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Role of nano-urea in optimizing nitrogen use efficiency, yield and quality of rice: A review

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Abstract
More than 20% of the rice used globally is produced in India. Fertilizer application is necessary to increase rice productivity. When hybrid rice was sprayed with nano-urea in addition to nitrogenous fertilizer (urea), better growth was noted. It is anticipated that applying nano-urea at active tillering stage will improve input efficiency and increase rice yield. Nitrogen particles on nanoscale reduce the need for conventional fertilizers by half or more while enhancing crop yield, soil health and nutrient quality of the produce. According to published research, using nano-urea led to a 25% reduction in nitrogen (urea) usage. The control of nitrogen can improve the quality of *Basmati* rice. Compared to regular urea, rice treated with nano-zeourea consistently had a better quality. Consequently, its application in agriculture seems like a viable strategy, which will encourage the conversion of outdated agricultural techniques into modernized systems, with a particular focus on the creation of environmentally sustainable and more effective methods.

Keywords: Growth, nitrogen, nano-urea, productivity, quality, rice, yield

Introduction
Rice (*Oryza sativa* L.), India's most important staple food crop belonging to the family *Poaceae*, is the second largest commodity produced all over the world. Rice, vital for half of the global nutrition, is essential in combating food insecurity, especially in economically weak countries (Dass *et al.*, 2016; Wasaya *et al.*, 2022) [14, 66]. India faces a predicted 50% supply-demand gap by 2030 due to the decline in availability of water (Gulati *et al.*, 2019). Our country, contributing 21% to global rice output, is facing challenge for meeting a projected demand of 130 million tonnes by 2025 for national food security and sustainable development goals of United Nation (Choudhary *et al.*, 2022) [12]. Despite being leading exporter of rice, the country's increasing population and dietary shifts impose a focus on increasing food production (Mohidem *et al.*, 2022) [43]. The area under rice crop in world in 2022 was 165.0 million hectares with a total production of about 776.5 million tonnes and average productivity 4.7 tonnes per hectare (Anonymous, 2022) [3], and the area under rice crop in India in 2022 was 46.4 million hectares, production 129.6 million tonnes and productivity 3.7 t ha^{-1} (Anonymous, 2021) [2].
Moreover, half of the world's population relies on rice as a main food source, making it recognized as the *Global Grain*. Increasing rice productivity across the board requires the use of fertilizers (Subramanian *et al.*, 2015) [60]. However, by coordinating the delivery of nitrogenous fertilizer with crop needs, nitrogen fertilizer utilization can be maximised (Jagtap *et al.*, 2018) [23]. Therefore, the supply of liquid nano-urea is presently considered as the best alternative to granular urea fertilizer due to reduced risk of nutrient loss (Rop *et al.*, 2019) [55]. Urea molecules of 20-50 nano-meter size provide nitrogen to the crops in a targeted manner. The size of one nano-urea liquid particle has 10,000 times more surface area to volume size as compared to conventional granular urea. Conventional use of nitrogenous fertilizer (urea) in rice causes low nutrient use efficiency (~30%), and it has been found lower than many other upland (50%) crops (Vijayakumar *et al.*, 2022) [64] but excessive use of nitrogen declines the crop quality, reduction in nitrogen use efficiency and detrimental effect on environment (Hanifuzzaman *et al.*, 2022) [20]. Due to ultra-small size and surface properties, the nano-urea liquid gets absorbed by the plants more effectively when sprayed on surface of their leaves (Valojai *et al.*, 2021; Midde *et al.*, 2022) [62, 42].

The choice of nutrient management practice significantly influences rice productivity. Organic and inorganic fertilizer applications, as well as integrated approaches, exhibit distinct effects on growth, nutrient uptake and yield parameters (Gajjela *et al*., 2023) [18].

Availability of nitrogen at right time is the key factor for higher rice productivity (Oenema *et al*., 2014) [47]. Advancement in nano-technology has opened a novel solution to sort out various agricultural problems through synthesis of smart fertilizers, which enable the plants to absorb nutrients efficiently (Raliya *et al*., 2017) [52]. Its application in agriculture appears to be a promising approach, fostering the transformation of conventional production systems into upgraded agricultural practices with a clear emphasis on the development of more efficient and environment friendly methodology (Lowry *et al*., 2019) [37], and it plays a significant role in crop production with environmental safety, ecological sustainability and economic stability (Kumar *et al*., 2020) [30]. In last decades, nano-technology has been considered as a prominent technology with copious application in agriculture (Marchiol *et al*., 2020) [40]. Nano-technology has wider areas of application in agriculture (Kumar *et al*., 2022) [29].

Nano-materials are distinct objects with minimum and maximum dimension of 1 and 100 nm, respectively (Liu and Lal, 2015) [36]. These nano-materials include different nano-fertilizers like nano-urea, nano-zinc, *etc*., which are more environment friendly (Baboo *et al*., 2021) [8]. The nano-fertilizers used as foliar fertilizers come from natural minerals without adding any chemical. Nano-urea in rice boosts yield, minimises fertilizer use and increases farmers' revenue along with improvement in nitrogen use efficiency and reduction in leaching loss (Midde *et al*., 2022) [42]. Based on soil test crop response, the application of nitrogen as urea (50%) and nano-urea (two sprays) at critical stages of paddy crop and recommended dosage of nitrogen as urea (50%) and nano-urea (two sprays) resulted in higher plant height, leaf area index and dry matter accumulation in paddy crop (Dhayalan *et al*., 2023) [15].

Number of experiments have been conducted to improve rice production through nano-fertilizers but only a few can be seen in the literature containing nano-materials (Huang *et al*., 2014) [22], which are defined as materials with a single unit at least one dimension, *i.e*., 1-100 nm, therefore, nano-fertilizers are nano-materials, which can supply either one or more than one nutrient to the plants, resulting in enhanced growth and yield or those, which facilitate better performance of conventional fertilizers, without directly providing crops with nutrients (Liu and Lal, 2015) [36]. Nano-structured formulations with altered physico-chemical properties can be a probable solution to the current problems through mechanisms, such as targeted delivery or slow/controlled release mechanisms and trigger controlled-release (Guru *et al*., 2015). Nano-urea might have synergistic effect on conventional urea fertilizer for better nutrient absorption by the plant cells, resulting to optimal growth and development of hybrid rice (Jyothi and Hebsur, 2017) [25]. Nano-fertilizers mainly delay the release of nutrients and extend the effective period of fertilizer utilization (Naeem *et al*., 2017) [44]. Nano-fertilizers are the formulations to deliver nutrients to plants, allowing controlled or slow-release of active ingredients, resulting in efficient uptake (Raliya *et al*., 2017) [52].

Slow-release and nano-fertilizers are suitable alternatives to conventional fertilizers for a controlled and gradual release of nutrients into the soil (Wang *et al*., 2015) [65]. Agricultural researchers strive to generate sustainable crop production with higher productivity while maintaining societal welfare (Flora, 2018) [16]. Usage of chemical fertilizers has been criticised due to its hazardous effects on environment and on the quality of agricultural produce (Kumar *et al*., 2019) [34]. Therefore, by utilizing unique properties of nano-particles, nano-fertilizers seek to boost the efficiency of nutrient utilization. Nano-fertilizers are nutrient transporters with substrates in the nano-dimension that may supply nutrients to the plant system for a prolonged period with no damage to the environment (Subramanian *et al*., 2017) [59]. Studies have shown that the use of nano-urea can lead to a reduction in greenhouse gas emissions and reduce nitrogen leaching and runoff, which can have harmful effects on aquatic ecosystems (Upadhyay *et al*., 2023) [61].

Nano-fertilizer effect on plant growth

The full recommended rate of conventional and nano-fertilizer (FRR-CF + FRR-NF) enhanced the plant height (Benzon *et al*., 2015) [10]. Better growth performance of hybrid rice was observed with foliar application of nano-urea in conjunction with inorganic N-fertilizer (urea), which might be due to higher nitrogen use efficiency (NUE) of nano-urea (Mejias *et al*., 2021) [41]. Increased concentration of nano-spray (0.4%) had significant impact on plant growth due to the increased availability of nitrogen within the plant system (Velmurugan *et al*., 2021) [63]. Enhanced plant height was recorded with the application of nano-nitrogen fertilizer by number of researchers (Rathnayaka *et al*., 2018; Velmurugan *et al*., 2021; Anushka *et al*., 2023) [54, 63, 4]. The growth parameters of tested hybrid rice, namely plant height, leaf area index, dry matter accumulation and crop growth rate were registered better with treatment T_2: 100% N(urea) + two foliar sprays of nano-urea than other treatments (Namasharma *et al*., 2023) [45]. Bhargavi and Sundari (2023) [11] found the application of 75% recommended dose of nitrogen + nano-urea (two foliar sprays) + phosphorus + potash to be the most productive in terms of plant height (32.1, 65.7 and 83.6 cm), dry matter production (3.2, 7.2 and 13.2 t/ha) at 30, 60 days after transplanting and at harvest, leaf area index (5.10) and number of productive tillers m^{-2} (17.6). Pal *et al*. (2023) [48] reported that the treatment T_6: 75% recommended dose of nitrogen + two foliar spray of nano-urea @ 4 ml/ L resulted in maximum plant height (95.66 cm), dry matter accumulation (1014.09 g m^{-2}), number of tillers (417.44 m^{-2}) and leaf area index at 90 DAS (4.85). Pedireddy *et al*. (2024) [50] reported that foliar spray of nano-urea resulted in higher plant height (120.1 cm), tillers number m^{-2} (265) and dry matter accumulation (741.9 kg ha^{-1}). Application of 75% nitrogen through urea + *Azospirillum* @ 5 kg ha^{-1} + foliar spray with nano-urea @ 4 ml per litre at active tillering and panicle initiation stage registered maximum plant height (113.44 and 107.52 cm, respectively), number of tillers per hill (21.88 and 19.49, respectively) during both the years of experimentation (Gajbhiye *et al*., 2024) [17]. The adoption of *Sesbania* as a green manure crop coupled with 0.2% nano-ZnO-coated urea module has been identified as an efficient method for maximizing growth in *Basmati* rice (Baral *et al*., 2024) [9]. Spraying nano-urea can improve the primary growth parameters, *viz*. plant height and number of tillers per plant of the paddy (Katre *et al*., 2024) [27]. Application of 75% RDN + spray of nano-urea at tillering and panicle initiation stage (4 ml L^{-1}) resulted in significantly higher growth attributes, *viz*. periodical plant height, number of tillers $plant^{-1}$, dry matter accumulation $plant^{-1}$, chlorophyll content and growth indices including leaf area index (LAI) at 60 and 90 DAS, crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate

(NAR) during 30-60 DAS, 60-90 DAS and 90 DAS-harvest (Chudasama *et al*., 2024) [13].

Nano-fertilizer effect on yield parameters

The full recommended rate of conventional and nano-fertilizer (FRR-CF + FRR-NF) enhanced the number of reproductive tillers, panicles and spikelets (Benzon *et al*., 2015) [10]. Reduction of nitrogen losses associated with nano-urea supplementation might have been the key reason for higher yield of hybrid rice (Norton *et al*., 2015) [46]. Benzon *et al*. (2015) [10] also recorded significant effect of the application of conventional fertilizer and its combination with nano-fertilizer on yield attributes like number of reproductive tillers, number of panicles and total number of spikelets (Jyothi and Hebsur, 2017) [25]. The increase in filled grain and decrease in empty grain might be further attributed to the efficiency of spraying nano-fertilizer when it is done at right concentration and at right time (Jassim *et al*., 2019) [24]. Nitrogen, a crucial nutrient, impacts crop yield (Zhang *et al*., 2020) [67], and nano-fertilizers, like those enhancing nutrient transport through nano-sized channels (Mahanta *et al*., 2019) [38] show promise in improving plant biomass and yield (Khalid *et al*., 2022) [28]. Attri *et al*. (2022) [5] 100% recommended NPK Zn + two foliar sprays of nano-urea each @ 2 ml/litre of water recorded significantly higher effective tillers m^{-2}, number of grains $panicle^{-1}$, 1000 grains weight and grain and straw yield and remained statistically at par with treatment 75% recommended N + recommended PK Zn + two foliar sprays of nano-urea each @ 2 ml/litre of water, 50% recommended N+ recommended PK Zn (25:25:15 kg ha^{-1}) + two foliar sprays of nano urea each @ 2 ml/litre of water), 50% recommended N + recommended PK Zn (25:25:15 kg ha^{-1}) + foliar sprays of nano-urea @ 4 ml/litre of water) and 100% recommended NPK Zn.

Nano-urea application at active tillering stage is predicted to enhance the input efficiency and boost rice yield (Velmurugan *et al*., 2021) [63]. Accelerated productivity of hybrid rice was achieved mainly because of increased growth of plant parts and metabolic processes, such as photosynthesis due to enhanced enzymatic activity that finally led to higher photosynthates accumulation and their translocation to economic parts of the plant (Midde *et al*., 2022; Sahu *et al*., 2022) [42, 56]. Nano-urea, when combined with urea (traditional N-source) enhances agricultural outcomes by promoting meristematic activity, cell elongation, photosynthate assimilation, and efficient resource translocation within plants, resulting in improved yield attributes and economics (Attri *et al*., 2022; Kannoj *et al*., 2022; Ranjan *et al*., 2023) [5, 53]. Due to their nano size, nano-scale nitrogen particles enhance nitrogen use efficiency and hence, yield of the crop (Kumar *et al*., 2021) [34]. The results revealed that the grain (4817.80 kg ha^{-1}), straw (5956.26 kg ha^{-1}) and biological (10774.06 kg ha^{-1}) yield of rice were ensured maximum under treatment receiving 50% N + 100% P_2O_5 and K_2O + three sprays of nano-urea @ 0.4% at 30, 45 and 60 DAT (Parve *et al*., 2023) [49]. Gajbhiye *et al*. (2024) [17] also suggested that trimming down the conventional fertilizer by using nano-urea and *Azospirillum* could help in gaining optimum yield. The adoption of *Sesbania* as a green manure crop coupled with 0.2% nano ZnO-coated urea module is identified as an efficient method for maximizing yield in *Basmati* rice (Baral *et al*., 2024) [9]. Recommended dose of nano-urea if applied properly holds immense potential for enhancing crop production efficiency and sustainability (Hasan *et al*., 2024) [21]. The yield stimulatory effects resulted from enhanced availability of nutrients during critical growth stages and overall growth promotion through improved metabolic effects, thus, nano-fertilizers also improved nutritional benefits in rice (Shahi *et al*., 2024) [57].

Among yield attributes of hybrid rice, the number of panicles m^{-2} (392), panicle length (32.46 cm) and panicle weight (5.58 g) were recorded maximum with treatment T_5: 125% nitrogen (urea) + two foliar sprays of nano-urea, while the filled grains per panicle (194), 1000 grains weight (24.18 g), grain yield (7.15 t ha^{-1}) and harvest index (50.71%) were obtained maximum from the treatment T_2: 100% N (urea) + two foliar sprays of nano-urea treatment (Namasharma *et al*., 2023) [45]. The number of tillers $meter^{-2}$, number of panicles $meter^{-2}$, number of filled grains per panicle, 1000 grains weight (g), grain yield (4899 kg ha^{-1}) and straw yield (6094 kg ha^{-1}) were recorded significantly maximum under the treatment T_2: 100% recommended dose of nitrogen through urea along with two foliar sprays of nano-urea (4 ml/L) at active tillering and panicle initiation (Ranjan *et al*., 2023) [53]. Bhargavi and Sundari (2023) [11] found the application of 75% recommended dose of nitrogen + nano-urea (two foliar sprays) + phosphorus + potash to be most productive in terms of higher grain (5485.2 kg/ha) and straw (7525.2 kg/ha) yield. The yield attributes like number of tillers per hill, number of panicles per hill, panicle length (cm), number of grains per panicle, weight of 1000 grains (g) and grain and straw yield (kg ha^{-1}) of rice were recorded significantly higher in treatment F_3: 100% RDF (Kumar *et al*., 2023) [31]. Nano-spray resulted in higher rice yield (15-21%) than NPK addition through chemical fertilizers (Velmurugan *et al*., 2021) [63]. The treatment T_6: 75% recommended dose of nitrogen + two foliar spray of nano-urea @ 4 ml/L resulted in maximum effective ear head (282.66 m^{-2}), grains per ear head (65.75), test weight (48.52 g) and grain (46.15 q/ha) and straw (57.92 q/ha) yield (Pal *et al*., 2023) [48]. The rice crop produced the significantly higher grain yield (4435 kg ha^{-1}) under treatment T_8: 75% RDN + spray of nano-urea (4 ml L^{-1}) at tillering and panicle initiation stage, which was 3.24% higher than 100% RDN through conventional urea (Chudasama *et al*., 2024) [13]. The grain (5.39 tonne ha^{-1}) and straw (6.73 tonne ha^{-1}) yield was harvested maximum with the application of 75% RDN + two foliar sprays of nano-urea @ 0.4% at active tillering and panicle initiation stage (Pedireddy *et al*., 2024) [50].

Nano-fertilizer effect on quality characters

The full recommended rate of conventional and nano-fertilizer (FRR-CF + FRR-NF) enhanced the chlorophyll content in leaves of paddy plants (Benzon *et al*., 2015) [10]. Nitrogen management can enhance the quality of *Basmati* rice (Aulakh *et al*., 2016) [6]. The quality of rice was consistently higher under nano-zeourea treatment than conventional urea (Manikandan and Subramanian, 2016) [60]. An urgent call for efficient nitrogen management strategies increased the nitrogen use efficiency (NUE) and overall crop quality (Prasad and Hobbs, 2018) [51]. Higher plant nutrient uptake might be due to slow and constant release of nitrogen from nano-urea (Jyothi and Hebsur, 2017; Kalia and Sharma, 2019) [25, 26]. Nano-scale nitrogen particles cut down the load of traditional fertilizer by half or more while improving the crop production, soil health and nutritional quality (Kumar *et al*., 2021) [34]. The results revealed that the nutrient (N, P and K) content and uptake by grain and straw and their total uptake by rice crop were ensured maximum under treatment receiving 50% N + 100% P_2O_5 and K_2O + three sprays of nano-urea @ 0.4% at 30, 45 and 60 DAT (Parve *et al*., 2023) [49]. Nitrogen also improves grain quality through higher tillering, grain formation, filling and protein synthesis (Hamoud *et al*., 2022) [19]. The quality parameters of rice were recorded

maximum with the application of 100% RDN + two spray of nano-N (8 ml/L) + nano-Zn (2 ml/L) and nano-Cu (2 ml/L) followed by 100% RDN + two spray of nano-N (8 ml/L) and nano-Zn (2 ml/L) treatment (Kumar *et al*., 2023a) [31]. Protein content was recorded maximum in treatment F_3: 100% recommended dose of fertilizer (Kumar *et al*., 2023b) [32]. Significantly higher protein content and protein yield was recorded in rice supply with 60% recommended dose of nitrogen through conventional urea + 40% through nano-urea, which was found statistically at par with 40% recommended dose of nitrogen through conventional urea + 60% RDN through nano-urea, showing superiority over rest of the treatments during both the years of investigations (Azam *et al*., 2024) [7]. The adoption of *Sesbania* as a green manure crop coupled with 0.2% nano-ZnO-coated urea module has been identified as an efficient method for maximizing milling attributes in *Basmati* rice (Baral *et al*., 2024) [9]. Foliar spray of nano-urea (liquid) with conventional fertilizer had a significant impact on grain quality of rice (Katre *et al*., 2024) [27]. Planting crop at a spacing of 20×10 cm coupled with 100% RDF + foliar spray of nano-urea @ 3000 ml ha^{-1} during tillering and panicle initiation stages exhibited better outcomes across all parameters of quality in rice (Singh *et al*., 2024) [50].

Nano-fertilizer effect on economics

In rice crop, Velmurugan *et al*. (2021) [63] recorded higher total cost for nano-spray than NPK addition since they recorded 12-16% higher yield over RDF addition, resulting in additional monetary benefit (₹7,937 to 10,082). With regard to net returns and benefit to cost ratio, 75% recommended N + recommended PK Zn + two foliar sprays of nano-urea each @ 2 ml/litre of water recorded maximum net returns and benefit to cost ratio to the tune of ₹79305 ha^{-1} and 1.70, respectively closely followed by 50% recommended N+ recommended PK Zn (25:25:15 kg ha^{-1}) + two foliar sprays of nano-urea each @ 2 ml/litre of water with net returns and benefit to cost ratio of ₹78,724 ha^{-1} and 1.69, respectively ((Attri *et al*., 2022) [5]. The total cost of cultivation was maximum in treatment T_5: 125% nitrogen (urea) + two foliar sprays of nano-urea (₹77712 ha^{-1}) but net return (₹43720 ha^{-1}) as well as benefit to cost ratio (1.57) was registered maximum with treatment T_2: 100% N (urea) + two foliar sprays of nano-urea, hence, the application of 100% recommended dose of nitrogen in conjunction with nano-urea spray twice at 25 and 50 days after transplanting had been found effective for higher productivity and profitability of hybrid rice cultivation (Namasharma *et al*., 2023) [45]. Economics of different treatments indicated that by higher grain yield, treatment T_2: 100% recommended dose of nitrogen through urea along with two foliar sprays of nano-urea (4 ml/L) at active tillering and panicle incitation exhibited maximum benefit to cost ratio (Ranjan *et al*., 2023) [53]. The research reflects the significant performance of 4 ml nano-urea with two sprays in reducing overall nitrogenous fertilizer and farmers' production costs in rice (Ahmed *et al*., 2023) [1]. The application of nano-urea resulted in saving of nitrogen (urea) to an extent of 25% (Pedireddy *et al*., 2024) [50]. The nitrogen management options followed the trend as RDN (120 kg)>75% RDN + nano-urea two sprays >50% RDN > zero nitrogen for all studied economic parameters (Kumari *et al*., 2024) [35].

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