

Research Article

Comparative Performances of Nano-Urea and Conventional Urea on Maize Yield, Grain Quality, and Soil Health

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ABSTRACT

Nano-fertilizers enhance nutrient use efficiency, enabling sustainable and higher crop yields with reduced environmental impact through precision nutrient delivery. This study investigated the comparative performance of nano-urea powder (NUP) and commercial urea (CU) on maize (*Zea mays* L.) plants in terms of nutritional profile, growth dynamics, yield attributes, kernel quality, and post-harvest soil health. The application of NUP caused a modest reduction ($p < 0.05$) in vegetative traits, including plant height and leaf number. However, it significantly increased grain yield by 13.8% ($p < 0.05$), and improvements in cob morphology and grain development were observed. In addition, NUP enhanced nutrient partitioning by promoting a more balanced source–sink relationship and improved reproductive efficiency. Nutritional analyses revealed increased starch and antioxidant content in NUP application, although protein levels declined slightly. Soil analysis after 50 days indicated that NUP improved pH stability and phosphorus availability, lowering electrical conductivity and organic matter content, suggesting more efficient nutrient cycling and uptake. These advantages demonstrate that nano-urea can maintain productivity while reducing its environmental footprint, offering a promising strategy for sustainable fertilizer management in intensive agriculture compared with conventional urea use.

Introduction

Maize (*Zea mays* L.) is a widely grown cereal and primary staple food crop in many countries. It is a potential cereal on the earth in terms of yield and nutrition and is called the “Queen of Cereals” (Kandil et al., 2020). Maize ranks as the third most important cereal crop in Bangladesh, after rice and wheat. It is considered a functional food and used as a supplement to address malnutrition. Its consumption is associated with a lowered risk of several chronic diseases, including diabetes, hypertension,

cardiovascular ailments, and constipation (Morimoto, 2025). According to the Food and Agriculture Organization (FAO), Bangladesh produced a record 5.2 million metric tons of maize in 2024 against a demand of >7 million metric ton (Bangladesh Wheat and Maize Research Institute (BWMRI). This demands primarily driven by the poultry, livestock, and food processing industries (Kandil et al., 2020). This production-consumption gap necessitates significant maize imports, incurring substantial foreign

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expenditure. With favorable climatic conditions and growing demand across multiple sectors, maize cultivation has substantial potential for expansion in Bangladesh. However, several agronomic challenges hinder this growth, such as access to appropriate agrochemicals, post-harvest processing, and marketing infrastructure (Islam and Hoshain, 2022).

To maintain agri-produce yield and its sustainable management, researchers have recently explored foliar and soil applications of green nanomaterials, including nano-fertilizers, -agrochemicals, -pesticides, -herbicides, -biosensors-based treatments for agricultural waste (Fatima et al., 2021; Ghosh and Bera, 2021; Gomez et al., 2021; Grillo et al., 2021; Usman et al., 2020).

Conventional fertilizers (CF), while essential for crop productivity, often have low nutrient-use efficiency because to leaching, volatilization, and runoff, leading to economic losses and ecological degradation (Asadu et al., 2024; Mim et al., 2025). In contrast to CF, Nanofertilizers (NFs), formulated with nutrients at the nanoscale, enable controlled and slow nutrient release (Derbew et al., 2025; Haydar et al., 2024), improved solubility (Kumar et al., 2025), and enhanced uptake by plants (Yadav et al., 2023). These properties significantly increase nutrient-use efficiency while reducing fertilizer requirements and environmental pollution (Saurabh et al., 2024). In agricultural practice, nanofertilizers can be applied through soil or foliar routes (Rahman et al., 2022) to supply essential macro- and micronutrients more precisely (Bekah et al., 2025), supporting balanced crop growth, improved yield, and soil health (Nayeri and Zakavi, 2025). Integrating them into cropping systems offers a viable strategy for sustainable agriculture intensification, particularly in resource-limited and environmentally vulnerable regions (Biswas et al., 2026; Garg, 2025). In agriculture, combining NFs with CFs produces a synergistic effect, resulting in greater overall benefits (Gopinath et al., 2025). Higher yields and better quality have been achieved when NFs and CFs are used together compared to their individual applications. This

typically results in a 25% to 50% reduction in CF use.

Among nano-fertilizers, nano-urea has emerged as a promising nitrogen source because of its high surface area, controlled nutrient-release characteristics, and improved interaction with plant tissues. Nano-urea formulations are designed to synchronize nitrogen availability with crop demand, thereby reducing nutrient losses through leaching, volatilization, and runoff while enhancing nutrient uptake efficiency. Recent studies have demonstrated nano-urea's potential to improve crop productivity and nutrient management while reducing dependence on conventional nitrogen fertilizers. Consequently, nano-urea has gained considerable attention as a sustainable nutrient management tool in modern agriculture. Recent field studies report positive responses to nano-urea application in cereals, oilseeds, and vegetable crops, with improved nitrogen-use efficiency, yield, and fertilizer savings (Fatima et al., 2021; Ghosh and Bera, 2021; Gomez et al., 2021). Consequently, nano-urea is increasingly being evaluated as a sustainable alternative or supplement to conventional nitrogen fertilizers under diverse agroecological conditions.

Despite the growing interest in nano-urea technology, information regarding the performance of nano-urea powder (NUP) under field conditions in Bangladesh remains limited. This work compares NUP and CU as nitrogen sources on *Maize* yield, growth and development, nutritional content, and soil properties while keeping all other fertilizers and agronomic conditions identical. The goal is to develop a viable, sustainable, and cost-effective fertilization approach that can contribute to resilient agricultural systems and improved food security in Bangladesh.

Materials and Methods

Chemicals

Urea, sodium hydroxide, Trisodium citrate, zinc chloride, copper chloride, and ferrous chloride were

used to prepare NUP. Potassium sulfate, 98% sulfuric acid, boric acid, petroleum ether, ethyl alcohol, and hydrochloric acid solution were utilized for proximate analysis. Potassium oxide, xylene, and nitric acid were used for mineral determination. Moreover, absolute methanol (99.9%), 10% sodium carbonate, Folin–Ciocalteu reagent, sodium nitrate, aluminum chloride, gallic acid, tannic acid, DPPH (2,2-diphenyl-1-picrylhydrazyl), potassium sulfate buffer, and ABTS (2,2-azino-bis-(3-ethylbenzothiazoline-6-sulfonate) were used to determine antioxidant activity. All the chemicals and reagents, including Triple Superphosphate (TSP), Muriate of Potash (MOP), and Magnesium Sulfide, were purchased from Sigma-Aldrich, China, and were of analytical grade.

Synthesis of Nano-urea

In this work, NUP is prepared according to our previous study (Rahman et al., 2022; Khan et al., 2021; Tarafder et al., 2020). NUP was prepared by mixing urea and trisodium citrate under optimum conditions. First, 3 g of urea with 8.6 g of trisodium citrate were mixed in a beaker. The mixture was then heated to 90 °C for 1 h on a hot plate.

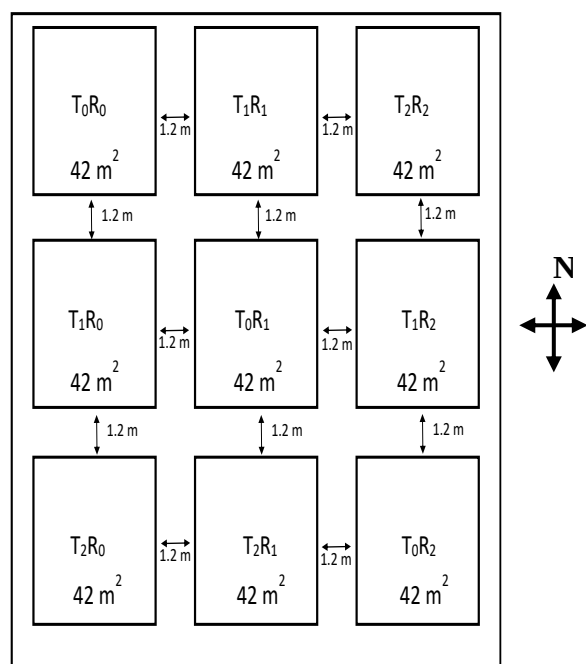


Fig. 1. Layout of the pots in the field.

Experimental Land and Maize Variety

A field experiment was conducted in Abdulpur, Churamankati, Jashore Sadar, Jashore, Bangladesh, from October 2024 to February 2025. The field is at 23° 10' North latitude and 89° 13' East longitude at a height of 9 m above sea level, according to the Global Positioning System (GPS). It belongs to the Gopalganj–Khulna Beels agroecological zone **High Ganges River Floodplain (AEZ 11)**. The research field is situated in a subtropical climatic zone, with an average annual temperature range of 15.4 to 34.6 °C, an average annual rainfall of 1651 mm, and an average annual relative humidity of 57%. The location of the experimental land, the temperature of the experimental land area, average rainfall, and humidity percentage are presented in Figure S1, Figure S2, and Figure S3, respectively. The experimental field soil is medium-high to high land with silt or silt-clay loam (Table 1), and the experimental layout is shown in Fig. 1. Pioneer P3355 was used in this experiment as a maize variety.

Table 1. Soil Chemical Properties of The Experimental Field.

Soil Parameter	Amount
pH	8.2
Organic Matter (%)	1.50
EC (dS/m)	1.35
Nitrogen (%)	0.085
Sulfur (µg/g)	8.42
Phosphorus (µg/g)	103.4
Zinc (µg/g)	3.80
Boron (µg/g)	1.35
Potassium (meq/100g)	0.5

The land was plowed twice with a moldboard plow followed by harrowing to bring the soil to fine tilth. The stubbles and weeds were collected and disposed to facilitate leveling. Plots were leveled to enable sowing. It was done on 15 October, 2024. The

maize seed was obtained from the local market of Jashore. Two seeds were dibbled per hill at a depth of 5 cm, with a spacing of 60 cm x 20 cm, on 17 October, 2024. Standard management practices, such as intercultural operations such as weeding, watering, and insecticide applications, were done as per traditional methods. The whole area was divided into three for treatments: (1) Control-No Fertilizer/ T_0 (2) Commercial Urea + other recommended fertilizer-treated field/ T_1 , (3) Nano Urea Powder + other recommended fertilizer-treated field/ T_2 . Each treatment was replicated across three plots in a Randomized Complete Block Design (RCBD).

Application of Fertilizers

The required fertilizer quantity, as per the treatment, was applied before sowing. Triple Superphosphate (TSP), Muriate of Potash (MOP), and Urea were used as source of phosphorus, potassium, and nitrogen, respectively, except T_0 . A full dose of phosphorus (TSP: 960 gm/decimal), potassium (MOP: 480 gm/decimal), and other nutrients (Gypsum: 480 gm/decimal, Boron: 50 gm/decimal, Magnesium Sulfide: 330 gm/decimal) was applied as the basal dose to T_1 and T_2 plots on 15th October 2024. Gap filling was carried out on the 8th day after sowing, and thinning on the 15th day after sowing, to keep only healthy and disease-free seedlings and maintain the necessary plant population.

The first dose of nitrogen (Urea: 750 gm/decimal for T_1 , Nano urea powder: 750 gm/decimal for T_2) along with additional phosphorus (TSP: 200 gm/decimal) and potassium (MOP: 400 gm/decimal) was applied on 31st October 2024. The second dose of nitrogen (Urea: 750 gm/decimal for T_1 , Nano urea powder: 750 gm/decimal for T_2) and magnesium (Magnesium Sulfide: 250 gm/decimal) was applied on 18th November 2024. The third dose of nitrogen (Urea: 750 gm/decimal for T_1 , Nano urea powder: 750 gm/decimal for T_2) was applied on 10th December 2024.

Vegetative Growth and Yield Contributing Measurements

The plant height was measured at 15, 30, 45, 60, 90, 105 days after sowing (DAS) and at the maturity stage, from the base to the base of the youngest fully opened top leaf until tassel emergence; afterward, plant height was measured from the base of the plant to the collar of the flag leaf and expressed in centimeters (cm). The number of functional leaves per plant indicate the plant's general vigor. The total number of functional leaves (fully opened) per plant was recorded on the same dates as plant height observations.

The number of cobs on each observational plant was counted. The mean number of cobs per plant was calculated using data from ten plants selected from each net plot. The cobs from each observation plant were removed, and the mean cob length was measured across five observation plants per treatment. The length of the cob was measured in centimeters (cm) from the base to the tip. The circumference (diameter) of individual cobs was measured from five randomly selected observational plants. Measurements were taken at the center of the de-husked cobs, and the average diameter of the cobs was recorded in centimeters (cm). Qualitative attributes, such as the number of rows per cob, the number of kernels per line, the number of kernels per cob, and the net weight of kernels, were also recorded. This was performed using a similar method, following an established method (Rahman et al., 2022).

Soil Parameters and Nutritional Analysis of Maize Grains

The major proximate components protein, fat, fiber, and carbohydrate were determined by following the official methods of analysis followed by AOAC methods (AOAC, 2000) Ojo et al (Ojo et al., 2017). However, the minerals contained in the soil were determined using an inductively coupled plasma atomic emission spectrometer (model, Trilogy-7). The TPC was measured using the Folin–Ciocalteu assay previously reported by Bao et al. (Bao et al., 2020).

Antioxidant activity, Phenolic content

The antioxidant capacity by the ABTS⁺⁺ assay was evaluated according to the previous method (Tan et al., 2020). The total phenolic contents (TPC) were measured using the Folin–Ciocalteu assay as previously followed (Bao et al., 2020), (Rahman et al., 2022). The results of TPC content were expressed as mg of gallic acid equivalent (GAE) and mg of tannic acid equivalent (TAE), respectively, per 100 g of the Maize sample. In addition, all sample analyses were performed in triplicate.

Statistical Analysis

The obtained data, except for the chemical compositions of maize grains, were mean values from three replications that were statistically analyzed and scientifically presented. The significance of the differences was estimated and compared using the Duncan test at a 5% probability level ($p < 0.05$). Finally, all statistical analyses were carried out using the “SPSS version 20” computer software package (2016).

Results and Discussion

Impact of T₀, T₁ and T₂ on Plant Growth, Development, and Yield

Table 2 states comparative data on vegetative plant growth (PVG) and product yield among the treatments T₀, T₁, and T₂. The T₂ treatment showed slight reductions in vegetative growth (height 0.74%; leaf number per plant 1.42%) compared to T₁. This phenomenon is attributed to the controlled, sustained nutrient release from NUPs. Unlike T₁, which releases nitrogen rapidly and may cause temporary PVG, nano-fertilizers supply nutrients gradually to match with crop metabolic demand (Stojanova et al., 2025). This balance reduces nitrogen loss from leaching or volatilization, while minimizing growth stress. In contrast, grain yield increased from 12.3 to 14 t/ha under the T₂ treatment (Fig. 2), an increase of approximate 13.8%. In the case of T₀, PVG and grain yields were hampered due to nutrient limitations. This clearly illustrates the potential of

nanofertilizers to optimize yield by improving nutrient-use efficiency (NUE) and redirecting assimilates toward reproductive structures. These results are corroborated with the finding of Guo et al. (Guo et al., 2022).

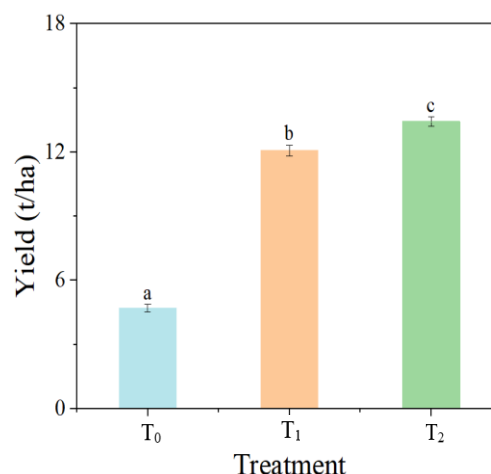


Fig. 2. Effects of treatment T₀, T₁, T₂ on Yields. All different letters (a–c) on the error bars in the figure are significantly different ($p < 0.05$).

Cob Morphology and Developmental Traits

Cob characteristics such as length and diameter are critical determinants of yield and marketability. As illustrated in Fig. 3 (A), T₂ treatment significantly improved these parameters over T₁ and T₀. Compared with T₁, Cob length increased by approximately 4.55%, and diameter by 13.33%. These improvements can be ascribed to enhanced nitrogen assimilation and improved source–sink relationships. NUP facilitates more effective nitrogen delivery, and the plant can maintain better photosynthetic activity. Grains per cob weight rose by 15.25% in T₂ compared with T₁ as shown in Fig. 3 (B). These improvements can be ascribed to enhanced nitrogen assimilation and improved source–sink relationships of nano fertilizer. NUP facilitates more effective sugar and carbohydrate synthesis (Yadav, 2025). These energy substrates are then mobilized and directed to sink tissues (i.e., developing cobs), improving cob size and mass (Raj et al., 2024) (Khan et al., 2020). Reduced cob diameter and length in T₀ result from inadequate fertilization (Khan et al., 2014).

Table 2. Effects of T₀, T₁ and T₂ on Maize Plant Height and No. of Leaves per Plant^a.

Days	Plant Height			No. of Leaves per Plant		
	T ₀	T ₁	T ₂	T ₀	T ₁	T ₂
15	22.35 ± 1.278c	35.29 ± 0.343b	34.17 ± 0.226a	5.20 ± 0.414a	5.47 ± 0.516a	5.20 ± 0.414a
30	63.61 ± 0.453d	88.17 ± 0.144e	86.06 ± 0.261f	7.53 ± 0.516b	8.20 ± 0.414c	8.00 ± 0.000c
45	105.19 ± 0.523g	160.95 ± 0.110i	160.25 ± 0.256j	9.53 ± 0.516d	10.40 ± 0.507e	10.20 ± 0.414e
60	152.49 ± 0.526h	211.65 ± 0.110m	210.65 ± 0.160n	11.27 ± 0.458f	12.80 ± 0.414h	12.40 ± 0.507g
90	189.45 ± 0.543k	257.23 ± 0.222o	255.96 ± 0.247p	12.33 ± 0.488g	13.80 ± 0.414i	13.53 ± 0.516i
Harvest	200.64 ± 0.385i	270.27 ± 0.139q	267.99 ± 0.252r	12.40 ± 0.507j	14.27 ± 0.704i	13.53 ± 0.915g

^aValues are expressed as means (n = 15) ± standard deviation. All similar subscript letters in the table are non-significantly different (p > 0.05). T₀; Control-No Fertilizer, T₁; Commercial Urea + other recommended fertilizer, T₂; Nano Urea + other recommended fertilizer.

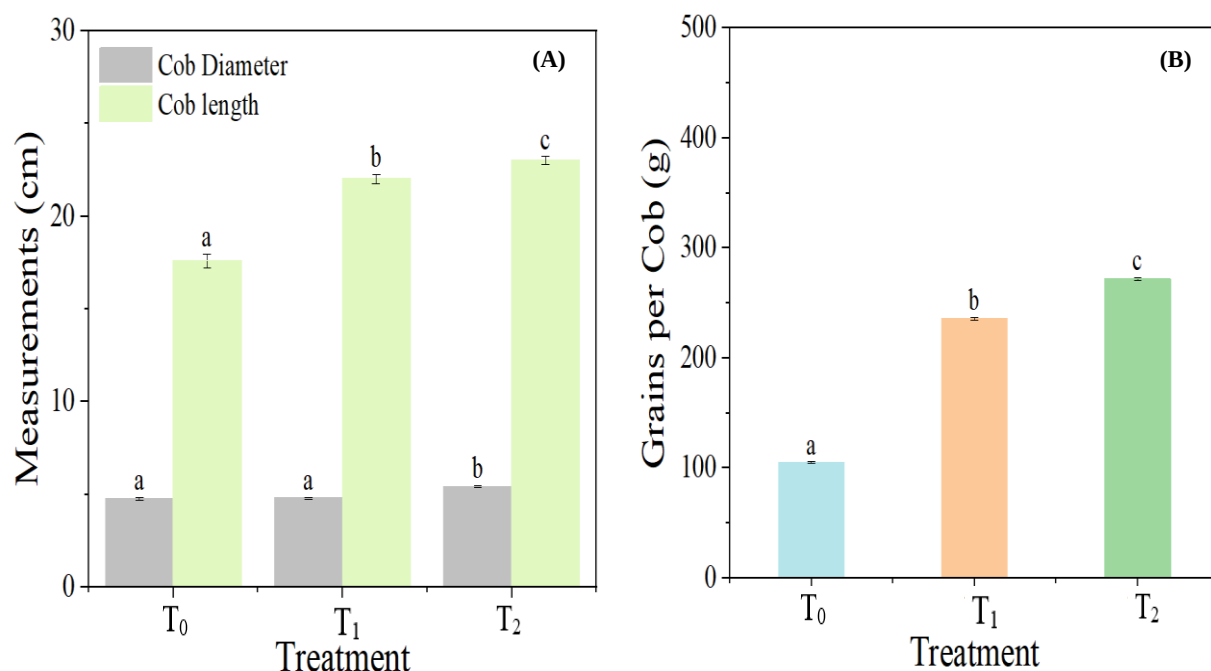


Fig. 3. Effect of treatment T₀, T₁, T₂ on cob diameter and length (A) and Grains per Cob (B). All different letters (a–c) on the error bars in the figure are significantly different (p < 0.05).

Grains Characteristics and Reproductive Performance

Beyond cob size, grain number, and arrangement directly contribute to grain yield. Fig. 4 (A) shows that T₂ treatment resulted in a 20.7% and 2.2% increase in rows per cob compared to T₀ and T₁, respectively. Fig. 4(B) shows that in T₂, the number of grains per row decreased slightly (2.1%) compared to T₁. As shown in Fig. 4 (C), T₂ showed a 22%, and 33.70% increase in grains per cob compared with T₁ and T₀, respectively. In contrast, the weight of 1000 grains decreased slightly in T₂ compared with T₁, as illustrated in Fig. 4 (D). The aforementioned findings suggest that the T₂ treatment created a better structure (larger, more productive cob) but produced a slightly lighter individual grain. The improvements are attributed

nano-fertilizers' ability to enhance nitrogen uptake during the grain-filling stage. It is known that adequate N₂ is essential for nucleic acid synthesis, enzymatic activities, and protein production during grain filling stage. However, the photoassimilates (energy) are distributed among more grains, slightly reducing the weight per grain (Kumari et al., 2024). T₂ treatment ensures synchronized nutrient availability during the critical V12 (Twelfth Leaf Collar) to R2 (Blister) stages, when grain set and grain filling occur (Gopinath et al., 2025). Moreover, the increase in kernel rows per cob suggests that nano fertilizers positively influenced early reproductive development, possibly by enhancing cell division and meristematic activity, facilitated by nitrogen availability (Gopinath et al., 2025).

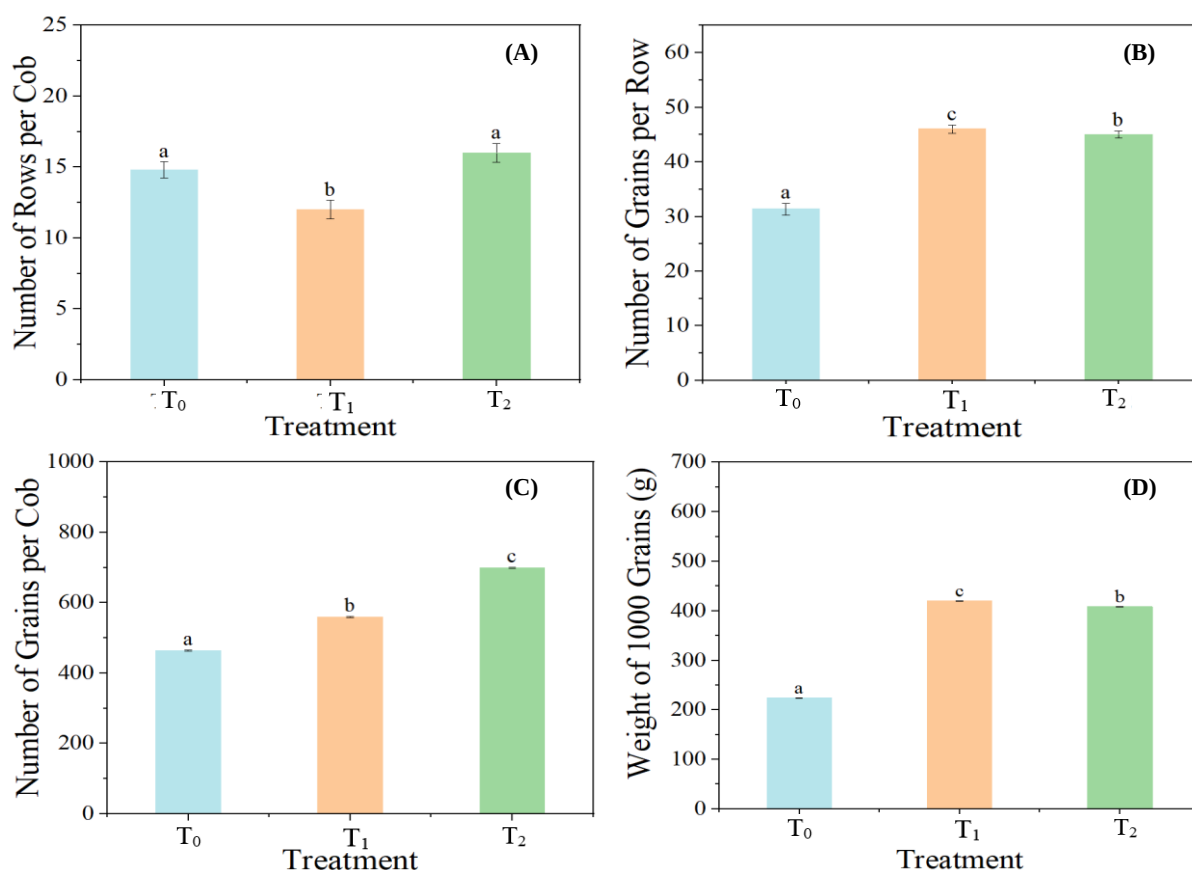


Fig. 4. Impact of treatment T₀; T₁; T₂. (A) Number of rows per cob, (B) Number of Grains per row, and (C) Number of grains per cob (D) Weight of 1000 grains. All different letters (a–c) on the error bars in the figure are significantly different (p < 0.05).

Nutritional Profile of Maize Grains

Proximate Composition

By improving nutrient uptake and utilization efficiency compared with conventional fertilizers, nanofertilizers can positively affect the proximate composition (nutritional qualities) of crops. According to studies, they can greatly raise the amounts of useful elements in harvested plants, such as ash, protein, and certain minerals (Rahman et al., 2022). As shown in Table 3, maize grains from T₂ plots contained higher fat (5.9%), fiber (5.63%), carbohydrate (4.58%), and starch (4.58%) compared to T₁ crops. These changes are consistent with previous findings (Rahman et al., 2022), (Ghosh and Bera, 2021). Interestingly, protein content declined by 11.13% compared to commercial based fertilizer. While this may initially appear unfavorable, but it is likely due to changes in nitrogen partitioning within the plant (AL-Hassan, 2019). The slow release of nitrogen may downregulate certain nitrogen-assimilation enzymes (e.g., glutamate synthase), thereby limiting protein biosynthesis (Meena et al., 2023).

Antioxidant Activity, Phenolic and Mineral Content

As presented in Table 4, antioxidant activity, total phenolic content (TPC), and mineral content of grains were higher in the T₂. TPC increased by 4.5%, antioxidant activity by 4.44%, and mineral content by 10%. NUP may enhance the expression of genes involved in the phenylpropanoid pathway, thereby elevating the synthesis of phenolic compounds. Additionally, nano urea promotes better nitrogen and micronutrient uptake, contributing to higher antioxidant defense and metabolic balance (Kale et al., 2024; Refaay et al., 2025; Zhang et al., 2024; Saikia et al., 2024).

Soil Health and Post-Harvest Fertility Dynamics

Application of NUP (T₂) and CU (T₁) induced notable alterations in key soil parameters after 50 days of treatment. These changes were evident in

soil pH, organic matter (OM) content, ionic conductivity, and macro- and micronutrient availability as shown in Table 5.

Table 3. Effects of T₁ and T₂ Treatment on Grains Proximate Composition (%).

Parameter	T ₁	T ₂	Change(%)
Protein	8.44	7.50	↓11.13
Fat	3.90	4.13	↑ 5.90
Fiber	2.13	2.25	↑ 5.63
Carbohydrate	69.80	73.00	↑ 4.58
Starch	69.80	73.00	↑ 4.58

Table 4. Effects of T₁ and T₂ Treatment on Antioxidant activity, Phenolic and Mineral Content.

Parameter	T ₁	T ₂	Change(%)
Antioxidant Activity (%)	63.00	65.80	↑ 4.44
Total Phenolic Content (mg/100g)	40.00	41.80	↑ 4.5
Mineral Content (%)	1.30	1.43	↑ 10

Table 5. Effects of T₁ and T₂ Treatment on Post-harvest Soil Properties (50 Days).

Parameter	T ₁	T ₂	Change (%)
pH	7.0	7.50	↑ 6.84
Organic Matter (%)	1.33	0.80	↓ 39.85
IC (dS/m)	2.62	1.00	↓ 61.83
Nitrogen (%)	0.077	0.046	↓ 40.25
Sulfur (µg/g)	0.13	11.14	↑ 8469.23
Phosphorus (µg/g)	92.80	93.31	↑ 0.55
Zinc (µg/g)	4.77	4.40	↓ 8.41
Boron (µg/g)	1.50	1.41	↓ 6.38
Potassium (meq/100g)	0.34	0.18	↓ 47.05

Soil pH

A higher soil pH was observed in the T₂ plot compared to T₁. Because, during the conversion of urea-based fertilizers, both conventional and nano forms produce ammonium (NH₄⁺) and subsequently nitrate (NO₃⁻), releasing hydrogen ions (H⁺) into the soil and contributing to acidification. However, nano urea's slow-release and targeted delivery properties modulate this process by slowing the rate and reducing the concentration at which nitrogen compounds are released into the soil matrix. As a result, the overall acidifying effect is less pronounced, leading to a comparatively more stable or higher soil pH (Huang et al., 2025).

Organic Matter (OM)

A decline in soil organic matter content was also recorded under treatment T₂. This can be attributed to enhanced microbial activity. The presence of nano urea is known to stimulate microbial metabolism by improving nutrient availability, especially nitrogen. This microbial stimulation accelerates the breakdown of organic substrates, releasing nutrients into plant-available forms (Javed et al., 2026). Furthermore, vigorous plant growth, driven by enhanced nitrogen uptake, can increase the extraction of organic carbon from soil pools, thereby lowering OM levels over time (Zhang et al., 2021; Sikka et al., 2024).

Ionic Conductivity (IC)

Soil electrical conductivity decreased more substantially under than under T₁. As nano urea's fine particle size and gradual dissolution limits the immediate availability of free ions in soil water and synchronously absorbed, fewer residual ions remain in the soil, thereby lowering IC levels (Madzokere et al., 2021; Subramanian and Thirunavukkarasu, 2017).

Nitrogen Content

A reduction in residual soil nitrogen was observed 50 days after nano urea application (T₂), despite its initial supply. This suggests that nano urea's higher surface area and faster foliar penetration enhanced the immediate bioavailability of nitrogen. While nano fertilizers typically support prolonged

nutrient release, the elevated nitrogen demand during peak maize development may have outpaced the release dynamics, especially in nutrient-rich root zones. This mismatch could lead to transient depletion of soil nitrogen pools (Mirbolook et al., 2023).

Micronutrient Interactions and Sulfur Enrichment

The interactions between nitrogen and other macro- and micronutrients (e.g., Zn, B, K, P) are complex and often interdependent. Nano urea may modify the soil's ionic environment enhance nutrient uptake. For instance, boron and zinc play key regulatory roles in nitrogen metabolism and can enhance its assimilation when present in optimal concentrations. Moreover, potassium and phosphorus mobility may increase due to shifts in ionic gradients facilitated by nano-sized particles (Aref, 2011; Luxmi and Sakshi, 2024). Interestingly, sulfur content in the soil increased with T₂ treatment to a great extent. This is likely due to both the sulfur inputs from nano urea, which enhance nutrient cycling. By improving plant absorption and minimizing nutrient loss, NUP enables more effective use of co-applied sulfur, potentially leading to its accumulation in the rhizosphere (Luxmi and Sakshi, 2024).

Phosphorus Availability

A noteworthy increase in available phosphorus (0.55%) was observed following T₂ treatment (Table 5), suggesting improved phosphorus mobilization. This may stem from nano urea's reduced phosphorus fixation effect, as its ultra-small particles can inhibit the formation of insoluble phosphate complexes in soil (Priyam et al., 2022)

Conclusion

This work demonstrated nano-urea powder (NUP) as an effective and sustainable alternative to conventional urea for maize cultivation. Compared with commercial urea, NUP significantly increased grain yield and enhanced grain quality attributes,

including carbohydrate, antioxidant, phenolic, and mineral contents. Although slight reductions in plant height, leaf number, and grain protein content were observed, these changes did not negatively affect final grain yield. Nano-urea application also influenced post-harvest soil physicochemical properties, indicating differences in nutrient dynamics compared with conventional urea. However, the present study did not quantify grain nitrogen concentration, total nitrogen uptake, stover yield, nitrogen use efficiency, or nitrogen balance; therefore, the mechanisms responsible for the increased grain yield and reduced grain protein content could not be fully elucidated. The experiment was conducted in a single field within a confined area, limiting the broader applicability of the findings. Therefore, multi-location and multi-season evaluations are necessary before drawing definitive conclusions. Future studies should evaluate nano-urea under reduced nitrogen application rates and assess nitrogen use efficiency and nitrogen balance to better determine its fertilizer-saving potential. Additionally, the observed reduction in protein content requires further investigation to clarify its potential nutritional implications.

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Authors contribution

Md. Ismail Hossain: Investigation, data collection, formal analysis, validation, visualization, and writing of the original draft. Kibreya Kabir Kanok: Analysis, data visualization, and writing of the original draft. Syed Imdadul Hossain: Analysis, writing of the original draft, and review and editing. Md. Zaved Hossain Khan: Conceptualization, experimental design, formal analysis, supervision,

project administration, and writing-review and editing of the manuscript.

Conflict of interest

The authors declare that there is no conflict of interest.

Data availability Statement

The datasets used and analyzed during the current study are available upon reasonable request from the corresponding author.

References

- Al-HassanB. Impact of nanonpk fertilizers to correlation between productivity, quality and flag leaf of some bread wheat varieties. *Iraqi J. Agric. Sci.* 2019; 50:171.
- Aref F. The effect of boron and zinc application on concentration and uptake of nitrogen, phosphorous and potassium in corn grain. *Indian J. Sci. Technol.* 2011; 4: 785–791.
- Asadu CO, Ezema CA, Ekwueme BN, Onu CE, Onoh, IM, Adejoh T, Ezeorba TPC, Ogbonna CC, Otuh PI, Okoye JO and Emmanuel UO. Enhanced efficiency fertilizers: Overview of production methods, materials used, nutrients release mechanisms, benefits and considerations. *Environ. Pollut. Manag.*, 2024; 1: 32–48.
- Bao Y, Reddivari L and Huang JY. Development of cold plasma pretreatment for improving phenolics extractability from tomato pomace. *Innov. Food Sci. Emerg. Technol.* 2020; 65: 102445
- Bekah D, Boyjoo Y, Panpadoo RM, White JC and BhawLuximon A. Nanostimulants and nanofertilizers for precision agriculture: transforming food production in the 21st century. *Environ. Sci. Nano*, 2025; 12: 1740–1766.
- Biswas A, Ghorai S, Kanthal S, Chatterjee A, Pramanick M, Ghosh PK, Asif SM, De P, Hazra S, Sengupta S, Mridha D, Majumder S, Ghosh S and Roychowdhury T. Nanotechnology for sustainable agriculture and global food systems. In: *Handbook of nanotechnology in agriculture*. Springer, Singapore, 2026; pp. 1–37.

- Derbew E, Ermias Benti N, Gizaw Terefe M, Taye Anbessa T, Mamo Mengistu W and Setarge Mekonnen Y. A comprehensive review on nano-fertilizers: preparation, development, utilization, and prospects for sustainable agriculture in Ethiopia. *Nanoscale Adv.* 2025; 7: 2131–2144.
- Fatima F, Hashim A andAnees S. Efficacy of nanoparticles as nanofertilizer production: a review. *Environ. Sci.Pollut. Res.*2021; 28(2): 1292–1303.
- Ghosh SK and Bera T. Molecular mechanism of nano-fertilizer in plant growth and development: A recent account. *Advances in Nano-Fertilizers and Nano-Pesticides in Agriculture: A Smart Delivery System for Crop Improvement*, 2021; 535–560.
- Gomez A, Narayan M, Zhao L, Jia X, Bernal RA, Lopez-Moreno ML and Peralta-Videa JR. Effects of nano-enabled agricultural strategies on food quality: Current knowledge and future research needs. *J. Hazard. Mater.*2021; 401: 123385.
- Grillo F, Piccoli I, Furlanetto I, Ragazzi F, Obber S, Bonato T, Meneghetti F andMorari F. Agro-environmental sustainability of anaerobic digestate fractions in intensive cropping systems: Insights regarding the nitrogen use efficiency and crop performance. *Agron.*2021; 11(4): 745.
- Garg S. Nanotechnology and sustainable agriculture: Transforming global farming.In: *handbook of nanotechnology in agriculture*. Springer Singapore, 2025: pp. 1–20.
- Gopinath KA, Kumari VV, Singh VK, Shanker AK, Reddy KS, Kundu S, Bhargavi B, Rajkumar B, Lavanya N, Chandana P, Sunitha B, Krupashankar MR and Singh T. Impact of conventional and nano fertilizers on rainfed maize yield, profitability and soil nitrogen. *Front., Nanotechnol.* 2025; 7: 1617500.
- Guo J, Fan J, Xiang Y, Zhang F, Yan S, Zhang X, Zheng J, Hou X, Tang Z and Li Z. Maize leaf functional responses to blending urea and slow-release nitrogen fertilizer under various drip irrigation regimes. *Agric. Water Manag.* 2022; 262: 107396.
- Haydar MS, Ghosh D and Roy S. Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. *Plant Nano Biol.* 2024; 7: 100058.
- Huang X, Yu C, Sun W, Shi P, Wu J, Yu J, Wang J and Mu T. Partial organic substitution for chemical fertilizer reduces N2O emissions but increases the risk of N loss through nitrification in Tibetan farmland. *Sci. Rep.* 2025; 15: 14503.
- Islam MR and Hoshain S. A Brief Review on the Present Status, Problems And Prospects of Maize Production in Bangladesh. *Res.Agric. Livest Fish*, 2022; 9: 89–96.
- Javed R, Islam Z, Rathnayake A, Padmaperuma OAD, Sharafat U, Lumactud RA, Abbey Lord Thomas R, Galagedara L and Cheema M. Carbon nanofertilizers in agriculture: A critical review of soil ecosystem impacts and phytotoxicity. *Plant Nano Biol.* 2026; 15: 100231.
- Kale SS, Chauhan R, Nigam B, Gosavi S and Chaudhary IJ. Effectiveness of nanoparticles in improving soil fertility and eco-friendly crop resistance: A comprehensive review. *Biocatal.Agric. Biotechnol.* 2024; 56: 103066.
- Kandil EE, Abdelsalam NR, Mansour MA, Ali HM and Siddiqui MH. Potentials of organic manure and potassium forms on maize (*Zea mays* L.) growth and production. *Sci. Rep.*, 2020; 10: 8752.
- Khan A, Munsif F, Akhtar K, Afridi MZ, ZahoorNbsp Ahmad Z, Fahad S, Ullah R, Khan FA and Din M. Response of Fodder Maize to Various Levels of Nitrogen and Phosphorus. *Am. J. Plant Sci.* 2014; 5: 2323–2329.
- Khan MZH, Islam MR, Nahar N, Al-Mamun MR, Khan MAS and Matin MA. Synthesis and

- characterization of nanozeolite based composite fertilizer for sustainable release and use efficiency of nutrients. *Heliyon*, 2021; 7: e06091.
- Khan W, Sagar A, Madhu M and Sekhar M. Performance of Sweet Corn (*Zea mays* L. saccharata) Varieties under Varying Phosphorus Levels. *Int. J. Curr. Microbiol. Appl. Sci.* 2020; 9: 1455–1461
- Kumar P, Jaisuriyan K and Gopika B. Nanofertilizers for Enhanced Nutrient Use Efficiency. Royal Society of Chemistry. 2025. p. 97-113.
- Kumari JJR, Indu Tand Singh R. Effect of nano urea and spacing on growth and yield of maize article type. *Int. J. Res. Agron.* 2024; 7: 278–281.
- Luxmi, Rana GS and Sakshi. The effect of foliar application of zinc, potassium, and boron on fruit set and retention in kinnow mandarin. *Asian J. Soil Sci. Plant Nutr.* 2024; 10: 627–638.
- Madzokere TC, Murombo LT and Chiririwa H. Nano-based slow releasing fertilizers for enhanced agricultural productivity. Second international symposium functional nanomaterials in industrial applications: Academy –industry meet. *Mater. Today Proc.* 2021; 45: 3709–3715.
- Meena BK, Ramawtar Balyan JK, Sharma RK, Nagar KC, Choudhary MC, Kumar S and Gochar PS. Effect of nano fertilizers on growth and yield of maize (*Zea mays* L.) in Southern Rajasthan. *Pharma Innov. J.* 2023; 12: 2123–2126.
- Mim JJ, Rahman SMM, Khan F, Paul D, Sikder S, Das HP, Khan S, Orny NT, Hossain SMR and Hossain N. Towards smart agriculture through nano-fertilizer-A review. *Mater. Today Sustain.* 2025; 30: 101100.
- Mirbolook A, Sadaghiani MR, Keshavarz P and Alikhani M. New slow-release urea fertilizer fortified with zinc for improving zinc availability and nitrogen use efficiency in Maize. *ACS Omega*, 2023; 8: 45715–45728.
- Morimoto N. Dietary fiber: Importance and impact on health parameters. In: *Handbook of Public Health Nutrition*. Springer Cham. 2025; pp. 1–26.
- Nayeri S and Zakavi M. Nanofertilizers in improving soil quality and crop plant growth. In: *Enhanced crop production setup under various micro and nano contaminants: Sustainable use, production and future prospects*. Husen, A. (Ed.), Springer Nat. Singapore, 2025; pp. 185–210.
- Ojo MO, Ariahu CC and Chinma CE. Proximate, functional and pasting properties of cassava starch and edible mushroom (*Pleurotus pulmonarius*) flour blends. *Am. J. Food Sci. Technol.* 2017; 5(1): 11–18.
- Priyam A, Yadav N, Reddy PM, Afonso LOB, Schultz AG and Singh PP. Fertilizing benefits of biogenic phosphorous nanonutrients on *Solanum lycopersicum* in soils with variable pH. *Heliyon*, 2022; 8: e09144.
- Rahman MH, Hasan MN, Amin R, Setu MAA, Akter S, Nigar S, Khan MZH and Hossain MZ. Mixed nanocomposite fertilizers influencing endophytic symbiosis and nutritional and antioxidant properties of *oryza sativa* as a sustainable alternative for commercial fertilizers. *ACS Omega*, 2022; 7: 6787–6794.
- Raj R, Umesha U and Kumar P. Effect of phosphorus and nano urea on growth and yield attributes of maize (*Zea mays* (L.)). *Int. J. Adv. Biochem. Res.* 2024; SP-8(7): 8665–8669.
- Refaay DA, El-Sheekh MM, Haroun SA, Ayyad AM and Senousy HH. Maize plant development and antioxidant defense influenced by selenium-enriched *Cyanobacteria* species. *South Afr. J. Bot.* 2025; 177: 487–499.
- Saikia P, Gogoi AS, Bhuyan RP, Rafique NT and Gogoi M. Effect of nano urea on leaf nutrients and some quality parameters of tea (*Camellia sinensis* (L) O. Kuntze). *J. Sci. Res.* 2024; 30: 131–137.
- Saurabh K, Prakash V, Dubey AK, Ghosh S, Kumari A, Sundaram PK, Jeet P, Sarkar B, Upadhyaya

- A, Das A, Kumar S, Makarana G, Kumar U, Kumar A and Singh RR. Enhancing sustainability in agriculture with nanofertilizers. *Discov. Appl. Sci.* 2024; 6: 559.
- Sikka R, Kalia A, Ahuja R, Sidhu SK and Chaitra P. Substitution of soil urea fertilization to foliar nano urea fertilization decreases growth and yield of rice and wheat. *Plant Soil*, 2024; 512(1-2): 1475-1491.
- Stojanova M, Demiri S, Stojanova MT, Djukic DA and Kaya Y. From cultivation to consumption: Evaluating the effects of nano fertilizers on food quality and safety. *Adv. Agrochem*, 2025; 4: 217–234.
- Subramanian KS and Thirunavukkarasu M. Nanofertilizers and nutrient transformations in soil. In: *Nanoscience and plant-soil systems*. Ghorbanpour, M., Manika, K., Varma, A. (Eds.), Springer Int. Publishing Cham. 2017; pp. 305–319.
- Tan S, Wang Z, Xiang Y, Deng T, Zhao X, Shi S, Zheng Q, Gao X and Li W. The effects of drying methods on chemical profiles and antioxidant activities of two cultivars of Psidium guajava fruits. *LWT*, 2020; 118(4): 108723.
- Tarafder C, Daizy M, Alam MM, Ali MR, Islam MJ, Islam R, Ahommed MS, Aly Saad Aly M and Khan MZH. Formulation of a hybrid nanofertilizer for slow and sustainable release of micronutrients. *ACS Omega*, 2020; 5: 23960–23966.
- Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, Rehman H ur, Ashraf I and Sanaullah M. Nanotechnology in agriculture: Current status, challenges and future opportunities. *Sci. Total Environ.* 2020; 721: 137778.
- Yadav A, Yadav K and Abd-El Salam KA. Exploring the potential of nanofertilizers for a sustainable agriculture. *Plant Nano Biol.*, 2023; 5: 100044.
- Yadav M. Nanoparticle-facilitated targeted nutrient delivery in plants: Breakthroughs and mechanistic insights. *Plant Nano Biol.* 2025; 1: 100156.
- Zhang L, Li C, Liu Y, Sun Z, He Y, Wen D, Wang Y, Chen X, Cai H and Li G. Participation of urea-N absorbed on biochar granules among soil and tobacco plant (*Nicotiana tabacum* L.) and its potential environmental impact. *Agric. Ecosyst. Environ.* 2021; 313: 107371.
- Zhang X, Yang X, Ruan J and Chen H. Epigallocatechin gallate (EGCG) nanoselenium application improves tea quality (*Camellia sinensis* L.) and soil quality index without losing microbial diversity: A pot experiment under field condition. *Sci. Total Environ.*, 2024; 914: 169923.