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REVIEW ARTICLE

Comprehensive analysis of nano-fertilizers in Indian agriculture - A review

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Abstract

This is a comprehensive review of studies of nano-fertilizers for their efficacy in stimulating plant growth, facilitating higher nutrient uptake and thus enhancing overall crop yield and productivity. The intricate insights into the mechanisms through which nano-fertilizers ensure sustained nutrient release, optimize nutrient absorption and augment nutrient utilization efficiency, have been reviewed. Several scientific studies indicate the potential of nanotechnology to enhance crop performance in terms of better crop growth and higher productivity. Regarding the economic implications of adopting nano-fertilizers, several findings indicate that nano-fertilizers could offer cost advantages over conventional fertilizers, potentially alleviating the government's subsidy burden and reducing import expenses on huge quantities of major commercial fertilizers. This comprehensive review also explores the challenges faced by Indian agriculture in crop production and the potential of nanotechnology to revolutionize productivity on a sustainable basis. The study emphasizes the urgent need for enhanced and sustained crop production and highlights the significance of nano-fertilizer application as an innovative and environmentally friendly solution. In conclusion, this comprehensive overview of the status of stagnant crop production in India identifies the challenges in augmenting productivity and proposes nanotechnology-based fertilizers and their utility in major agricultural crops cultivation as a promising solution. The findings underscore the need for further research and the widespread adoption of nanotechnology-based fertilizers in Indian agriculture to ensure sustainable and enhanced production and productivity.

Keywords

growth attributes; nano-fertilizers; pulses; yield components and yield

Introduction

Food and nutritional insecurities, along with environmental crises, represent critical global challenges that demand urgent scientific and policy interventions (1). Population growth and industrial development contribute to rising levels of toxic pollutants in the environment (2). With the global population projected to reach 11 billion by 2100, current food production must increase by 60-70% to meet the energy demands of this rapidly expanding population (3). Meeting future global demand for food requires enhancing resource utilization efficiency while sustaining agricultural productivity, primarily through advancements in modern science and technology. Chemical fertilizers have been instrumental in boosting the productivity of crops, especially food grain crops, but the excessive use has led to declines in both food quality and soil health. Chemical fertilizers contribute approximately 50-55% of crop yield increases in developing countries. However, the nutrient use efficiency of these fertilizers remains low, with nitrogen (N) at 30-40%, phosphorus (P) at 15-20%, potassium (K) at 50-55% and micronutrients at only 2-5% (4, 5). Additionally, the degradation of arable land poses a significant barrier to crop production, exacerbated by limited resources and increasing urbanization. To address these challenges, farmers have increasingly relied over the past few decades on fertilizers, pesticides, genetically modified crops and pest-disease-resistant varieties (6).

Given the low yield of food grain crops as conventional fertilizers are not sufficient for production, are nano-fertilizers the best alternative? Utilizing nanotechnology in the form of nano-fertilizers offers an innovative, effective and environmentally friendly substitute for conventional synthetic fertilizers. Nano-fertilizers enable a gradual and sustained nutrient release, thus facilitating better plant growth and development besides the conservation and diversity of beneficial microbiome (7). Nano-fertilization is becoming increasingly popular because of its demonstrated practicality and high effectiveness as indicated by research (8-10).

Nowadays, various nano-devices and nano-materials have been found to play distinctive and prominent roles in agriculture. These include nano-biosensors for detecting soil moisture content and available nutrient status, enabling location -specific irrigation water and nutrient management. Additionally, nano-fertilizers ensure cost-effective nutrient application, nano-herbicides confirm targeted and precise weed control in crop fields, nano-nutrients enhance seed vigor and viability and nano-pesticides enable efficient insect pest management (11).

Importance

The rapid progress of the Indian populace has led to a continuous rise in food demand, a challenge that cannot be overlooked. Factors such as increasing population, rising incomes and globalization in India are driving the need for greater quantities of high-quality, nutritious food. This places significant pressure on shrinking cultivable land to produce enough food to meet the needs of India's expanding population (3). Addressing food security and increasing food production and productivity require the adoption of innovative and forward-thinking advancements and technologies to enhance cultivation methods, yields and land productivity. However, challenges such as limited agricultural land, water scarcity, climate change, crop pests and disease incidence, poor nutrient use efficiency (NUE) and constrained crop productivity hinder India's food security

vision and mission. The indiscriminate use of chemical fertilizers not only escalates the costs of cultivation but also reduces the profit margins of farmers. Traditional fertilizers often result in low NUEs due to their rapid release rates, which may exceed the actual nutrient absorption capacity of plants or result in the conversion of nutrients into other forms, that are not readily available to pulse crops (4). Nanotechnology plays a significant role in the enhancement of food grain production to meet the growing demand of the population while ensuring environmental security, sustainability and economic stability (12). Hence, there is a need for the development of nano-based fertilizer formulations with multifunctional capabilities (13).

Nano-fertilizer technology represents a highly innovative approach. Within nano-fertilizers, micro or macro-nutrients can be enclosed within nano-materials, shielded by a delicate protective layer, or administered in the form of nano-emulsions or nano-particles (8). Nano-fertilizers utility enables precise, slow and controlled release of nutrients in the rhizosphere of the plants, thereby mitigating the risk of eutrophication and pollution of water resources (14). In contrast to traditional fertilizers, nano-fertilizers significantly moderate nutrient release patterns while simultaneously enhancing their stability through processes such as aggregation or adsorption. Importantly, these adjustments occur without altering chemical specifications due to factors like pH-oriented phenomena, redox potential, or the availability of ligands in the soil (15). Nano-fertilizer serves as an asset in agriculture, maximizing crop growth, grain yield and quality traits through enhanced nutrient utilization efficiency, minimal fertilizer losses and a significant reduction in cultivation expenses (16).

Due to their formulation and synthesis process, nano-fertilizers have the potential for quick solubility in contrast to conventional fertilizers and possess the capability to discharge their constituents in reaction to various biotic and abiotic triggers. This regulated release process can effectively enhance nutrient accessibility to plants. Furthermore, the utilization of nano-fertilizers holds promise in enhancing fertilizer utilization efficiency, consequently boosting crop productivity (17). Foliar fertilization proves to be an effective and supplementary approach to soil fertilization, as it ensures that plants receive essential nutrients during critical growth stages that roots may struggle to provide. Moreover, it offers simpler and cost-effective techniques for nutrient management; hence, it is considered an alternative to the conventional soil fertilizer application (18).

History of nano-fertilizers

Nano oxide forms of zinc, manganese and iron elements have been synthesized through a green chemistry approach employing a microwave-assisted hydrothermal method (19). These nano-particles (NPs) exhibited an average particle size ranging from 20 to 60 nm, with minimal surface areas. They were subsequently sprayed as foliar nano-fertilizers on squash plants. The findings demonstrated that foliar application of NPs-derived manganese oxide resulted in superior vegetative growth characteristics, fruit traits, yield and higher levels of photosynthetic pigments. Conversely, squash fruits sprayed with iron oxide NPs exhibited the highest values for organic matter, protein, lipids and energy content.

NP-based iron and manganese nutrients were biosynthesized through the rapid and straightforward method using bacterial supernatant enriched with an auxin composite (specifically, indole-3-acetic acid (IAA)) and then assessed for their efficacy as crops nano-fertilizers. The synthesized NPs exhibited promising potential as micronutrient fertilizer sources for crop cultivation. Among them, NPs of bimetallic MnO_x/FeO_x derived from bacterial supernatant solution demonstrated the most favourable outcomes on crop growth, particularly in terms of maize crop germination rates, its root development and fresh-weight of seedlings, suggesting their suitability as micronutrient nano-fertilizers (20).

In December 2002, the United States Department of Agriculture (USDA) formulated the inaugural "roadmap" globally for integrating nanotechnology into agriculture and food. A significant assembly comprising policymakers, representatives from land-grant universities and corporate scientists convened at Cornell University in New York to collectively envision the transformation of agriculture through nanoscale technologies (10).

Nanotechnology involves a comprehensive manipulation process and utilizes materials on a microscopic scale, normally ranging from 1 to 100 nanometers (nm) in size. To provide context, consider that a single human hair measures approximately 80000 nm to 100000 nm wide. When materials were scaled down to such tiny dimensions, they displayed distinctive properties significantly divergent from their larger forms, largely attributed to quantum effects (21).

Nano Urea Liquid, a pioneering product, has been developed domestically using proprietary technology at Nano Biotechnology Research Centre (NBRC), Indian Farmers Fertilizers Cooperative (IFFCO) located at Kalol, Gujarat, India in 2021 (22). The developer claims that it is feasible to substitute a 45 kg bag of urea (equivalent to 20.7 kg of N) with a 500 mL bottle of foliar fertilizer containing 4% w/v nano urea (equal to 43 g of urea or 20 g of N). Further, the company claims that farmers could achieve an average yield increase of 8% while using 50% less N, resulting in substantial reductions in fertilizer costs (23). In April 2023, IFFCO introduced nano DAP liquid fertilizer under the Fertilizer Control Order. This innovative product aims to empower farmers by enhancing crop productivity and augmenting income. Nano DAP liquid serves as an effective N and P source, addressing deficiencies in plants for improved growth and better crop yield per unit area (24).

Mechanism of action of nano-fertilizers

The higher reactivity of nano-materials ensures complete nutrient uptake by plants, resulting in higher utilization efficiency and, thereby lower losses when compared to normal synthetic fertilizers (25). The effectiveness of absorption, distribution and accumulation of nano-fertilizers relies on several reasons, which include soil reaction, soil organic matter status and soil textural classes. Additionally, inherent NP characteristics *viz*., size of the particle and coating methods, contribute to these processes (26, 27). Macronutrient nano-fertilizers have been found to enhance plant development by 19%, whereas micronutrient nano-fertilizers exhibit an 18% improvement and carriers for macronutrients in nano-fertilizers boost growth by 29% compared to conventional fertilizers (28).

The absorption of NPs is contingent on the physiological characteristics of plants. Generally, these particles are taken up through trichomes, stomata, stigma and hydathode parts present in the plants and subsequently transported within the plant system through the phloem and xylem (29). Through the advantage of lesions present in the Casparian strip, NPs can also be absorbed through root-tip meristematic tissue or points of lateral roots and consequently navigate through cell walls and plasma membranes to reach the epidermal portion of the roots. Subsequently, NP access vascular tissue bundles specifically the xylem. Though the pore size of 3 to 8 nm present in the cell wall is considered very small for NPs entry, studies have confirmed that they encourage the larger pore size formation in cell walls, which facilitates their entry to the cell wall (30).

Reducing the dimension of conventional fertilizers to nano-size while modifying their surface properties has the potential to decrease the necessary dosage compared to conventional fertilizers or delivery methods in crop systems. The size is a crucial factor influencing the entry of NPs through pores present in the cell wall or stomata and it is directly correlated with NP absorption (31). Nano-fertilizers possess extensive surface areas, considerable sorption capabilities and controlled-release kinetics tailored to precise locations, rendering them an ingenious method of delivery (32).

Plant growth attributes and growth analysis

Plant height

Soil application of 40 kg N ha^{-1} combined with foliage nutrition of nano urea at 4 mL litre^{-1} applied at tillering and pre-flowering stages recorded the highest values of plant height (104.9 cm) in finger millet (33). While foliar spray of nano Di-Ammonium Phosphate (nano DAP) at 2-4 mL litre^{-1} of spray solution combined with conventional soil application of 100% NK + 50% P (120:30:40 kg ha^{-1}) to 100% NK + 75% P (120:45:40 kg ha^{-1}), significantly maximized the plant height of rice crop from 97.25 cm to 126.51 cm and 91.9 cm to 121.14 cm in *kharif* 2021 and *kharif* 2022 respectively (34). Whereas integrated application of 100% recommended dose of nutrients and foliar supplement of nano urea at at 4 mL litre^{-1} significantly registered greater plant height of 108.1 cm at 60 days after sowing (DAS) in maize crop (35).

Foliar application of nano-fertilizers at various stages of field pea combined with conventional fertilizers at 54 kg DAP ha^{-1} produced higher plant growth at all the stages when compared to conventional fertilizer application alone. At 15 DAS, foliar application of nano Zn + 0.2% nano urea recorded a higher plant height of 8.32 cm, whereas at 30 DAS, foliar spraying nano Zn at 0.1% + nano urea at 0.2% concentration recorded a maximum plant height of 22.6 cm (36). Similarly, in onion crops, integrated application of conventional fertilizer at 75:50:50 kg N:P_2O_5:K_2O ha^{-1} combined with foliar nutrition of nano urea at 0.4% concentration significantly registered higher plant height of 57.82 cm at 90 days after transplanting (DAT). The foliar uptake of nano urea can lead to the enhancement of processes such as cell division, elongation and protein synthesis, which results in higher growth (37).

The cauliflower curd length exhibited a significantly higher growth of 13.7% and 17.8% in 2020-21 and 2021-22 respectively by integrated application of urban compost at 6.25 tonnes ha^{-1}, Consortia of NPK Bio-fertilizer at 1.25 litre ha^{-1}, Sagarika granular at 25 kg ha^{-1} and three foliar sprays each of nano-N, nano- and Sagarika than the application of 100% recommended dose of fertilizers (RDF) (125:50:50 kg N:P_2O_5:K_2O ha^{-1}) (31). In wheat crops, utilizing nano-coated fertilizers resulted in a notable enhancement in plant height. Application of the recommended dose of N and P_2O_5 (including 10% $KFeO_2$ nano-coated-DAP + urea without potassium) led to the highest plant heights of 60.3 cm and 80.7 cm at tillering and booting growth stages, respectively (38).

In cluster bean crop, the highest plant heights of 26.10 cm, 68.44 cm and 80.24 cm at 30, 60 and 90 DAS respectively were observed with the application of NPK at 100% rate (20:40:60 kg ha^{-1}), along with nano urea at 0.5 mL and FYM at 10 t ha^{-1} (39). While in vegetable cowpea (*Vigna unguiculata* subsp. *unguiculata* (L.)), the treatment comprising 100% RDF (40:30:10 kg NPK ha^{-1}) along with nano-Zn at 2 mL litre^{-1} resulted in tallest plants, at 30 DAS (47.75 cm). Conversely, at 60 DAS and harvest stages, the treatment involving 50% recommended dose of nitrogen (RDN) (20 kg ha^{-1}) and 100% PK (30:10 kg ha^{-1}) + nano-N at 2 mL litre^{-1}at 15 DAS and 30 DAS + nano-Zn at 2 mL litre^{-1}at 30 DAS, produced the tallest plants, measuring 77.63 cm and 82.08 cm, respectively (40).

Plant dry weight

Integrated application of 100% RDN (120:60:60 kg NPK ha^{-1}) + nano urea foliar spray at 4 mL litre^{-1} recorded the supreme plant dry weight of maize (61.2 g) at 60 DAS (35). The enhanced availability and utilization of nutrients from nano urea foliar spray are believed to contribute to increased biomass, ultimately leading to the observed higher plant dry weight. Likewise, the highest biomass in lettuce plants was recorded when the foliar nutrition of nano urea was combined with the application of VAM biofertilizer (41). Application of nano N alone at 5000 mg litre^{-1} and combined application of nano N at 3750 mg litre^{-1} + VAM biofertilizer recorded 12.8% and 155.7% increment in biomass respectively than control plot (12.1 g plant^{-1}). Application of any nutrients in nano-synthesized form leads to enhancement in plant biomass when compared with conventional fertilizer application. Foliar application of nano NPK and Fe + Zn recorded a substantial increase (14%) in plant biomass of chickpeas when compared with plants nourished with conventional fertilizers (42).

Integration of nano-nutrients along with 75% NPK (112.5:45:30 kg ha^{-1}) or 100% NPK (150:60:40 kg ha^{-1}) resulted in substantial enhancement in dry matter build-up of wheat crop. United application of 75% NPK and foliar nutrition of nano-N, nano-P, nano-K, nano-Zn and nano-N+P+K+Zn recorded significant enhancements in plant dry weight of wheat crop at harvest stages (10.6%, 8.8%, 8.1%, 10.3% and 15.8%, respectively) than 100% RDF alone (43). Additionally, when nano-fertilizers were combined with 100% NPK, the respective increases in plant dry weight were 13.2%, 9.8%, 9.3%, 8.2% and 18.7% higher than 100% NPK alone. However, the treatment consisting of 50% P (40 kg ha^{-1}), 100% NK (130:80 kg ha^{-1}), along with a foliar spray of nano-DAP at 2 mL litre^{-1} at 25-30 DAT registered the highest leaf dry weight (0.95 g) in cabbage plants at 30 DAT (44). While at 60 DAT, the maximum leaf dry weight (4.11 g) was observed in the treatment combination of NK nutrients at 130:80 kg ha^{-1}, along with seedling root-dipping at 5 mL litre^{-1} and a foliar spray of nano-DAP at 5 mL litre^{-1}, applied at 25-30 DAT. In vegetable cowpea (*V. unguiculata* subsp. *unguiculata* (L.)), the highest dry matter production (3.86 g plant^{-1})was observed at 30 DAS, in the treatment comprising 50% N (20 kg ha^{-1}) and 100% PK (30:10 kg ha^{-1}) applied as basal, with the remaining half dose of N administered at 15 DAS. This result was comparable to the treatment involving 100% RDF (40:30:10 kg NPK ha^{-1}) along with nano-Zn at 2 mL litre^{-1} of water applied at 30 DAS and 45 DAS. However, at 60 DAS and the final harvest, the treatment involving 50% N along with nano-N at 2 mL litre^{-1} of water and nano-Zn at 2 mL litre^{-1} of water applied at 30 DAS, produced considerably higher dry matter of 24.89 g plant^{-1} and 37.36 g plant^{-1}, respectively (40).

Crop growth rate (CGR)

A higher CGR of 8.71g m^{-2} day^{-1}was recordedin field peas by integrated application of conventional fertilizer (54 kg DAP ha^{-1}) + foliar nutrition of nano-fertilizer (nano Zn at 0.1% + nano urea at 0.2%) applied at 30 DAS when compared with control treatment (5.51g m^{-2} day^{-1}) (36). In the case of wheat, the combined nutrient management of 100% RDN (120:60:40 kg NPK ha^{-1}) and foliar spray of nano urea twice at a concentration of 4 mL litre^{-1} resulted in significantly higher CGR of 11.33 g m^{-2} day^{-1} when compared with the control (45).

Application of mycorrhiza in conjunction with nano-B led to the most elevated CGR of 3.40 g day^{-1} m^{-2} in peanuts (46). Similarly, the unified application of 75% RDF (30:15:7.5 kg NPK ha^{-1}), nano-fertilizer seed treatment and nano-fertilizer foliar application at active tillering and 7 to 10 days prior to the flowering stage led to the highest CGR of 0.29 g day^{-1} m^{-2} in little millet, exceeding all the conventional fertilizer treatments (47).

Leaf area

In marigolds, the treatment combination involving application of 50% N and P_2O_5 (45:37.5 kg ha^{-1}) and foliar nutrition of nano-urea at 3 mL litre^{-1}and nano-DAP at 5 mL litre^{-1}sprayed at 30 and 45 DAT significantly resulted the maximum leaf area of 7.03 cm^2, 9.34 cm^2 and 13.40 cm^2 at 40, 55 and 70 DAT, respectively (48). Nano urea, when applied as foliar nutrients, effectively penetrates through stomata and other openings, fostering leaf growth and elongation by regulating the rate of cell division or size. Similarly in the cabbage crop, collective application of 50% P (40 kg ha^{-1}) and 100% NK (130:80 kg ha^{-1}), along with a foliar spray of nano-DAP at 2 mL litre^{-1} at 25-30 DAT, exhibited the highest leaf area measurements of 88.33 cm^2 and 183.70 cm^2 at 30 and 60 DAT, respectively (44).

Leaf area index

The impact of foliar spray of nano-N on the leaf area index (LAI) of sunflower crops was studied, revealing that the application of 50% RDN (37.5 kg ha^{-1}) as basal fertilizer and foliage spraying of nano-N at 2 mL litre^{-1}twice-once at star bud stage and again at 50% flowering-resulted in 18% increase in LAI compared to absolute control (no N application) (49). This implies that nano-N, when applied to the foliage of the crops, is efficiently absorbed and transported to the growing region of plants, thus leading to higher cell division and growth. Similarly, a remarkable influence of nitrogenous fertilizers on the LAI of sorghum at different growth stages has been recorded (50). The highest value for the LAI of 0.95 was observed in a treatment combination of a basal application of 50% recommended N as neem-coated urea and the remaining 50% N as nano urea, along with 100% P and K, during the tillering and pre-flowering stages.

In the wheat crop, the highest LAI (4.50) at 90 DAS was recorded in the treatment combination of application of 100% RDN (120:60:40 kg NPK ha^{-1}) + foliar application of nano urea twice at 4 mL litre^{-1}(45). Whereas in maize crop, the highest LAI of 4.55 was achieved at 90 DAS using a 50% recommended dose of Zn and 100% NPK, coupled with two foliar sprays of nano-Zn at a concentration of 4 mL litre^{-1}at 25 and 50 DAS. A significant increase in LAI of maize was noted in nano-processed zinc micronutrient foliar spray indicating the systematic and substantial impact of macro and micronutrient supply on leaf growth (51).

Combined application of 75% RDF (30:15:7.5kg NPK ha^{-1}) + seed treatment with nano-fertilizers + foliar spray of nano-fertilizer twice-once at active tillering stage and again at 7-10 days earlier to flowering stage-was found to enhance LAI of little millet significantly (47). This finding implies that the higher surface area, increased density of active sites and improved reactivity of particle surfaces of nano-fertilizers all contribute to their higher efficiency of applied nutrients. In soybean crops, foliar application of nano-silica at 3.75 mL $litre^{-1}$ resulted in the highest LAI value of 2.10 at 45 DAS (52).

At 30 DAS, the treatment involving 100% RDF (20:30:10 kg NPK ha^{-1}) along with nano-Zn at 2 mL $litre^{-1}$ achieved significantly the highest LAI of 1.02. However, at 60 DAS and harvest stages, the treatment comprising 50% RDF along with nano-N at 2 mL $litre^{-1}$ and nano-Zn at 2 mL $litre^{-1}$ at 30 DAS, resulted in higher LAI values of 1.57 and 0.90, respectively in vegetable cowpea (*V. unguiculata* subsp. *unguiculata* (L.)) (40).

Physiological parameters

Enzymatic activities

Integrated nutrient management of 100% NPK (150:75:75 kg ha^{-1}) and nano-urea at 4 mL $litre^{-1}$ and nano Zn at 2 mL $litre^{-1}$ resulted in distinctly higher dehydrogenase activities at the flowering stage of wheat crop, recording values of 38.3µg and 36.0µg TPF (triphenyl formazan) g^{-1} 24 hr^{-1} in first and second crops, respectively. Similarly, in maize, the highest dehydrogenase activity values of 35.5µg TPF g^{-1} 24 h^{-1} were recorded under the treatment combination of 100% recommended rate of NPK in combination with nano-N at 4 mL $litre^{-1}$ and nano-Zn at 2 mL $litre^{-1}$ foliar spray. This enzymatic activity level was comparable to treatments involving 100% NPK combined with nano-N, nano-Zn and nano-Cu, as well as 75% N (112.5 kg ha^{-1}) + 100% PK (75:75 kg ha^{-1}) combined with nano-N and nano-Zn (53).

The highest dehydrogenase enzyme activity in lentils was observed when the crops were fertilized with a 50% Recommended dose of N applied through conventional fertilizer (10:20:20 kg N:P_2O_5:K_2O ha^{-1}) in combination with 50% through farmyard manure and foliar spray of nano Zn at 10 mg $litre^{-1}$. This nutrient schedule significantly enhanced dehydrogenase enzyme activity by 1.75% and 1.42% at 30 and 60 DAS respectively (54). In paddy crop, application of nano-DAP foliar sprays at tillering stage (20-25 DAT) and panicle initiation stages (45-50 DAT) in combination with 100% NPK (150:60:40kg ha^{-1}) resulted in the maximum Glutamine Synthetase Activity of 1.29 µmol mg^{-1} min^{-1}. This enhanced enzymatic value suggests that the foliar spray of nano-DAP plays a key role in influencing the supply of ammonium to the crop, which is a main catalyst in stimulating Glutamine Synthetase activity in rice (55).

Chlorophyll content

Foliar spraying of nano-fertilizer in rice led to a remarkable enhancement in their chlorophyll content when compared with other fertilizer treatments. Nano silicon foliar spray at 2 mL $litre^{-1}$ led to a significant increase in chlorophyll content, which recorded 38.28 SPAD units compared to control plants with a chlorophyll content of 37.71 SPAD units (indicative of chlorophyll content). Besides, the combined use of soil application of DAP at 120 kg ha^{-1} + nano-fertilizer foliar spray at 2 g $litre^{-1}$ applied at the tillering stage and 14 days thereafter of the first application augmented the chlorophyll content in the leaves of rice plants (56). While in pearl millet, foliar application of zinc nano-fertilizer at a concentration of 10 mg $litre^{-1}$ during the critical growth stage (6 weeks after sowing) resulted in significant increases of 24.4% in chlorophyll and 38.7% in total soluble leaf protein, respectively, compared to the control (57).

In green gram, the application of nano Slow-Releasing Fertilizers (nano SRF) led to higher concentrations of total chlorophyll and carotenoids compared to conventional fertilizer treatments. At 40 DAS, nano SRF-treated plants registered significantly higher chlorophyll concentration of 9.5 mg g^{-1} as compared to 4.8 mg g^{-1} in the control plot (). The improved levels of photosynthetic pigments can be attributed to their increased rate of synthesis which is directly influenced by the availability of N by nano SRF (58). While, in peanut plants, the highest chlorophyll content values, 46.8 and 50.4 mg g^{-1} were attained through the inoculation of seeds with mycorrhiza and the application of nano-B through foliar spraying at a concentration of 200 ppm in the initial (2020) and subsequent season (2021) respectively (46).

The application of Super Micro Plus (SMP) nano-fertilizer with elevated essential nutrient content at 100 and 150 mL per 100 litres of water applied at 120 and 134 days after planting resulted in the maximum value of chlorophyll content (58.22 SPAD units) in wheat crop leaves (59). However, the application of RDN and P_2O_5 (120:90 kg ha^{-1}), which included 10% $KFeO_2$ nano -coated DAP + urea without potassium, exhibited a maximum SPAD value of 60.8 in wheat crop, which is 24% higher than SPAD value recorded in conventional NPK fertilizer treatment (38). While the combined nutrient practices of 75% N (112.5 kg ha^{-1}) + nano urea foliar nutrition at 2 mL $litre^{-1}$ applied twice in marigold crops significantly recorded the highest leaf chlorophyll content of 33.56, 46.18 and 52.92 SPAD units at 40, 55 and 70 DAT, respectively.

In rice, the highest mean total chlorophyll contents of 3.26, 3.68, 4.48 and 4.83 mg g^{-1} of fresh weight at 30, 37, 54 and 61 DAT were observed with 50% RDF (50:25:25 kg NPK ha^{-1}) combined with seedling root dipping with nano DAP at 5 mL $litre^{-1}$ and two foliar sprays of nano DAP at 4 mL $litre^{-1}$ applied at 25 and 45 DAT (60).

Yield attributes and yield

Pods per plant

In black gram, foliar application nano urea at 2 - 4 mL $litre^{-1}$ of spray solution applied at active growth stages resulted in a significant increase in pods per plant (48.33 pods per plant) compared to farmer's conventional nutrient management practices (44 pods per plant) and absolute control (40 pods per plant) (61). Whereas in faba bean, foliar spraying of nano-boron at the concentration of 10 mg $litre^{-1}$ consistently resulted in more pods per plant (16.6) as compared to the treatment with no spray which recorded the lowest value of 11.52 pods per plant. In pulse crops, boron nutrient plays a significant role in enhancing the pollination process and stimulating reproductive and biological processes during peak vegetative growth and flowering phases of the crops, which contributes to enhanced fertilization and thus results in more pods per plant (62). While in soybean, united application of 100% RDF (40:80:25 kg N: P_2O_5: K_2O ha^{-1}) + foliar sprays of nano-DAP at 4 mL $litre^{-1}$ sprayed at 30 and 45 DAS significantly produced maximum pods per plant (65.2) compared to the absolute control (22.5 pods per plant).

Nevertheless, this result was comparable to the treatment combination of 100% RDF (40:80:25 kg N: P_2O_5: K_2O ha^{-1}) + foliar nutrition of nano-DAP at 2 mL litre^{-1} sprayed at 30 and 45 DAS. These results clearly indicate the supportive role of nano-DAP applied as foliar nutrition in enhancing various growth parameters and yield attributes, including enlargement of plant cells, nutrient composition and enzymatic activities (63).

In chickpea crops, combined application of 100% RDF and foliar nutrition of nano DAP at 4 mL litre^{-1} of water resulted in a notably increased number of pods per plant (23.52). Conversely, employing 75% RDF in amalgamation with foliar application of nano DAP at 4 mL litre^{-1} of water yielded a comparable number of pods per plant (23.25 pods per plant) (16). In Faba bean (*Vicia faba* L.), the application of micro-nano fertilizer at concentrations of 1500 mg litre^{-1}, administered during 3-5 leaves stage, flowering initiation and at 50% flowering stages, resulted in the highest average number of pods per plant, reaching 13.11 pods. Conversely, plants that did not receive this spray treatment exhibited the lowest average pod count, at 8.29 pods per plant (64).

Seeds per pod

The application of nano urea (2-4 mL in 1 litre of water sprayed at active growth stages) as foliar nutrition led to a substantial increase in the number of seeds per pod (6 seeds) in black gram, when compared with the treatments of farmer's practices and control which recorded 4.67 and 3.67 seeds per pod, respectively (61). This result of the experiment amplifies the fact that the application of nano urea as foliar nutrition augments leaf area, which facilitates enhanced element absorption by the leaves and thus results in maximum pod production per plant. Besides, it also plays a significant role in improved flower production and enhanced fertilization process. Additionally, it also contributes to the acceleration of sugar transport from source locations to reproductive and economic parts of the plants during the reproductive phase. This research evidence is supported by another research in which foliar nutrition of nano Zn at 0.1% + nano urea at 0.2% applied at 30 DAS in field pea, considerably maximized the seed count per pod (9.33 seeds per pod).

In a study , it was assessed that foliar spray of super micro plus nano-fertilizers at a concentration of 2 g litre^{-1} of spray liquid considerably enhanced the grain number of rice per panicle (123.33 grains) compared to the concentration of 2 g litre^{-1} (117 grains per panicle) and absolute control (114 grains per panicle) (65). This superior value of grain conversion is likely attributed to the role of the effectiveness of nano-nutritional fertilizers, contributing to a substantial improvement in filled grains count and a drop in unfilled grains in rice panicles. Alike, integrated application of 100% N and K (150 and 40 kg ha^{-1}, respectively) + 75% P (45 kg ha^{-1}) + foliar nutrition of nano-DAP at 2%, applied at an interval of 20-25 and 45-50 DAT, recorded the maximum number of filled grains per panicle (297.00) and ultimately contributed to an enhanced rice yield (55).

In green gram crop, adopting a combination of 100% RDF (25:50:25 kg NPK ha^{-1}) and foliar spray of nano urea at 4 mL litre^{-1} of water applied twice at flower onset and 15 days later resulted in a significantly higher value of seeds per pod (12.7) (66).

Grain yield

In maize crops, a higher grain yield of 6.41 t ha^{-1} was recorded by integrated application of 100% RDN (120:60:60 kg NPK ha^{-1}) and foliar spray of nano urea at 4 mL litre^{-1}. The enhanced grain yield of maize is mainly attributed to the beneficial impact of N applied in the form of nano urea, which prospectively contributed to augmenting photosynthetic source size and establishing a favourable source-sink relationship. While in black gram, nano urea at 2 – 4 mL litre^{-1} applied as foliar feeding at the flowering phase led to recording a higher grain yield of 1587.33 kg ha^{-1}. The increase in seed yield of black gram crops through foliar application of nano urea is primarily attributed to enhanced photosynthetic efficiency and better conversion of photosynthates to economic part (61). While the combined foliar spraying of nano Zn at 0.1% + nano urea 0.2% concentration applied at 30 DAS recorded maximum grain yield in field pea (2.63 t ha^{-1}) (36). This appreciated grain yield of field peas is chiefly attributed to a significant rise in pods per plant and seeds per pod.

In wheat crop, the combined application of 50% RDN and additional nutrients supply through foliar spraying of N, zinc and copper in nano form recorded the maximum grain yield of 4628 kg ha^{-1}, which is 6.87% higher than the yield (4330.5 kg ha^{-1}) obtained in farmer's fertilizer practice (67). Similarly, the field experiments carried out at the Regional Research Station in Anand, Gujarat, revealed that united application of 50% RDN and foliar spray of nano-N (2-4 mL litre^{-1} of water) applied at tillering stages (25 DAS) + nano-Zn (2 mL litre^{-1} of water) sprayed at 38 DAS and nano-Cu (2 mL litre^{-1} of water) applied at 53 DAS significantly enhanced grain yield (5813kg ha^{-1}) and straw yield (6933kg ha^{-1}) of wheat crop. Likely, the effectiveness of NPs on yield parameters and yield of cotton hybrid RCH-659 was assessed during the 2020-21 season, also revealed that foliar application of nano-fertilizers, specifically nano urea at 4ml litre^{-1} + nano Zn and nano copper at 2ml litre^{-1} in conjunction with conventional application of 50% RDF showed better seed-cotton yield of 1892 kg ha^{-1} (68). While in the rice crop, integrated application of 75% RDF (75:37.5:22.5 kg NPK ha^{-1}) + two foliar sprays of nano urea, led to a significantly superior grain yield of (5195.83 kg ha^{-1}). The realization of better grain yield under this treatment is likely attributed to the ample supply of nitrogen provided through both conventional fertilizer and nano urea foliar nutrition at a critical stage of rice crops. This consistent nitrogen supply is thought to have sustained activity of meristematic tissues and elongation of cells in plants, eventually leading to maximum yield attributes and thus, higher yield (69).

On-farm field demonstrations carried out by IFFCO in various districts of Uttar Pradesh, India, revealed that foliar application of liquid nano urea twice at peak vegetative and flowering stages (2 to 4 mL litre^{-1} of water) facilitates reduction of 50% of the RDN supplied through conventional N fertilizer required to meet the actual N requirement of the crops. Field experiments on wheat, maize, chickpea and mustard exhibited significant yield improvement of 5.77%, 7.29%, 8.36% and 3.77%, respectively (70). However, in rice crops, integrated application of 100% recommended NPK and Zn and foliar sprays of nano-urea twice at a concentration of 2ml litre^{-1} of spray liquid resulted in a significantly higher grain yield of 4215.09 kg ha^{-1} (71).

A remarkable increase in yield of cauliflower has been observed through the integrated application of city compost (6.25 t ha^{-1}) + Bio-fertilizer NPK consortium (1250 mL ha^{-1}) +

Sagarika granular (a seaweed extract-based fertilizer) (25 kg ha^{-1}) + foliar spray of nano N (4 mL litre^{-1}) + nano DAP (3 mL litre^{-1}) and Sagarika thrice at 25, 40 and 55 DAT. The overall cauliflower yield productivity witnessed a significant increase of 12.2% and 15.4% than in soil nutrient management of 100% RDF (125:50:50 kg ha^{-1}) alone during 2020-21 and 2021-22, respectively (31). Similarly, combined application of 50% N and P and foliar application of nano urea at 3 mL litre^{-1} + nano-DAP at at 5 mL litre^{-1} applied twice at 30 and 45 DAT significantly resulted in the highest flower yield (11.46 t ha^{-1}) in marigold. The enhanced flower yield might be attributed to the ample availability of N and P supplied through both soil and foliar ways, thus facilitating maximum photosynthetic activity, assimilation of carbohydrates and consequently acceleration of higher flower production (48). Likewise, integrated application of 100% RDF (40:80:25 kg NPK ha^{-1}) + foliar spray of nano-DAP at 4 mL litre^{-1}ofspray solution applied at 30 and 45 DAS, resulted in considerably elevated seed yield of soybean (25.45 g plant^{-1}) than yield obtained in absolute control (9.37 g plant^{-1}), although this result was comparable to the treatment combination of 100% RDF + nano-DAP foliar nutrition at 2 mL litre^{-1}appliedat 30 and 45 DAS, which registered the seed yield of 23.68 g plant^{-1} (63).

Application of 100% RDF combined with a foliar application of nano DAP at 4 mL litre^{-1} of water registered significantly higher seed yield in chickpeas (1868 kg ha^{-1}). This increase was primarily attributed to the synergistic interaction between conventional soil-applied urea and SSP fertilizers, along with the foliar application of nano DAP, which facilitated the uptake of N and P (16). In cluster bean, the highest pod yield (55.12 q ha^{-1}) was observed with the application of NPK at 100% recommended level (20:40:60 kg ha^{-1}), along with nano urea at 0.5 mL litre^{-1} and FYM at 10 t ha^{-1} (39).

While in vegetable cowpea *(V. unguiculata* subsp. *unguiculata* (L.)), a significant improvement in pod yield (3.14%) was observed with the treatment consisting of 50% RDN (20 kg N ha^{-1},) along with the 100% phosphorus and potassium (30:10 kg ha^{-1}) and supplemented with foliar nutrition of nano-N at 2 mL litre^{-1} and nano-Zn at 2 mL litre^{-1} applied at 30 DAS, compared to conventional practices, which comprising 50% N, 100% P and K applied as basal and 50% N at 15 DAS (40). In Faba bean (*V. faba* L.), foliar application of micro-nano fertilizer at a concentration of 1500 mg litre^{-1} of water, applied during 3-5 leaves, flower onset and at 50% flowering stages, significantly resulted in higher average seed yield of 5150 kg ha^{-1}. This represented a significant increase of 23.26% compared to the control treatment, which yielded the lowest average seed yield of 4174 kg ha^{-1}. This boost in seed yield can likely be attributed to the rise in both pod numbers per plant and seeds per pod, consequently enhancing the overall seed yield (64).

Applying nano urea spray at 5 mL litre^{-1} of water in black gram crop during active growth stages resulted in the highest yield seed yield (1625.32 kg ha^{-1}) followed by the farmer's conventional practice, which involved applying RDF as a basal and top dressing at rates of 25:45:25 kg NPK ha^{-1} during active growth (1485.23 kg ha^{-1}). The significant enhancement in seed yield of black gram is mainly attributed to the improvement in pods per plant, 100 seed weight and seeds per pod (72). In green gram crop, combined application of 100% RDF (25:50:25 kg NPK ha^{-1}) and foliar spraying of nano urea at 4 mL litre^{-1} of spray fluid applied at flower initiation and 15 days later resulted in the highest grain yield of 1291 kg ha^{-1}. Nevertheless, this yield was comparable to the combination of 80% RDN (20 kg N ha^{-1}) + foliar nutrition of nano urea applied at the same concentration and stages, which yielded 1289 kg ha^{-1} (66).

Stover / straw yield

As per a study report, the treatment involving soil application of 100% RDN (120:60:60 kg NPK ha^{-1}) and foliar spraying of nano urea at 4 mL litre^{-1} led to significantly higher stover yield of 8.65 t ha^{-1} in *rabi* maize (35). Likely, the highest stover yield of mustard (2452 kg ha^{-1}) was registered under integrated nutrient management practices comprising basal application of 50% recommended nutrients + nano-N foliar spray at 1250 mL ha^{-1} applied before flowering (73). This significant observation in stover yield of the mustard crop is prospectively attributed to the rapid absorption and translocation of nano-fertilizers applied through the foliage of the plants and this, in turn, led to an elevated rate of photosynthesis and a greater accumulation of dry matter at harvest stage of the crop.

Foliar application of combined nutrients of nano Zn at 0.1% + 0.2% nano urea at 30 DAS significantly enhanced the field pea stover yield (3.70 t ha^{-1}) (36). Similarly, applying nano silicon fertilizer as foliar nutrition (2 mL litre^{-1}) along with a recommended dose of conventional fertilizer (300 kg urea, 240 kg DAP ha^{-1}) registered a substantial increase in biological yield of rice crop to the level of 14.74% as compared to straw yield observed in absolute control plot (16.28t ha^{-1}) (56). The use of 100% RDF combined with foliar spraying of nano DAP at 4 mL litre^{-1} of water resulted in a significantly higher haulm yield (3550 kg ha^{-1}) in chickpea, which was equivalent to the yield obtained (3504 kg ha^{-1}) under the treatment combination of 75% RDF + foliar application of nano DAP at 4 mL litre^{-1} of water (16).

Foliar nutrition of nano urea at 4 mL litre^{-1} of water applied at flower onset and 15 days after the first spray resulted in a significantly higher haulm yield of 2862 kg ha^{-1} in green gram and this was narrowly trailed by a foliar supplement of nano urea at 3ml litre^{-1} of water (2805 kg ha^{-1}) (66).

A significantly higher straw yield of wheat (7869 kg ha^{-1}) was recorded with 75% of the recommended dose of N and P (90 and 45 kg ha^{-1}), combined with a foliar spray of nano DAP at 2 mL litre^{-1} applied at 25 DAS, which was on par with the yield obtained from 50% dose of N and P + foliar spray of nano DAP at 4 mL litre^{-1} (7268 kg ha^{-1}) (67). Whereas, in pigeon pea, the highest stalk yield (5138 kg ha^{-1}) was achieved with basal application of 100% RDF (25:50:00 kg NPK ha^{-1}) combined with a foliar spray of nano DAP at 6 mL litre^{-1} (74).

Harvest index (HI)

The highest harvest index value of 42.57% was observed in field pea crops when treated with foliar nutrition of nano Zn + nano urea at 0.2% concentration applied on 30 and 50 DAS (36). While in the rice crop, a numerically higher harvest index of 45.42%, was recorded under the treatment combination of 75% RDN (75:37.5:22.5 kg NPK ha^{-1}) integrated with two foliar sprays of nano urea applied at post tillering and at panicle initiation (34). However, nano-fertilizer spraying specifically nano silicon, complete nano and a combination of nano silicon and complete nano had positively manifested the harvest index of rice crops to the level of 5.68%, 7.50% and 2.42% compared to the value recorded in the control treatment (24.81%) (56). While in wheat crop, it was observed that treatment involving the recommended dose of N&P (300 kg urea and 240 kg DAP ha^{-1}), featuring 10% $KFeO_2$ nano-coated DAP + urea without potassium resulted in a harvest index of 60%. This highest harvest index value suggests the superior performance of nano-formulated fertilizers compared to the traditional use of DAP and the farmer practice, specifically the application of conventional fertilizers of NP&K and N & P (38).

Post-harvest analysis

Nutrient removal by crops

The application of 100% RDN (25:50:25 kg N:P_2O_5: K_2O ha^{-1} for pigeon pea and 150:60:40 kg N:P_2O_5: K_2O ha^{-1}for sweet corn) resulted in significantly higher total N uptake of 196.6 kg ha^{-1} by the sweetcorn under pigeon pea + sweet corn intercropping system, however, these nutrient removals were equivalent with integrated nutrient management practices of 50% RDN + nano urea foliar spray at 4 mL litre^{-1}of solution applied twice, which recorded the N uptake value of 189.1 kg ha^{-1}(75). While, integrated application of 100% Recommended Rate of N and foliar nutrition of nano-N at 4 mL litre^{-1} + nano-Zn at 2 mL litre^{-1} significantly affected the total N uptake in various crops including maize (174-181 kg ha^{-1}), wheat (123 kg ha^{-1}), pearl millet (114 - 172 kg ha^{-1}) and mustard (195-204 kg ha^{-1}) (53). Whereas, P, K and zinc absorption by wheat crops were judiciously improved by foliar application of nano-fertilizers and it was found that treatment involving 100% RDF (90:60:35 kg NPK ha^{-1}) and foliar feeding of nano-Zn at 14 and 28 DAS significantly enhanced the P uptake of 17.58 and 14.84 kg ha^{-1}, K uptake of 28.54 and 101.10 kg ha^{-1}and zinc uptake of 330.32 and 1305.88 g ha^{-1} by wheat grain and straw, respectively (76).

Soybean crop showed a significantly elevated uptake of NPK and sulphur, amounting to 180.39, 44.21, 75.38 and 24.91kg ha^{-1}, respectively, when treated with 100% RDF (40:80:25 kg NPK ha^{-1}) and a foliar spray of nano-DAP at 4 mL litre^{-1} applied at 30 and 45 DAS. This increase in nutrient uptake is mainly attributed to the foliar application of nano-DAP, which covers a larger surface area and the smaller particles in nano-DAP can penetrate the plant more effectively through the pores in the leaves, leading to improved nutrient absorption (77). While rice crop exhibited significantly enhanced uptake of nutrients *viz*., 71.2, 16.0 and 19.9 kg NPK ha^{-1} in grain, 43.2, 11.0, 98.0 kg NPK ha^{-1} in straw and 114.3, 27.0, 117.9 kg NPK ha^{-1} in rice + straw, under the treatment combination of soil application of 50% P (40 kg ha^{-1}) + 100% NK (100:60 kg ha^{-1}) + root dipping and foliar feeding of Nano-DAP twice at the interval of 20-25 DAT and 45-50 DAT (78).

In a study conducted in lentil crop, it was observed that treatments involving soil application of 100% Zn + B (20 kg Zn and 1.6 kg B ha^{-1}) foliar nutrition of nano Zn + B (120 mg Zn + 6.5 mg B litre^{-1}) applied thrice at 4 to 6 leaf stage, 30 days after flowering initiation and pod filling stage recorded the highest values of available N (298.22 kg ha^{-1} and 198.50 kg ha^{-1}), P (31.53 kg ha^{-1} and 28.76 kg ha^{-1}) and K (201.63 kg ha^{-1} and 179.29 kg ha^{-1}) at 0 - 15 cm and 15 - 30 cm soil depth respectively while the control showed the lowest available N values of 250.17 and 180.37 kg ha^{-1}, P values of 22.29 kg ha^{-1} and 20.26 kg ha^{-1} and K values of 123.18 kg ha^{-1} each at respectively at 0 - 15 cm and 15-30 cm soil depth respectively (79).

Agronomic efficiency (AE)

In the pigeon pea + sweet corn intercropping system, integrated nutrient management of 50% RDN and foliar spraying of nano urea twice recorded the highest AE of 13.4 kg kg^{-1} in pigeon pea based intercropping systems compared with other nitrogen + foliar spray treatments combinations. In pigeon pea + sweet corn intercropping, pigeon pea efficiently assimilates more nitrogen from the atmosphere, while sweet corn easily absorbs the applied nano urea owing to its nano size and higher surface area, thus facilitating entry into the plants through stomata and other pores (75). In pure baby corn crop systems, the treatment involving integrated application of 125% RDF (187.5: 93.75: 93.75 kg NPK ha^{-1}) through nano fertilizers significantly lead to the highest AE of 169.16 kg kg^{-1} (80). In rice crop, soil application of 50% P (40 kg ha^{-1}) + 100% NK (100:60 kg ha^{-1}) + root dipping of rice seedlings + foliar feeding of nano-DAP sprayed at 20-25 and 45-50 DAT registered maximum AE of nitrogen (31.0 kg kg^{-1}) and potassium (77 kg kg^{-1}), while the treatment combination of 25% P (20 kg ha^{-1}) + 100% NK (100:60 kg ha^{-1}), along with root dipping of rice seedlings and foliar nutrition of nano-DAP sprayed at 20-25 and 45-50 DAT recorded maximum AE of phosphorus (127.3kg kg^{-1}) (78).

Economics

The integrated nutrient management practices involving soil application of 50% N through neem-coated urea + 100% P and K + foliar application of 50% N through nano urea recorded the highest net return of Rs. 95903 ha^{-1} (50). The progressive rise in net returns associated with elevated nutrient levels of N and P_2O_5 implies a progressive relationship between improved grain and straw yield and the benefit-cost ratio of sorghum cultivation. Whereas improved nutrient management practices involving Farmers' Fertilizer Practice (FFP) + 50% RDN + collective foliar spray of nano synthesised N + Zn + Cu each at 1% concentration recorded the higher economic return over FFP of Rs. 5726.88 ha^{-1} in wheat (68).

The integrated application of city compost (6.25 t ha^{-1}), Bio-fertilizer NPK consortium (1250 mL ha^{-1}), Sagarika granular (25 kg ha^{-1}) and foliar feeding of nano-N at 4 mL litre^{-1}+ nano-DAP at 3 mL litre^{-1} + Sagarika at 2.5 mL litre^{-1} reduced the cost of cultivation of cauliflower to the level of 1.3% and 1.2%, whereas it maximized the gross income to the level of 12.2% and 15.4% respectively than nutrient management practices of soil application RDF (125:50:50 kg NPK ha^{-1}) alone (31). Whereas in rice cultivation, the integrated application of 75% RDN (37.5 kg N ha^{-1}) + 100% recommended dose of P K Zn (25:15:20 kg ha^{-1}) + foliar sprays of nano-urea at a concentration of 2 mL litre^{-1} of solution applied twice registered higher net returns (Rs.79265.74 ha^{-1}) and benefit-cost (B:C) ratio (1.70) (70).

In pearl millet and mustard crops, the treatment involving 100% RDF + foliar spraying of Nano-Zn sprayed twice at 2 mL litre^{-1} resulted in B:C ratios of 3.36 and 4.09 respectively. Conversely, the highest B:C ratio of 2.73 in wheat was recorded under integrated application of 100% RDF + Nano-N sprayed twice at 4 mL litre^{-1} and Nano-Zn sprayed twice at 2 mL litre^{-1} (53). The combination of supplying 100% RDF (25:50:25 kg NPK ha^{-1}) as a basal and foliar feeding of nano urea at 4 mL litre^{-1} of spray fluid applied at the flower initiation stage and 15 days later, as well as the combination of applying 80% of the recommended N dose (20 kg ha^{-1}) as a basal dose integrated with foliar spray of nano urea at the same concentration and stages, both resulted in higher gross returns of ₹100114 ha^{-1} and ₹99976 ha^{-1}, net returns of ₹53549 ha^{-1} and ₹53475 ha^{-1} and B:C ratios of 2.15 each, respectively in green gram (66).

In pigeon pea, the treatment with basal application of 100% RDF (25:50:00 kg NPK ha^{-1}) combined with a foliar spray of nano-DAP at 6 mL litre^{-1} achieved higher gross returns (Rs. 124255 ha^{-1}) and net returns (Rs. 87329 ha^{-1}). However, the highest B:C ratio of 3.40 was observed in the 100% RDF combined with nano DAP foliar sprays at 4 mL litre^{-1} and 2 mL litre^{-1} (74).

Conclusion

Addressing sustainable global food security is becoming increasingly critical in the face of shifting climate variables, a growing population and diminishing arable land, necessitating the exploration of innovative and suitable agricultural practices to achieve production targets. The development of engineered nano -materials represents a revolutionary achievement in material design and the creation of innovative consumer and commercial products. Incorporating nano-materials into fertilizer manufacturing and development has proved considerable promise in improving plant growth and development, physiological attributes, yield and yield attributes, nutrient uptake, post-harvest available soil nutrients and overall profitability of crops, as discussed. Although nanotechnology's principles and nano-based products in agriculture are still in their early phases, their confirmative and transformative potential for the agricultural production system is undeniable. The ongoing exploration and application of nanotechnology in agriculture underscore its pivotal role in shaping the future of farming practices, offering a promising avenue for sustainable and efficient agricultural systems. As research seeks to shed light on the extensive uncertainties, it is crucial for stakeholders, ranging from policymakers to farmers, to tread this path with informed vigilance. Collaborative endeavours will be essential, integrating expertise from various fields to guarantee that while we exploit the opportunities presented by nanotechnology, we also honour and safeguard the fragile equilibrium of our ecosystems.

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Authors' contributions

BR collected literature and prepared a manuscript on the effect of nano fertilizers on different crops. MS conceptualization of review article, overall proofread and guided as chairman of the advisory committee. GP helped with agronomical parameters. MG proofread and helped in the microbial study. VBR did proofreading of physiological parameters. All the authors have gone through the material and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The writers admitted not having any conflicts of interest.

Ethical issues: None

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