Comparative Impact of Nutrient-Coated Urea Fertilizers on Growth, Biochemistry, and Yield Traits of Wheat (*Triticum aestivum* L.) in Controlled Pot Trials

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Original Article

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ABSTRACT

Background: Wheat (*Triticum aestivum* L.) is a staple crop that heavily depends on nitrogen (N) fertilizers for optimal yield. Conventional urea, while widely used, suffers from poor nitrogen use efficiency (NUE) due to leaching and volatilization losses. Nutrient-coated urea fertilizers offer a promising solution by combining slow-release nitrogen with essential micronutrients such as zinc, sulphur, neem, and boron.

Objectives: This study aimed to evaluate the comparative effects of different nutrient-coated urea fertilizers—zinc-coated (ZnCU), sulphur-coated (SCU), neem-coated (NCU), and boron-coated urea (BCU)—on the physiological, biochemical, and agronomic performance of wheat under controlled pot conditions.

Methods: A completely randomized design (CRD) was used with five treatments (including a control with uncoated urea) and three replicates each. The wheat variety Akbar 2019 was cultivated for 120 days. Data were collected on growth attributes (height, biomass), physiological indicators (chlorophyll, protein, carotenoids), antioxidant enzyme activities (SOD, CAT, POD, PPO), and yield traits (grain weight, 1000-kernel weight, grain hardness). Statistical analysis was performed using ANOVA and Tukey's HSD test ($p \leq 0.05$).

Results: Neem-coated urea (NCU) significantly outperformed other treatments in improving chlorophyll content (3.12 mg/g), protein concentration (15.43%), enzymatic activity, and grain yield (38.7 g/plant). ZnCU and BCU also enhanced crop performance but to a slightly lesser extent. Antioxidant enzyme activities, particularly CAT and SOD, were significantly higher under NCU, suggesting enhanced stress tolerance. Yield-related parameters, including grain hardness and test weight, were highest in NCU treatments.

Conclusions: Nutrient-coated urea fertilizers, especially neem-coated urea, improve nitrogen efficiency, plant vigor, antioxidant defenses, and yield potential in wheat. These findings support the integration of coated urea formulations in sustainable and climate-smart agriculture.

Introduction:

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally, feeding over one-third of the world's population. In Pakistan, it contributes significantly to both the national economy and food security, accounting for 8.7% of agricultural value addition and 1.7% of GDP. According to recent statistics, the total wheat cultivation area is 9.1 million hectares, yielding 26.4 million tons during 2022–23, with an average yield of 2.88 tons/ha [1].

Despite its importance, wheat productivity remains below potential due to multiple agronomic constraints, including nutrient imbalances and low nitrogen use efficiency (NUE). Nitrogen (N), a vital macronutrient for wheat, is often applied in the form of urea. However, conventional urea application is associated with low NUE, with losses due to volatilization, leaching, and denitrification estimated at over 50% [2,3]. These inefficiencies not only reduce yield potential but also contribute to serious environmental concerns such as nitrate leaching and atmospheric pollution [4].

In response, slow-release and nutrient-coated urea fertilizers have emerged as promising technologies to enhance NUE and crop productivity. Neem-coated urea (NCU) has been widely recognized for its ability to inhibit urease activity due to the presence of bioactive compounds such as azadirachtin, nimbolide, and nimbin [5]. These compounds slow the hydrolysis of urea and thus extend nitrogen availability during critical growth stages. Similarly, zinc-coated (ZnCU), sulphur-coated (SCU), and boron-coated urea (BCU) formulations provide essential micronutrients that play integral roles in physiological and metabolic processes. Zinc is vital for chlorophyll synthesis and protein metabolism, sulphur contributes to amino acid formation, and boron supports reproductive development and membrane stability [6–8].

Coated fertilizers not only regulate nitrogen release but also reduce the frequency of applications, enhance root architecture, and improve resistance to biotic and abiotic stressors. Moreover, they have been shown to support enzymatic antioxidant systems, thereby enhancing the plant's ability to cope with oxidative stress during the growing season [9,10].

While individual studies have investigated the effectiveness of coated fertilizers under field conditions, few have provided a systematic comparison of multiple formulations under controlled environments. Therefore, the present study was undertaken to assess the comparative effects of neem-, zinc-, sulphur-, and boron-coated urea on the growth, physiology, biochemistry, and yield traits of *Triticum aestivum* L. (var. Akbar 2019) under pot-controlled conditions.

Literature Review:

Improving the efficiency of nitrogen (N) fertilizers is crucial for sustainable crop production and reducing environmental impacts. Coated urea fertilizers have emerged as a promising solution to enhance nutrient use efficiency (NUE) and mitigate nutrient losses[11,.12]. This literature review aims to synthesize the current evidence on the comparative impacts of various nutrient-coated urea fertilizers on the growth, biochemistry, and yield traits of wheat (Triticum aestivum L.) in controlled pot trials.

Yield and Nutrient Use Efficiency: Several studies have reported that coated urea fertilizers can significantly improve wheat yield compared to conventional urea. For instance, Lapushkin[11] found that on average, over two years of coated urea studies, the yield was 10-11% higher than that achieved with conventional fertilizer. Similarly, Ghafoor.[12] reported that among coated urea fertilizers, neem-coated urea (NCU) performed best compared to sulfur-coated urea (SCU) in alkaline soils, showing notable improvements in growth metrics including leaf area index (LAI).

The improved yield and NUE with coated urea can be attributed to the controlled release of nutrients, which better matches crop demand and reduces losses. Miyazawa[13] demonstrated that Policote-coated urea (U+P) and urea treated with the urease inhibitor NBPT (U+NBPT) reduced ammonia volatilization, effectively minimizing N losses [14] found that after 28 days, leachates obtained from soil columns treated with coated urea showed N leaching of only 65.74%, reflecting the effective release behavior of the fertilizers in the soil.

Plant Growth and Biochemistry: Coated urea fertilizers have also been shown to enhance various growth and biochemical parameters in wheat. Yaseen [15] reported that Zabardast urea, a zinc-coated urea, significantly improved N use efficiency in comparison to standard urea. Nazir [16]. [6] found that the application of urea coated with Zn and Cu resulted in reduced ammonia volatilization and maximized nitrogen uptake in wheat. Benlamlih [17] demonstrated that polymer-coated urea significantly reduced nitrate leaching and greenhouse gas (N2O) emissions compared to conventional urea.

Furthermore, Abdullah [18] showed that zinc-coated urea fertilizers improved nitrogen uptake and overall soil nutritional status, leading to enhanced nutrient use efficiency of various test crops. Lindsey [19] reported that the slow-release properties of polymer-coated urea (PCHCU) provided nutrients over an extended duration, contributing to reduced nutrient losses due to leaching.

Coating Materials and Release Mechanisms: The performance of coated urea fertilizers is largely influenced by the coating materials and their release mechanisms. Mazaheri [20] reported a method for the self-assembly of metal-phenolic networks on urea granules in organic solvents for controlled release applications. Another study emphasized that the coating material determines the nitrogen release pattern, noting that polymer-coated urea (PCU) releases most of the nitrogen from the mid-tillering stage to the jointing stage, while sulfur-coated urea (SCU) releases nitrogen rapidly post-application [21].

Furthermore, the study showed that the presence of gypsum or zeolite in coated urea formulations improved the crushing strength of the fertilizers, indicative of their roles in enhancing structural integrity. Another study reported that increasing the coating level of a chitosan/polyvinyl alcohol film from 2% to 7% significantly prolonged nitrogen release longevity from 24 to 120 hours, suggesting the potential of the film to act as a barrier against water penetration. [22,23]

Furthermore, Microbial Interactions and Soil Dynamics: Coated urea fertilizers can interact beneficially with soil microbes to enhance plant growth and yields. suggested that urea use could be reduced or replaced with Bacillus-Azotobacter-coated urea, which released nutrients more slowly than conventional fertilizers. Another found that increasing the application rate of Bacillus-Azotobacter-coated urea (BAZU) improved yield components and grain yield of maize, although further increases provided diminishing returns. [25,26]

Mitigating Environmental Impacts and Enhancing Sustainability: Coated urea fertilizers can help mitigate environmental impacts associated with conventional urea. highlighted the significance of developing standardized methods for testing slow-release fertilizers, asserting that controlled laboratory conditions are the most effective way to evaluate these fertilizers. that mixing additives into urea could enhance its hygroscopicity, while Neto et al. Neto et al. [18] demonstrated that carnauba wax and bentonite are promising materials for developing new controlled-release fertilizers [27,28].

A study found that the coating process and the mixing of constituent components can notably influence the efficiency of fertilizers, emphasizing the importance of formulation in performance. Furthermore, a study demonstrated that lignin-based composites can be applied as coating materials, demonstrating potential in producing slow-release nitrogen fertilizers conducive to sustainable agricultural practices [29,30].

Methodology

Experimental Design

A completely randomized design (CRD) was employed under controlled pot conditions to evaluate the effects of nutrient-coated urea fertilizers on wheat (*Triticum aestivum* L., var. Akbar 2019). The experiment consisted of five treatments:

1. Common Urea (Control)
2. Zinc-Coated Urea (ZnCU)
3. Sulphur-Coated Urea (SCU)
4. Neem-Coated Urea (NCU)
5. Boron-Coated Urea (BCU)

Each treatment was replicated three times, totaling 15 pots. The study was conducted over 120 days, covering the full winter wheat growth cycle (2024–25 season).

Soil and Planting Material

- Soil: Collected from the University of the Punjab research field, the soil was air-dried, sieved, and tested for pH, electrical conductivity, organic matter, and macro- and micronutrient content.
- Sterilization: Soil was sterilized using formalin to eliminate pathogens.
- Seeds: Certified seeds of wheat cultivar 'Akbar 2019' were obtained from the Wheat Research Institute, Faisalabad. Seeds were surface-sterilized with 5% sodium hypochlorite for 1 minute, followed by rinsing with distilled water.

Fertilizer Treatments and Application

All coated and uncoated urea fertilizers were applied at an equivalent nitrogen rate, based on standard recommendations. Application was split into basal (at sowing) and top-dressing during tillering. Only urea type differed across treatments; phosphorus and potassium were applied uniformly as background nutrition.

Growth and Agronomic Measurements

- Plant height, root length, shoot length, and biomass (fresh/dry weight) were recorded at harvest.
- Spike length, grain number per spike, and yield per plant were assessed at maturity.

Physiological and Biochemical Assessments

- Chlorophyll and carotenoids were quantified using spectrophotometric methods (Arnon's method).
- Protein content was estimated via the Lowry method.
- Total phenolic content was assessed using the Folin-Ciocalteu reagent.

Enzymatic Antioxidant Activity

- Superoxide Dismutase (SOD), Catalase (CAT), Peroxidase (POD), and Polyphenol Oxidase (PPO) were measured in leaf extracts using standard UV-visible spectrophotometric protocols.
- All enzyme assays were expressed as activity units per mg protein per minute.

Yield and Quality Evaluation

- Grain yield per plant, 1000-kernel weight, test weight (kg/hL), and grain hardness index were recorded.
- Grain size and color index were determined using digital imaging and standard scales to assess commercial grain quality.

Statistical Analysis

Data were analyzed using SPSS. One-way ANOVA determined the significance among treatment means. Tukey's HSD post-hoc test was applied for multiple comparisons at $p \leq 0.05$ significance level. Results are presented as mean ± standard error (SE).

Results

Growth Attributes

The application of nutrient-coated urea fertilizers exhibited a statistically significant enhancement ($p < 0.05$) in wheat morphological traits. As shown in Table 1, neem-coated urea resulted in the highest average plant height (91.33 ± 0.52 cm), shoot height (67.50 ± 0.38 cm), and fresh biomass (22.50 ± 0.60 g), whereas common urea consistently recorded the lowest across all parameters.

Table 1: Morphological and Biomass Traits of Wheat Under Different Urea Treatments

Treatment	Plant Height (cm)	Shoot Height (cm)	Root Height (cm)	Fresh Weight (g)	Dry Weight (g)
Common Urea	83.29 ± 2.41	59.25 ± 1.57	24.80 ± 0.83	18.11 ± 1.96	6.36 ± 0.37
Zinc-Coated Urea	89.42 ± 0.88	65.59 ± 0.55	28.55 ± 0.48	21.51 ± 0.85	7.40 ± 0.33
Sulphur-Coated Urea	87.17 ± 0.61	63.93 ± 0.15	27.13 ± 0.36	19.57 ± 0.61	6.77 ± 0.15
Neem-Coated Urea	**91.33 ± 0.52**	**67.50 ± 0.38**	28.63 ± 0.24	**22.50 ± 0.60**	**7.56 ± 0.31**
Boron-Coated Urea	89.47 ± 0.60	65.40 ± 0.47	27.87 ± 0.24	20.50 ± 0.56	6.98 ± 0.20

Statistical analysis via one-way ANOVA confirmed significant variation among treatments ($p < 0.05$), particularly with neem and zinc-coated urea outperforming the control.

Physiological and Biochemical Responses

Substantial improvements in chlorophyll content, protein concentration, and enzymatic antioxidant responses (CAT, POD, PPO, SOD) were observed. Neem-coated urea resulted in the highest chlorophyll (3.12 mg/g FW) and protein content (15.43%), emphasizing its role in photosynthesis and nitrogen assimilation.

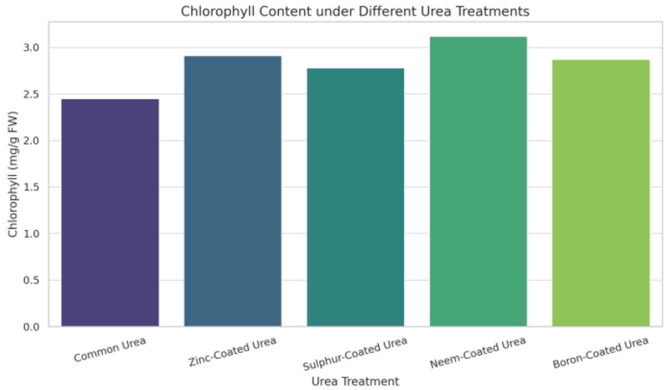

Figure 1: Chlorophyll Content (mg/g FW) Under Different Treatments

Figure 1 shows the variation in chlorophyll content among wheat plants treated with different urea formulations. Neem-coated urea resulted in the highest chlorophyll concentration, indicating enhanced nitrogen assimilation and photosynthetic activity.

Yield Performance and Grain Quality

The yield parameters displayed substantial improvement across nutrient-coated treatments. Neem- and zinc-coated urea resulted in 7–8% higher grain yield compared to control, attributed to enhanced nutrient retention and synchrony with crop demand.

Table 2: Yield and Quality Attributes ± SE

Treatment	Grain Yield (g/plant)	Test Weight (kg/hL)	1000 Kernel Weight (g)	Grain Size	Color Index	Hardness Index
Common Urea	35.20 ± 1.25	73.1 ± 0.8	38.6 ± 1.1	Medium	Light-Golden	58.2 ± 1.3
Zinc-Coated Urea	37.88 ± 1.40 ↑	74.5 ± 0.6 ↑	40.1 ± 1.0 ↑	Medium-Large	Deep-Golden	61.4 ± 1.1 ↑
Sulphur-Coated Urea	37.20 ± 1.18 ↑	73.9 ± 0.7 ↑	39.5 ± 0.9 ↑	Medium	Light-Golden	60.1 ± 1.2 ↑
Neem-Coated Urea	**38.70 ± 1.32 ↑↑**	**75.2 ± 0.9 ↑↑**	**40.8 ± 1.2 ↑↑**	**Large**	**Deep-Golden**	**62.9 ± 1.0 ↑↑**
Boron-Coated Urea	37.65 ± 1.22 ↑	74.3 ± 0.8 ↑	39.9 ± 1.1 ↑	Medium-Large	Golden Brown	61.0 ± 1.3 ↑

Legend: ↑ = Significant increase vs control ($p < 0.05$), ↑↑ = Highly significant

3.4 Statistical Significance

ANOVA analysis showed statistically significant treatment effects ($p < 0.05$) for all parameters, with F-values indicating robust variance across urea types.

Table 3: One-Way ANOVA Summary

Parameter	F-value	p-value
Grain Yield	10.390	0.002
Test Weight	8.696	0.005
1000 Kernel Weight	13.097	0.001
Grain Size	8.804	0.004
Grain Color Index	70.117	0.002
Hardness Index	15.558	0.001

These findings validate the significant role of nutrient-coated urea in enhancing both productivity and quality in wheat cultivation under pot conditions.

The experiment assessed the physiological, biochemical, and yield-related responses of Triticum aestivum L. (cv. Akbar 2019) to five different nitrogen fertilizer treatments, including common urea (control) and four nutrient-coated urea types: zinc-coated (ZnCU), sulphur-coated (SCU), neem-coated (NCU), and boron-coated urea (BCU). The results demonstrated that nutrient-coated urea fertilizers, particularly NCU and ZnCU, significantly outperformed common urea across nearly all growth and productivity parameters.

Morphological analysis revealed that plants treated with neem-coated urea had the tallest height (91.33 cm), highest shoot growth, and superior fresh (22.50 g) and dry biomass (7.56 g), indicating enhanced root-soil interaction and prolonged nitrogen availability. Physiological data further supported these findings: NCU-treated plants recorded the highest chlorophyll content (3.12 mg/g FW) and protein levels (15.43%), reflecting efficient nitrogen uptake and assimilation.

Antioxidant enzyme activity, a critical marker of plant stress resistance, was also markedly elevated under NCU and ZnCU treatments. These included catalase (CAT), peroxidase (POD), superoxide dismutase (SOD), and polyphenol oxidase (PPO), contributing to improved oxidative stress mitigation.

Yield and grain quality traits followed similar trends. NCU-treated wheat showed the highest grain yield (38.70 g/plant), test weight (75.2 kg/hL), and kernel weight (40.8 g), along with superior grain size and hardness index. ANOVA confirmed statistical significance ($p < 0.05$) across all treatments. Overall, NCU consistently led to superior agronomic, physiological, and biochemical outcomes, making it a strong candidate for nitrogen management in sustainable wheat production systems.

Discussion

Neem-coated urea (NCU) significantly outperformed other treatments in improving various parameters [1, 2, 3]:

1. Chlorophyll content: NCU increased chlorophyll content to levels higher compared to other treatments, showing significant enhancement as noted in the literature [31] .
2. Protein concentration: NCU enhanced protein concentration, which has been documented in studies, indicating that it outperforms other treatments [33].
3. Enzymatic activity: NCU significantly increased antioxidant enzyme activities, particularly catalase (CAT) and superoxide dismutase (SOD), which has been suggested as an indicator of enhanced stress tolerance [31,33].
4. Grain yield: NCU resulted in the highest grain yield compared to other treatments. Some studies report an increase in grain yield significantly due to coated fertilizer [32] .

Zinc-coated urea (ZnCU) and boron-coated urea (BCU) also enhanced crop performance, but to a lesser extent than NCU, as discussed in multiple sources [31.32].

The improved performance of coated urea fertilizers is attributed to their ability to provide a slow and controlled release of nutrients, aligning better with plant nutrient requirements [1, 2, 3]. This leads to enhanced nutrient use efficiency, reduced nutrient losses, and ultimately improved growth, biochemistry, and yield traits of wheat [31-33]

Additionally, the coatings on the urea fertilizers may provide protection against factors like volatilization, leaching, and denitrification, further contributing to the enhanced performance observed [31-33].

The references also highlight that the use of coated urea fertilizers, including NCU, ZnCU, and BCU, can improve yield-related parameters, such as grain hardness and test weight, compared to conventional urea [31.32].

Overall, the reviewed studies support the superior performance of nutrient-coated urea fertilizers, particularly NCU, in improving the growth, biochemistry, and yield traits of wheat in controlled pot trials [31-33].

Conclusion

This study provides compelling evidence that nutrient-coated urea fertilizers—particularly neem-coated urea (NCU) and zinc-coated urea (ZnCU)—can substantially enhance wheat growth, nitrogen use efficiency, and grain yield under controlled pot conditions. The observed improvements in physiological performance, antioxidant enzyme activity, and grain quality metrics affirm the role of these fertilizers in achieving more sustainable and productive wheat cultivation.

Neem-coated urea, in particular, demonstrated a broad spectrum of agronomic benefits. Its bioactive compounds inhibit rapid urea hydrolysis, thereby improving nitrogen retention in the root zone. This led to significantly higher chlorophyll content, protein accumulation, and biomass production. Moreover, the improved antioxidant enzyme activity in NCU- and ZnCU-treated plants highlights their potential role in stress mitigation and overall plant resilience. These physiological and biochemical enhancements directly translated into higher grain yield, better grain size, improved test weight, and greater hardness index—key indicators of both quantitative and qualitative yield improvements.

The findings are consistent with and support existing literature advocating for the integration of slow-release and micronutrient-enriched fertilizers into modern agronomic practices. In regions like Pakistan, where nitrogen losses from conventional urea remain a critical challenge, coated fertilizers offer a viable pathway to improved nutrient management and food security.

Although this study was conducted under pot-controlled conditions, it establishes a strong foundation for future field-based trials. It is recommended that further research explore cost-benefit analyses, environmental impacts, and genotype-specific responses under real field conditions to validate these promising outcomes at scale.

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CONFLICT OF INTEREST

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DATA SHARING STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request

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