxidant activity. Some research findings prove that nano-fertilizer treatment boosts antioxidant potential in rice (Benzon *et al.* 2015).

The usage of nano N and nano K lowered the amylose content while nano phosphorus had increased the amylose content in rice (Sadati Valojai *et al.* 2021). Different conventional and nano fertilization treatments resulted in a significant drop in gel consistency of rice grains regardless of cultivars. Nano TiO₂ foliar spray improved plant dry matter production by improving nitrogen absorption, electron transport chain and photo reduction activities of

PS-II, chlorophyll content, anthocyanins, carotenoids and scavenging Reactive Oxygen Species (ROS) on maize (Morteza *et al.* 2013).

Liu *et al.* (2008) concluded that foliar application of nano-fertilizer on wheat lowered protein content while increasing fat content. Ghafari and Razmjoo (2003) discovered that treating wheat plants with 2 g/l nano-iron oxide boosted antioxidant enzyme activity and chlorophyll content, which resulted in higher grain production, harvest index, 1000-grain weight, protein and carbohydrate content. Maize plants treated with Fe NP (27 µM) at 60 DAS showed enhanced membrane stability, proline content and total soluble protein. Plants, however, showed reduced amounts of total soluble sugar (Elanchezhian *et al.* 2017).

In comparison to the FRR-CF + FRR-NF treatment in rice, HRR-NF significantly increased reducing power, total phenolic content and ABTS scavenging activity by 36.28%, 51.67%, and 20.93%, respectively. Against the assertion made above, the FRR-CF + FRR-NF treatment had the highest hydroxyl scavenging activity (55.11%) (Benzon *et al.* 2015). At 60 and 45 DAT, the chlorophyll content was measured. Except for HRR-NF, every treatment improved it. The FRR-CF+ FRR-NF has the greatest value (2.72% higher than FRR-NF) (Benzon *et al.* 2015). The usage of nano carbon as a slow-release fertilizer boosted rice, grain yield, chlorophyll content, and nitrogen use efficiency. SNP-induced increases in chlorophyll content may improve photosynthesis, resulting in increased yield and biomass (Jhanzab *et al.* 2015) (Fig. 3)

Jamadar (2016) discovered that foliar spraying of nano-particles improved zinc uptake in upland paddy by 48% and enzyme activity by 53% compared to control. Zinc fertilizers may increase soluble carbohydrate concentration by promoting enzyme carbonic anhydrase, starch formation and chlorophyll synthesis which accelerates carbohydrate formation. Similarly, plants treated with less Fe nano-particles concentrations (27 μ M) showed an increase in antioxidant enzyme activity in maize (Elanchezhian *et al.* 2017).

Effect of nano-fertilization on stress alleviation

Because of their large surface area and nanoscale size, nano-fertilizers have a high potential to reduce abiotic/biotic stressors on cultivated plants via a variety of methods. Nano-fertilizers can increase the morphological, biochemical, and physiological indices of farmed plants, such as photosynthetic rate and efficiency, nutrient uptake efficiency, phytohormone modulation, and plant defence system augmentation. As a result, the actions of nano-fertilizers on agricultural productivity under stress may include: a reduction in oxidative stress, which leads to an increase in plant stress tolerance; and the stimulation of many biochemical processes in stressed plants. The mechanisms of nano-fertilizers are primarily dependent on nano active ingredients (large specific surface areas), which may result in appropriate reactivity and boost the

efficient uptake of nutrient elements for the growth of farmed plants and their metabolic processes. Nano-fertilizers enable the encapsulation of nutrients by nanomaterials, their distribution as nano-particles or emulsions, or the regulated release of nutrients as smart nano-fertilizers. Abiotic stresses such as drought and salinity can reduce crop productivity by 50% (Wang *et al.* 2003). Hussein and Abou-Baker (2018) concluded that nano zinc increased nutrient uptake and root penetration to alleviate saline stress. Because of nano-particles increased surface area and reactive regions they improve enzyme activity for salt tolerance. Foliar spraying of SiO₂ may improve cell wall strength, turgidity and flexibility during growth extension that can tolerate stress condition (Yassen *et al.* 2017). Nano TiO₂ treatment boosts wheat starch and gluten content during water stress due to a positive association with photosynthetic rate. Under water stress conditions, nano Zn foliar spraying in maize crops boosted yield and yield components. Foliar treatment of 2.5 μ M nano-silicon reduced cadmium (Cd) stress in rice seedlings by improving Zn, Fe, and Mg nutrition, as well as chlorophyll a concentration. It also reduced Cd buildup and translocation from roots to shoots. Foliar nano-particles application of Fe₃O₄ to maize crops, whether at high or low concentrations, can alter photosynthesis and interfere with the plasma membrane ion channels (Racuciu and Creanga 2007).

Effect of nano-fertilization on quantitative traits

Yield attributes: Nano-fertilizers improve seed germination, vigour, growth parameters (plant height, leaf area, leaf area index, number of leaves/plant), dry matter production, chlorophyll production, and photosynthesis rate, resulting in increased production and translocation of photosynthates throughout the plant. The application of nano NPK yielded the highest rates of head rice recovery. When compared to traditional fertilizers (N and NPK), the use of nano N and nano NPK considerably boosted the grain yield and milled rice yield. And in comparison, between nano N and nano NPK the greatest increase in grain yield and milled rice yield was observed in nano NPK. The combined use of conventional and nano-fertilizers (NPK + nano NPK), also boosted grain yield (GY) and milled rice yield (MRY) in rice cultivars (Sadati Valojai *et al.* 2021). The application of phosphorus and potassium fertilizer to paddy considerably increases the brown rice recovery (BRR), milled rice recovery (MRR), and head rice recovery (HRR) (Fahad *et al.* 2016). Rice grain production increases with the applying of nano potassium fertilizer. When compared to K (traditional K), the application of nano K dramatically boosted brown rice recovery and head rice recovery. Nevertheless, the usage of N and P in nano-particle forms (nN and nP) had a negative influence on head rice recovery (Sadati Valojai *et al.* 2021). Nano-bentonite and nano-active carbon-coated nitrogen fertilizer enhanced absorption and transportation of N, P, and K to seed, resulting in dramatically increased rice yield. Treatment with nano-scale zinc oxide particles at 40 ppm resulted with higher rice grain production and

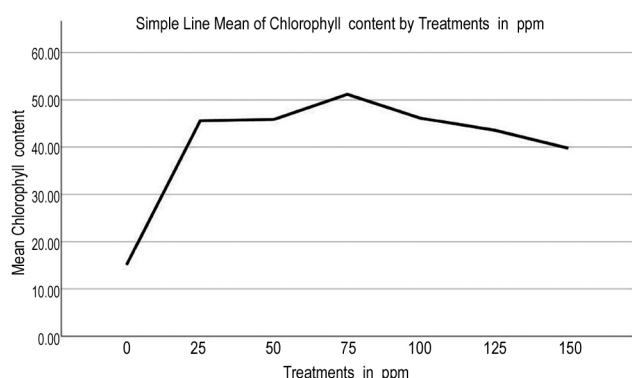


Fig. 3 Effect of silver nano particles (SNPs) on chlorophyll content of wheat cultivar.

components during the mid tillering and PI stages (Ghasemi *et al.* 2017).

In wheat silver nano-particles at 25 ppm considerably increased leaf area, yield, and N, P and K use efficiency. Similarly, SNPs at 75 ppm increased chlorophyll content, while SNPs at 50 ppm produced a greater number of grains (Jhanzab *et al.* 2015). Nano-fertilizer application boosted grain Zn concentration without reducing yield, protein, 1000-grain weight and spikelets per spike. This was attributed to improved enzyme activity and carbohydrate metabolism, resulting in greater yield. In comparison to the control, foliar application of nano-iron at concentrations ranging from 2 to 6% increased wheat grain yield by 12 to 20% (Armin *et al.* 2014).

Applying zinc nano-fertilizer as a foliar spray to pearl millet considerably enhanced the grain yield by 37.7%. Spraying 40 kg N/ha + nano urea @ 4 ml/litre resulted in the highest number of effective tillers/m² (39.0), earheads/plant (5.9), fingers/earhead (8.8), grains/earhead (1458.3), and finger length (5.9 cm) and also resulted in the highest grain yield (1351.7 kg/ha), straw yield (4029.3 kg/ha), and biological yield (5381.1 kg/ha) in finger millet (Samanta *et al.* 2022).

Although nanotechnology has received little attention in agriculture, research indicates that it could play a critical role in establishing smart delivery systems. This allows plants to produce more biomass by exploiting available nutrients in the rhizosphere, while minimizing environmental impact. While it is difficult to foresee the impact of nanotechnology on fertilizers in the future, there is a unique chance to gain insight into what is to come. This understanding can help researchers contribute to the growing discipline and fulfill its full potential. The controlled release system delivers agrochemicals to the soil over time, reducing the amount of chemicals, manpower, and energy required for application devices. Nanotechnology in agriculture has improved crop productivity and protection compared to traditional materials on a larger scale. There is currently little information available on the regulated release of agrochemicals from nano-structured materials. Nano-fertilizers outperform conventional fertilizers in terms of soil fertility, crop quality and environmental, and human safety. They also reduce costs and enhance profits. Nano particles improve nutrient efficiency and reduce environmental costs. Using nano-fertilizers can improve agricultural productivity, lower fertilizer costs, and reduce pollution. Nano-fertilizers enhance crop growth and output at optimal doses and concentrations, but can limit productivity and plant development at higher concentrations. Nano-fertilizers have a significant role in crop production, enhancing yield, crop growth and quality, resulting in higher yields and high-quality food for human and animal use. Nano-fertilizers enhance cereals growth, production, and quality, resulting in increased nutrient-use efficiency. The application of nano-fertilizers enhances rice crop growth, yield, antioxidant activity and total phenolic content and has the potential to boost plant nutrition and crop productivity. In wheat it can be finalized that SNPs

can play a crucial role in increasing wheat growth via improving NUE (Jhanzab *et al.* 2015). Nano-fertilizer dramatically improved plant growth and nutrient content in wheat. Applying various nano-fertilizers can significantly improve cereals productivity. This reduces fertilizer costs for crop production while minimizing pollution. The optimal concentration of Fe nano-particle treatment improved the maize growth parameters and chlorophyll content, while sub-optimal concentrations only improved leaf growth, total soluble protein, proline content, and membrane stability (Elanchezhian *et al.* 2017). Overall, nano-fertilizers enhance the yield, growth parameters, qualitative characteristics, and nutrient-use efficiency of majority cereals, and in final nano-fertilizers are going to be a promising resource for nutrient management in agricultural crops in the future.

Conclusion

Nanotechnology provides a promising approach to fulfilling the nutrient requirements of cereals, crops that usually depend heavily on large amounts of inorganic fertilizers. Nano-fertilizers enhance nutrient-use efficiency and crop yield in cereals by improving absorption of nutrients and addressing the limitations of conventional fertilizers. The benefits of nano-fertilizers, viz. increased drought tolerance, better soil health, increasing yield and growth parameters are making them a promising solution for sustainable agriculture. The impact and effectiveness of nano-fertilizers on the growth of cereal crops along with the detailed relationship between physiological, qualitative and quantitative traits are detailed in this review. Overall, nano-fertilizers represent a significant solution and advancement in nutrient management for cereal crops in near future.

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