



OPEN Effects of coating agents on nitrogen dynamics and yield of wheat (*Triticum aestivum* L.) under irrigated and rainfed conditions

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Nitrogenous (N) fertilizers are widely applied in agriculture for improving crop yield. However, significant quantity of chemically-applied N is lost leading to low nitrogen use efficiency (NUE). Therefore, two laboratory incubation studies were designed to evaluate the effects of different coating agents [no coating, neem (*Azadirachta indica*) oil coating and potassium ammonium phosphate (PAP) coating] on urea hydrolysis and nitrification under varying temperatures (25, 35 and 40 °C) and moisture regimes (30, 60 and 90% of field capacity). Results revealed that the NH_4^+ and NO_3^- concentrations increased both with temperature and moisture levels. Using the organic-coated neem oil coated urea (NOCU) significantly reduced the release of NH_4^+ and NO_3^- . Thereafter, a field experiment was conducted to explore the best coating agent [N_0 , 100% conventional urea, 75, 50 and 25% of recommended neem oil coated urea (NOCU)] using irrigated (Akbar-2019) and rainfed (Barani-2017) wheat cultivars. Even the reduced rates (50%) of the recommended NOCU performed at par to 100% recommended uncoated urea fertilizers. Application of 1% NOCU @ 75% of the recommended urea resulted in maximum grain yield (3.65 Mg ha⁻¹), N in roots (0.87%), N in straw (0.85%) and N in grains (1.07%) in irrigated wheat variety (Akbar-2019). Thus, using 1% neem oil coated urea @ 75% of the recommended uncoated urea has the potential to enhance the growth, yield, N uptake and NUE in wheat effectively under both rain fed and irrigated conditions.

Keywords Neem oil coated urea, Slow-concentration fertilizer, Nitrogen, Wheat, Urea hydrolysis

According to Food and Agriculture Organization (FAO) projections, global grain production must be increased by 140% or more by the year 2050 to meet the food demands of the growing population^{1,2}. A considerable improvement in crop yield in developing nations would alleviate the pressure of the global grain demand and ensure food security^{3,4}. However, the crop yield in developing countries is far below the potential because of the lack of knowledge, meagre resources, degraded soils and improper management practices. Among the nutrients, N is the most critical macronutrient for ensuring high-quality crop production⁵. Nitrogen (N) deficiency is a significant concern in many agricultural regions worldwide. That's why, N fertilizers are important foundation for sustainable crop production⁶. Nitrogen application improve the yield and quality of almost all crops because it affect the growth and development of plants under diverse agro-climatic environments^{7–10}.

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Nitrate (NO_3^-) and ammonium (NH_4^+) are two bio-available forms of N for plant use. Fertilizers like urea (46% N) are commonly used to replenish soil N, and N assimilation and biomass of plants because of its high N content¹¹. However, utilization of large quantities of urea fertilizer in agriculture leads to the environmental problems (eutrophication of waterways, greenhouse gas emission and soil degradation). Excessive application of N fertilizer has adverse impacts on groundwater and atmosphere by runoff, denitrification, leaching and volatilization of N¹² thus decreasing N recovery efficiency (NRE), which in turn can reduce crop yield^{13,14}. Ozone depletion is another problem associated with nitric (NO_2) and nitrous oxide (N_2O) or production^{15,16}. Using excessive fertilizer that is high in N content is not only wasteful, but also has the potential to contaminate groundwater¹⁷ and leads to environmental and health issues. Thus, present study aimed to explore more sustainable N management solutions, such as natural and polymer-coated fertilizers.

The use of 4R strategy (right rate, source, placement and timing) to ensure N availability as per crop need to enhance its yield is an important part of effective N management^{18,19}. Indiscriminate and excessive use of conventional fertilizers is discouraged due to negative effects on the environment^{19,20} animal and human health²¹ and agricultural products²¹ whereas the goal of agriculture is to produce more from less while restoring the environment. Thus, researchers are exploring several options. Effective management of fertilizers by using innovative formulations can reduce N losses via volatilization, denitrification and leaching²². Therefore, using plant-based and other natural materials that contain urease, volatilization or nitrification inhibitors may reduce N losses, and improve crop yield in eco-friendly manner^{23–26}. Sulfur-coated urea (SCU) was the first coated slow-release fertilizer (SRF), but its high N content makes it challenging to synchronise with the time at which plant needs N^{27,28}. Scientist have refined the coating material and developed polymer-coated fertilizers to enhance the efficacy of SRF. Crop yield and nitrogen use efficacy (NUE) can be improved by introducing polymer-coated fertilizers because the rate of N release well matches with the nutritional demands of crops²⁹. However, the manufacturing of polymer-coated SRF is complex and costly^{30–33}. Similarly, natural zeolites are a suitable option to reduce nutrient leaching. However, there exists a strong need for conducting batch and column tests for site-specific soil while also simultaneously validating the data under field conditions^{34–38}. On other hand, in potassium ammonium phosphate coated fertilizers, the phosphate reduces the loss of nitrogen by volatilization³⁹. Therefore, in order to prevent denitrification-related losses, N should remain in the ammonium form for an extended period of time⁴⁰. Nitrogen use efficiency (NUE) can also be improved by coating urea granules natural oil extracted from neem because neem oil coated urea (NOCU) can delay nitrification thereby, lower the N release making it suitable to fulfil plants' needs⁴¹.

The performance of coating-based products (polymer coated, sulphur coated and urea formaldehyde) depends upon soil and climatic conditions^{42–44}. Furthermore, these formulations are costly and labour-intensive. Therefore, the present study was designed to compare the performance of natural and chemical coating agents on urea hydrolysis and nitrification under different temperature and moisture regimes under laboratory conditions and to further validate the performance of best treatments under field conditions while using different wheat cultivars as a test crop. Specific objectives of the study were (a) Selection of suitable coating agents to slow N concentration from urea. (b) Determination of effect of different coating agents on NUE of urea and yield of wheat and (c) Dose optimization of NOCU for two different wheat varieties grown at two different locations. Following hypotheses were tested (a) Different coating agents (natural and chemical) significantly decreased the N concentration from urea as compared to uncoated urea and (b) Use of coated urea improved the NUE and yield of wheat under irrigated and rainfed conditions.

Results

Effect of coating agents and temperature level on urea hydrolysis and nitrification

The analysis of data revealed that the NH_4^+ concentration decreased over time in uncoated urea but the it was still much higher than that drawn from all types of coated urea under all temperature regimes (Table 1). While, in coated urea, NH_4^+ concentration was the lowest at 10 days of incubation at 25 and 35 °C temperature that was slightly increased at later intervals but it was yet much lower than that from the uncoated urea. At 40 °C temperatures NH_4^+ concentration was the highest at 20 days of incubation (1485.0 mg kg⁻¹) under coated urea that decreased at later intervals. However, the uncoated urea caused the highest NH_4^+ concentration at the first interval and that was 1385.0 mg kg⁻¹. Among coating materials, both NOCU (neem oil coated urea) and PAPCU (potassium ammonium phosphate coated urea) had a strong impact on NH_4^+ concentration in comparison to uncoated urea. Use of NOCU resulted in 64.53%, 61.39% and 61.66% decrease in NH_4^+ concentration at 25, 35 and 40 °C in comparison to uncoated urea, respectively. PAPCU performed more effectively than NOCU in decreasing NH_4^+ concentration with 64.77%, 64.69% and 65.85% decrease in NH_4^+ concentration after first interval at 25, 35 and 40 °C, respectively. Though all materials performed effectively, but the results were statistically non-significant for NH_4^+ concentration among all coated urea treatments.

The ANOVA indicated a decreasing trend in NO_3^- concentration over time for uncoated urea but the concentration was still much higher than that drawn from all types of coated urea and under all temperature regimes. While in coated urea, NO_3^- concentration was the lowest at 10 days of incubation at 25 and 35 °C temperature that was slightly increased at later time intervals but it was yet much lower than that under the uncoated urea. At 40 °C temperature, NH_4^+ concentration was the highest at 20 days of incubation from coated urea which decreased at later intervals, but uncoated urea caused the highest NO_3^- concentration at the first interval (971 mg kg⁻¹, 1007 mg kg⁻¹, 1121 mg kg⁻¹) under all temperature regimes. Among coating materials, neem oil was the most effective (971 mg kg⁻¹, 1007 mg kg⁻¹, 1121 mg kg⁻¹) in reducing NO_3^- concentration showing 72.09%, 68.52% and 70.65% decrease in NO_3^- concentration in comparison with the uncoated urea and 71.27%, 71.1% and 73.68% decrease in NO_3^- concentration with 1.5% PAPCU at 25, 35 and 40 °C temperature respectively, as compared to uncoated urea. However, all materials were effective in reducing NO_3^- concentration and the results were non-significant for NO_3^- concentration among all types of coated urea.

Temperature levels	Treatment	Ammonium concentration (mg kg ⁻¹)			Nitrates concentration (mg kg ⁻¹)		
		10 days	20 days	30 days	10 days	20 days	30 days
Temperature 25 °C	Control (N ₀)	1.7 h	0.7 h	0.4 h	1 u	0.6 u	0.5 u
	Uncoated urea	1263 b	293 f	185 g	971 c	745 f	315 r
	NOCU (1.0%) D	448 e	1271 a	832 c	271 t	590 l	679 i
	PAPCU (1.5%) D	445 e	1260 b	826 d	279 t	461 o	663 j
Temperature 35 °C	Control (N ₀)	1.7 h	0.7 h	0.4 h	1 u	0.6 u	0.5 u
	Uncoated urea	1365 b	316 f	219 g	1007 b	789 e	326 pq
	NOCU (1.0%) D	527 e	1363 a	919 c	317 qr	619 k	693
	PAPCU (1.5%) D	482 e	1293 b	916 d	291 s	487 n	681 i
Temperature 40 °C	Control (N ₀)	1.7 h	0.7 h	0.4 h	1 u	0.6 u	0.5 u
	Uncoated urea	1385 b	337 f	239 g	1121 a	804 d	331 p
	NOCU (1.0%) D	531 e	1485 a	956 c	329 p	525 m	706 g
	PAPCU (1.5%) D	473 e	1311 b	925 d	295 s	491 n	688 hi

Table 1. Effect of organic and mineral coating agents on Urea hydrolysis and nitrification under different levels of temperature. The means with different letters in each category are statistically different at $\alpha = 0.05$. N₀, UNC, NOCU and PAPCU represent control, uncoated urea, neem oil coated urea (1%), and potassium ammonium phosphate (1.5%) coated urea and field capacity.

Effect of coating agents on urea hydrolysis and nitrification in soil at different moisture levels

The results regarding NH_4^+ and NO_3^- concentration as affected by different coating agents under varying moisture regimes are presented in Table 2. The maximum NH_4^+ concentration was observed for uncoated urea (1217.0 mg kg⁻¹) at 90% of field capacity that was relatively decreased with decreasing moisture levels but was yet the highest than those under all other treatments at respective moisture levels at 10 days of incubation period. Similarly, NH_4^+ concentration from coated treatments were also lowered with a decrease in moisture content. But the time of incubation indicated different trend, as NH_4^+ concentration from uncoated urea was lowered with the time. However, from coated treatments it was relatively increased. Among coating materials, PAPCU (1.5%) induced lowest NH_4^+ concentration with least observed value (295.0 mg kg⁻¹) at 30% of field capacity at first interval. PAPCU was most effective in reducing NH_4^+ concentration after 10 days intervals with values of 72.25%, 71.07% and 70.95% decrease in NH_4^+ concentration at 30, 60 and 90% of the field capacity. NOCU was more effective with 71.03%, 70.32% and 68.99% decrease in NH_4^+ concentration as compared to uncoated urea at 30, 60 and 90% of field capacity after 10 days of incubation. NOCU resulted in the highest N concentration (1407.0 mg kg⁻¹) after 20 days of incubation at moisture levels of 90% of the field capacity (Table 2).

The highest reduction in NO_3^- concentration from all types of coated urea over uncoated urea was at 10 days of incubation at all moisture levels which was significantly higher than later incubation intervals (Table 2). Similarly, NO_3^- concentration from coated treatments was also increased by rising soil moisture content. An opposite trend was observed regarding time of incubation, as the NO_3^- concentration from uncoated urea was lowered with the passage of time compared to coated treatments where it was relatively increased. At first

Moisture level	Treatment	Ammonium concentration (mg kg ⁻¹)			Nitrates concentration (mg kg ⁻¹)		
		10 days	20 days	30 days	10 days	20 days	30 days
30% of field capacity	Control (N ₀)	1.7 x	0.7 x	0.4 x	1 u	0.6 u	0.5 u
	Uncoated urea	1063 i	373 q	265 u	987 c	645 h	215 t
	NOCU (1.0%) D	308 s	1281 e	812 j	267 r	443 n	529 m
	PAPCU (1.5%) D	295 t	1230 f	796 k	252 s	411 o	623 k
60% of field capacity	Control (N ₀)	1.7 x	0.7 x	0.6 x	1 u	0.6 u	0.5 u
	Uncoated urea	1196 h	307 s	214 v	1046 b	764 e	362 pq
	NOCU (1.0%) D	355 r	1348 c	542 m	371 p	542 l	598 j
	PAPCU (1.5%) D	346 r	1321 d	527 o	356 q	527 m	583 e
90% of field capacity	Control (N ₀)	1.7 x	0.7 x	0.4 x	1 u	0.6 u	0.5 u
	Uncoated urea	1217 g	261 u	163 w	1276 a	781 d	258 rs
	NOCU (1.0%) D	396 p	1407 a	651 l	452 n	697 f	623 i
	PAPCU (1.5%) D	371 q	1394 b	426 n	446 n	659 g	603 j

Table 2. Effect of organic and mineral coating agents on Urea hydrolysis and nitrification under different soil moisture levels. The means with different letters in each category are statistically different at $\alpha = 0.05$. N₀, UNC, NOCU and PAPCU represent control, uncoated urea, neem oil coated urea (1%), and potassium ammonium phosphate (1.5%) coated urea and field capacity.

interval, PAPCU (1.5%) proved more effective in decreasing NO_3^- concentration with 74.47%, 65.97% and 65.05% decrease in NO_3^- concentration over uncoated urea at 30, 60 and 90% of field capacity respectively, after 10 days of incubation. The reduction in NO_3^- concentration over uncoated urea from NOCU was 72.95% (267 mg kg^{-1}), 64.53% (371 mg kg^{-1}) and 64.58% (452 mg kg^{-1}) as compared to uncoated urea at 30, 60 and 90% of field capacity after 10 days of incubation respectively.

Plant height, grain and biological yield of wheat as affected by NOCU

Plant height, grain and biological yield were significantly affected by NOCU (Fig. 1a–c). The maximum plant height (94.2 cm) was observed where 75% NOCU was used as compared to recommended rate of commercial urea followed by uncoated recommended urea (88.2 cm) in irrigated wheat variety “Akbar-2019” (Fig. 1a). A reduced rate of all types of coated urea was also effective in increasing plant growth. Use of 25% of the recommended rate NOCU resulted in 76.1 cm plant height. Furthermore, in rainfed wheat variety “Barani-2017” the 75% NOCU produced more plant height (86.8 cm) in comparison to all other treatments. Regarding the rate of urea, 50% of the recommended coated treatments resulted in slightly lower plant height (81.6 cm) than recommended rate of uncoated urea (83.6 cm). However, 25% of the recommended rate was the least effective, as it produced much smaller plant height than the recommended rate of uncoated urea (76.1 and 72.4 cm) in both varieties, respectively.

The data in Fig. 1b show a significant increase in grain yield when compared to control receiving zero N in both tested wheat varieties. Minimum grain yields (2521 and 2393 kg ha^{-1}) were observed in control where no N fertilizer was applied in irrigated and rainfed wheat varieties. A significant improvement in grain yield was noticed with the application of 25% of the recommended rate of NOCU showing numerical values of 2761 and 2661 kg ha^{-1} , respectively. Grain yield was further improved with 3292 and 3054 kg ha^{-1} of grain yield recorded when 50% of recommended rate of NOCU was applied in both tested varieties. However, recommended rate of uncoated urea produced higher grain yield in both varieties (3440 and 3305 kg ha^{-1}). Maximum grain yield (3648 and 3419 kg ha^{-1}) was recorded when 75% of the recommended rate of NOCU was applied compared to all other treatments.

The biological yield was significantly improved with N application as compared to control in both tested wheat varieties (Fig. 1c). Maximum biological yield (9162 kg ha^{-1}) was obtained where 75% of the recommended NOCU was applied followed by the 100% recommended uncoated urea (8799 kg ha^{-1}) in irrigated wheat variety “Akbar-2019”. Application of 50% of recommended NOCU produced significantly lower biological yield (8527 kg ha^{-1}) than uncoated urea but it was yet higher than 25% of recommended NOCU (8074 kg ha^{-1}). Same trend was observed in rainfed wheat variety where maximum biological yield (8618 kg ha^{-1}) was obtained with 75% of the NOCU followed by the recommended rate of uncoated urea (8255 kg ha^{-1}).

Chlorophyll contents ($\mu\text{mol m}^{-2}$)

The chlorophyll content showed a significant improvement in response to the application of coated or uncoated urea as compared to control (N0) regardless of varieties used (Fig. 2). Regarding rates of NOCU, 75% of recommended NOCU produced the highest chlorophyll content of 49 and 47 SPAD compared to 100% recommended urea in wheat varieties Akbar-2019 and Barani 2017, respectively. The lowest chlorophyll content of 33 and 30 SPAD were observed in control (N0) in wheat varieties Akbar-2019 and Barani 2017, respectively. Addition of coated urea fertilizer efficiently improved the chlorophyll content in wheat leaf as compared to the control. Thus, chlorophyll content in wheat leaf was significantly increased by enhanced level of N showing the positive effect of N on wheat plant development.

Agronomic N use efficiency (NUE)

The agronomic NUE was significantly improved in treated plants compared to control in both tested wheat varieties (Fig. 3). The highest NUE (12.85) was observed under plots treated with 50% of recommended coated urea followed by treatment with 75% coated urea (12.52%) in case of irrigated wheat variety (Akbar- 2019). Both of these treatments were proved non significant when tested statistically. The NUE at 25% of the recommended NOCU was significantly lower (8) than 75% and 50% of the recommended NOCU but was significantly higher than 100% recommended uncoated urea (7.68). Similar results were also observed in rainfed wheat variety. The highest NUE was found when under 75% recommended NOCU (11.4) followed by 50% of recommended NOCU (11). The lowest NUE (7.58) was recorded under 100% uncoated urea. Thus, coating of urea with neem oil maximally improved the NUE of applied fertilizer.

Nitrogen concentration (%) in root, straw and grain

The N concentration in different plant parts of both varieties were significantly improved with the application of N as conventional urea or NOCU compared to control (Fig. 4a). The 75% of recommended NOCU produced highest N concentration in roots (0.87%) than 100% of the recommended uncoated urea (0.76%) as presented in Fig. 4a. The NOCU applied at the rate of 25% of the recommended rate resulted in 0.61% N in roots that was much higher (0.48%) than that under the control treatment (N0) in irrigated wheat variety “Akbar-2019”. Similarly, in the rainfed variety, maximum N concentration (0.79%) was achieved with 75% of recommended NOCU.

Nitrogen concentration in straw was significantly increased in treated plants compared to control in both tested wheat varieties (Fig. 4b). The maximum N concentration (0.85%) in wheat straw was observed under 75% of NOCU followed by 100 recommended uncoated urea (0.73%). However, N concentration in wheat straw (0.39%) of plants grown under 25% of recommended NOCU was slightly higher than that under the control treatment (0.27%) in irrigated wheat variety (Akbar-2019). Similar results were also observed for straw N content of rainfed wheat variety. The lowest N concentration in straw (0.21%) was observed in control while

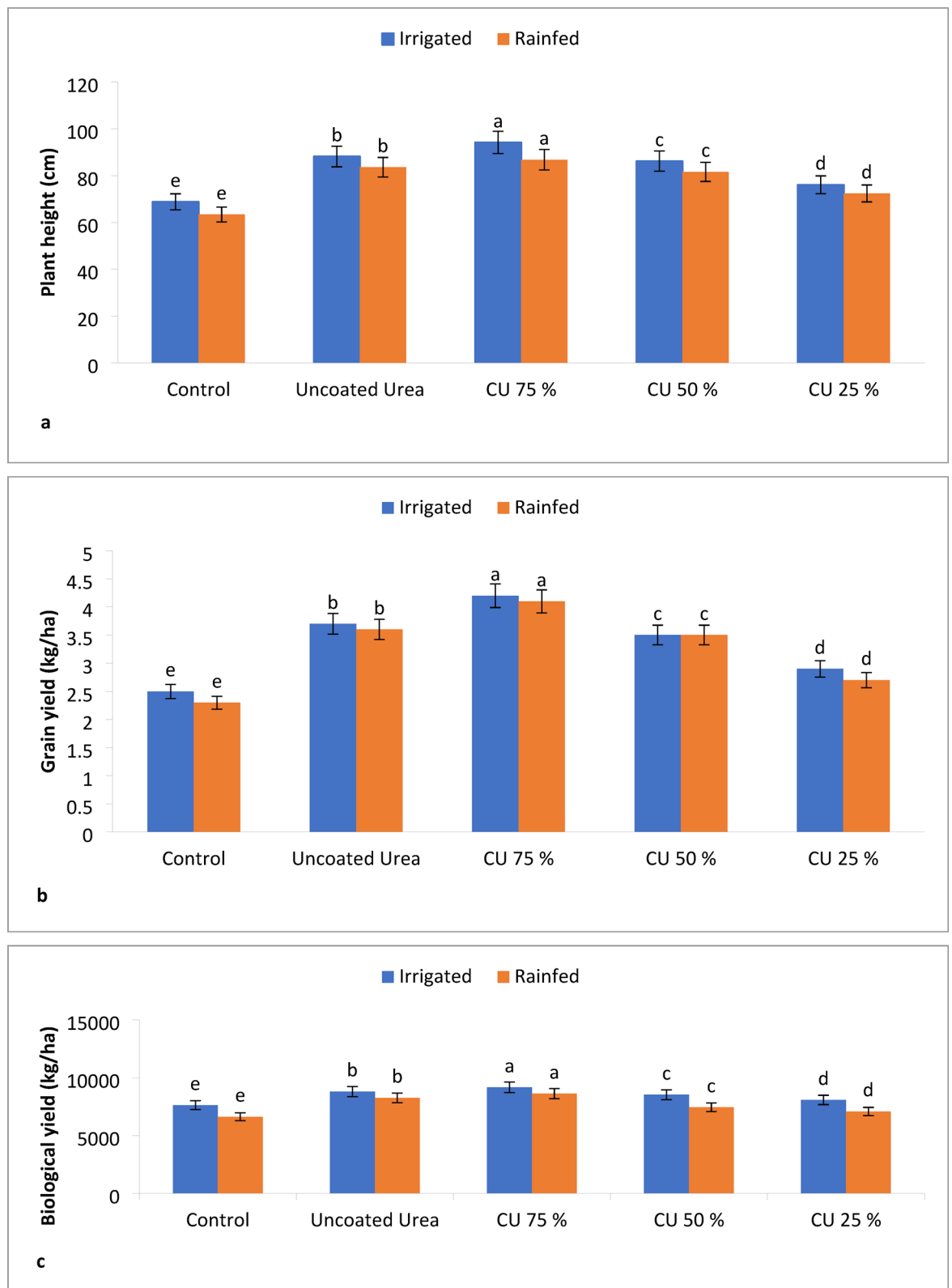


Fig. 1. Impact of different rates of NOCU on plant height (a), grain yield (b) and biological yield (c) of different wheat varieties. The bars on chart represents standard error of mean for triplicates while bars with different letters are significantly different at $\alpha = 0.05$.

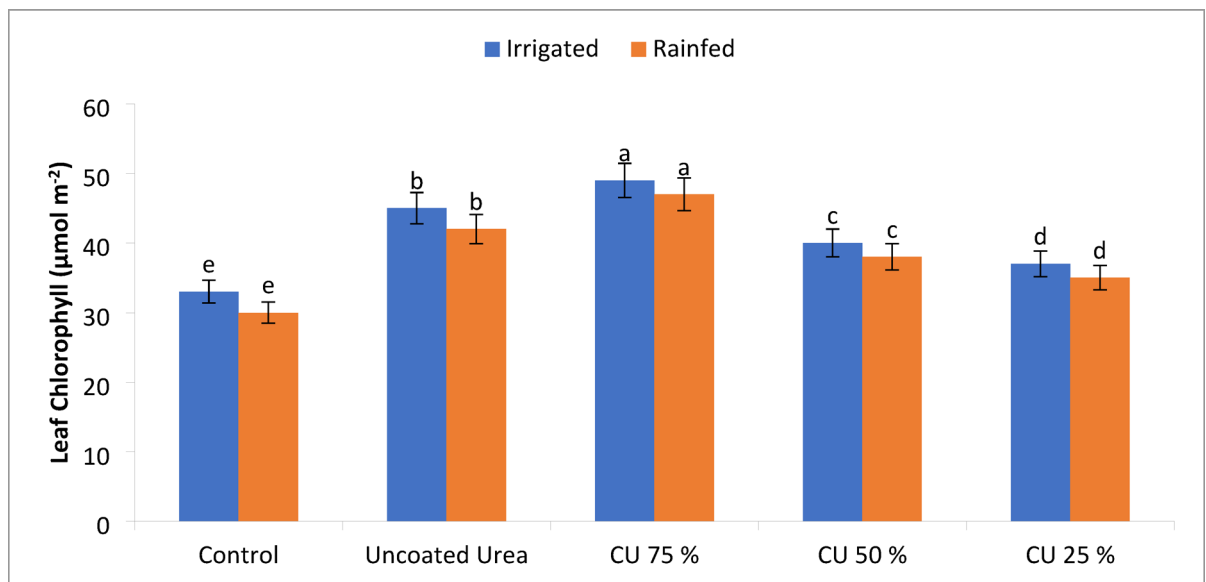


Fig. 2. Impact of different rates of NOCU on chlorophyll content (SPAD) of different wheat varieties. The bars on chart represents standard error of mean for triplicates while bars with different letters are significantly different at $\alpha = 0.05$.

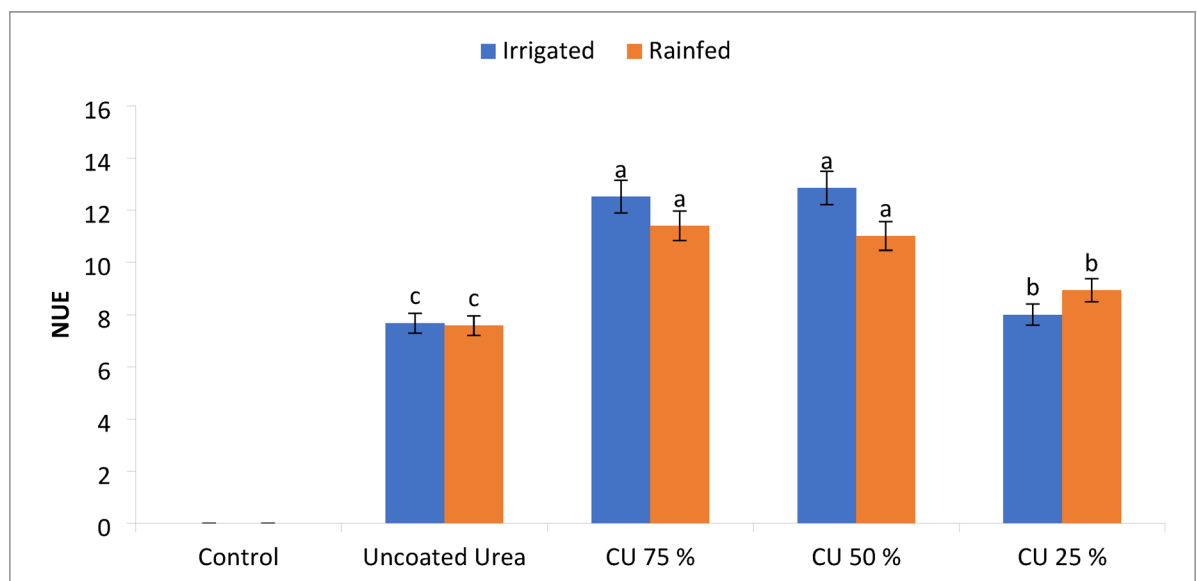


Fig. 3. Impact of different rates of NOCU on NUE of different wheat varieties. The bars on chart represents standard error of mean for triplicates while bars with different letters are significantly different at $\alpha = 0.05$.

the maximum of 0.74% N was observed with 75% of recommended NOCU treatment which was significantly higher than 100% of uncoated urea.

The N concentration in wheat grain was also significantly increased with application of N in any form compared to control regardless of cultivars (Fig. 4c). The lowest N concentration (0.44 and 0.29%) in wheat grains of both tested varieties was observed under control (N0). An increase in N concentration was recorded when coated or uncoated urea was applied. However, the maximum concentration of N in wheat grains (1.07 and 0.95%) was observed where 75% of the recommended NOCU was applied that was followed by the 100% of the recommended uncoated urea (0.93 and 0.88%).

Total N concentration in soil (%)

The total N concentration in soil was significantly increased when urea was applied regardless of form and rates. The lowest total N content was observed in control treatment (N0) as shown in Fig. 5 which was improved

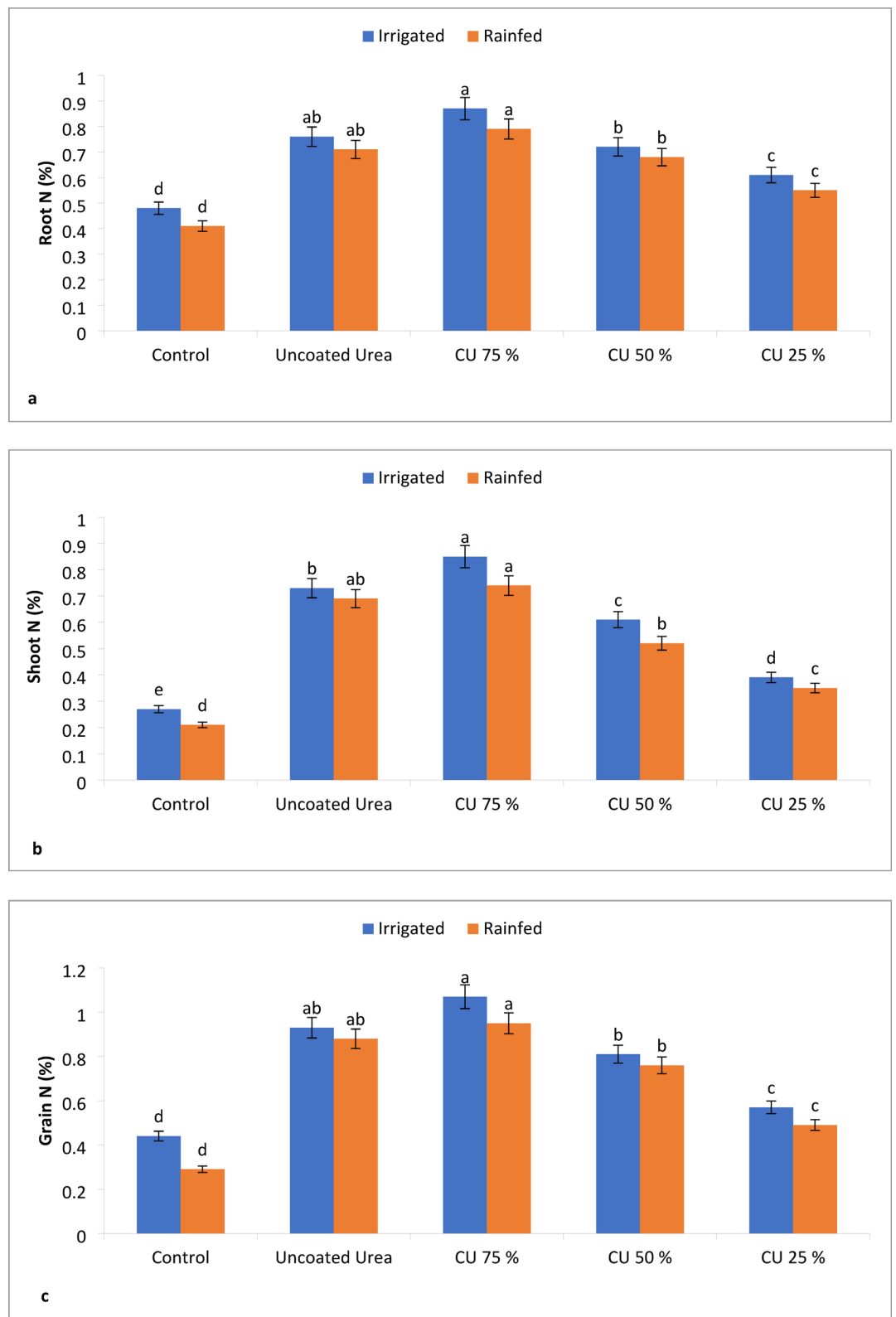


Fig. 4. Impact of different rates of NOCU on N content (%) in root (a), straw (b) grains (c) of different wheat varieties. The bars on chart represents standard error of mean for triplicates while bars with different letters are significantly different at $\alpha = 0.05$.

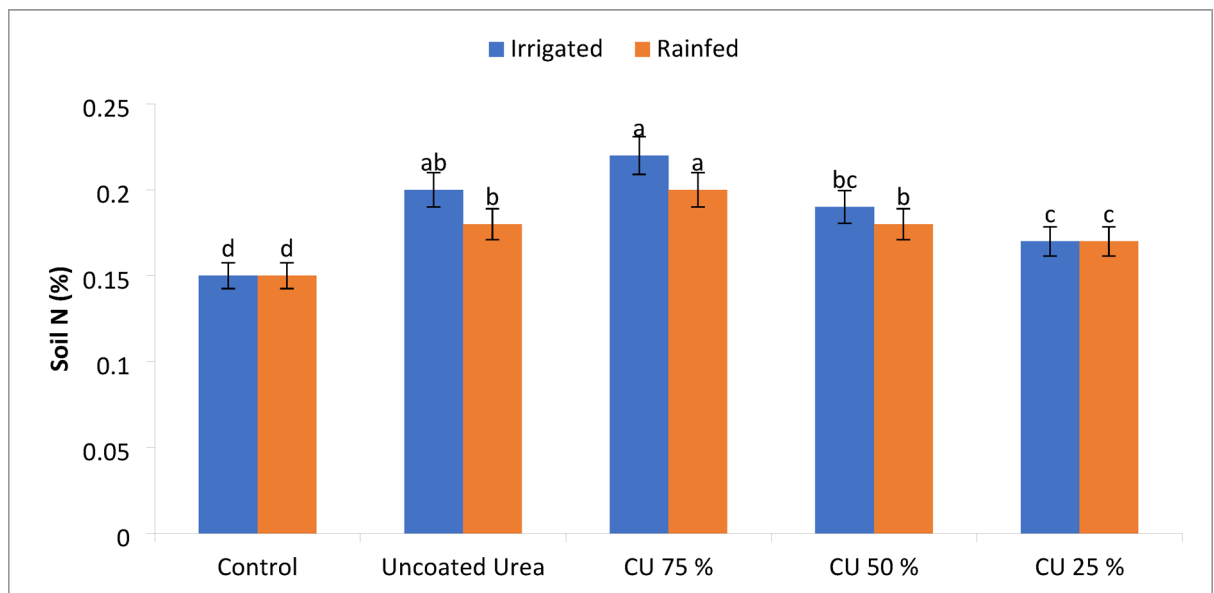


Fig. 5. Impact of different rates of NOCU on total N (%) in different soil areas. The bars on chart represents standard error of mean for triplicates while bars with different letters are significantly different at $\alpha=0.05$.

the the application of urea. The effect of NOCU was more pronounced at all three applied levels. A gradual improvement in total N content of soil was observed with numerical values of 0.19, 0.20 and 0.22% when NOCU was applied @ 25, 50 and 75% respectively in irrigated wheat variety. Similar trend was reflected in rainfed wheat variety where maximum N concentration in soil was (0.20%) obtained where 75% of NOCU was applied followed by the 100% of recommended uncoated urea (0.18%).

Discussion

The application of chemical fertilizers, particularly those containing N, has become a cornerstone in modern agriculture due to its significant role in boosting crop yields²⁸. However, the introduction of chemical N fertilizers into the soil is accompanied by numerous challenges, primarily related to substantial N losses through various processes such as nitrification and denitrification^{45,46}. Research has shown that applied N undergoes a series of complex mechanisms, involving chemical interactions with soil bacteria and plant roots, which often lead to its loss in the form of N_2O or NO_2 ^{47–49}. Due to high solubility and negative charges the significant portion of nitrate form of N is subjected to losses by the process of leaching and runoff. When nitrates from fertilizers are washed away by rain or irrigation, they can seep into groundwater, leading to contamination of drinking water sources. This can cause health issues such as methemoglobinemia, or “blue baby syndrome,” in infants. Nitrate runoff into surface waters, such as rivers and lakes, can lead to eutrophication, where excessive nutrients cause algae blooms that deplete oxygen levels, harming aquatic life and disrupting ecosystems^{50,51}. Hence, it is critical to closely monitor the N dynamics in the soil to mitigate these impacts.

Therefore, this study was designed to enhance NUE of wheat by utilizing coated urea fertilizers. In the laboratory experiments, the performance of standard urea granules was compared with 1.0% neem oil and 1.5% potassium ammonium phosphate coated urea. These specific coatings were selected based on their proven efficacy in ensuring a more consistent release of N, as observed in previous studies by Noor and colleagues⁵². Our lab findings indicated that the coated urea treatments exhibited significantly lower nitrification rates compared to uncoated urea. This reduction in nitrification can be attributed to the presence of nitrification inhibitory compounds in the coatings, particularly melacin and azadirachtin found in neem oil^{53,54}. These results are in accord with the Kumar and colleagues⁵⁵, who also demonstrated that lower concentrations of neem oil effectively improved NUE in irrigated rice⁵⁵.

In the present study, the coated urea treatments notably reduced N release efficiency (NRE) by decreasing the release of NH_4^+ , NO_3^- , and cumulative N in soil at earlier intervals. However, over time and with increasing temperature, the NRE of the coated urea improved. This phenomenon can be explained by the coating material acting as a physical barrier, which regulates the release of nutrients from the fertilizer granules. The coating materials has ability to slow the release of N was further validated by a model characterizing the kinetics of N release from coated urea⁵⁶. The environmental implications of heavily subsidized N fertilizers are also of significant concern. These fertilizers contribute to pollution by emitting gases such as NH_3 into the atmosphere. Ammonia is a toxic gas that poses health risks, causing cardiovascular problems in humans and animals, and negatively impacting crop growth⁵⁷. Although various techniques have been employed in the past to mitigate these losses, many were either prohibitively expensive for common farmers or difficult to implement⁵⁸. In the laboratory experiments, coated urea fertilizers were evaluated for their potential to reduce volatilization losses and ensure the effective use of these materials under different moisture and temperature conditions.

The data presented herein showed that both NH_3 and NO_3 releases were significantly increased from uncoated and coated urea with higher moisture and temperature levels. This increase can be attributed to the urea reacting with water in the presence of urease, with the coated materials' antimicrobial properties playing a role in reducing losses^{59–61}. The results are in accord with those of Ali and colleagues, who reported a decline in N losses from neem oil-coated fertilizers⁶². The significant reduction in NH_3 and NO_3 release from coated fertilizers, compared to uncoated urea, highlighted the efficacy of the coating materials (NOCU and PAPCU), with reductions of up to 90% at 10-day intervals. Although this reduction decreased at later intervals, the effect was still prominent, particularly with neem oil, which contains compounds that reduce urease activity in the soil^{63–65}.

Laboratory results showed that both coating agents decreased nitrification rates however, the performance of neem oil coating was better than PAPCU. Similar findings were mirrored in field trials, where the 75% of recommended NOCU yielded comparable or improved crop performance than 100% recommended un-coated urea. The field results showed that wheat yield, chlorophyll, and N content in plants were higher with all levels of coated urea compared to the control. Even at a reduced application rate (75% of the recommended dose), coated urea outperformed (100%) uncoated urea, providing a consistent N supply that supported vegetative and physiological plant functions^{66,67}.

The field trials, conducted in both irrigated and rainfed conditions, confirmed that neem oil-coated urea at 75% of the recommended rate resulted in the highest growth attributes, including shoot weight, grain yield, and biological yield. This improvement is likely due to the prolonged availability of N in the plant root zone, which is essential for vegetative growth and various metabolic processes^{68–70}. Higher chlorophyll content observed in wheat leaves treated with neem oil-coated urea further supports this, as N is a key component of chlorophyll^{71,72}.

The benefits of neem oil-coated urea are not limited to wheat. Similar positive outcomes have been reported for other crops, such as rice, where NOCU improved grain yield and NUE compared to conventional urea^{73–78}. The enhanced NUEs can be attributed to the coating materials acting as cation exchange sites, which facilitate better nutrient uptake by plants⁷⁹. Furthermore, it is important to highlight the broader implications of these findings. The ability of coated urea fertilizers to slow down the release of N has significant ramifications for sustainable agriculture. By reducing the frequency of fertilizer applications and minimizing N losses, farmers can achieve higher efficiency and lower costs, ultimately leading to more sustainable agricultural practices. Additionally, the reduction in N runoff and leaching into water bodies can help protect aquatic ecosystems and reduce the occurrence of algal blooms and other forms of water pollution. This aspect is crucial for maintaining the health of both natural ecosystems and human populations that rely on these water resources.

Overall, the neem oil-coated urea demonstrated superior performance over uncoated urea in enhancing wheat growth, yield, N concentration and NUE. The protective coating layer slows the release of N, allowing for more efficient use by crops⁸⁰. This study underscores the potential of coated urea fertilizers in improving NUE and reducing environmental impacts in agricultural practices. Future researcher should focus on optimizing coating formulations and testing in diverse agro-climatic conditions, as well as exploring the potential of integrating neem oil-coated urea with other sustainable agricultural practices such as precision farming, to enhance overall crop productivity and environmental sustainability. Furthermore, exploring the synergistic effects of combining coated urea with other sustainable agricultural practices, such as integrated nutrient management and precision farming, could provide a holistic approach to enhancing crop productivity and sustainability in agriculture.

Conclusions

The use of different coating agents, both natural and synthetic, improved nitrogen (N) release from urea compared to uncoated urea. Among the coating agents, NOCU (1.0%) performed better than PAPCU (1.5%) in decelerating ammonium (NH_4) and nitrate (NO_3) release. However, their release were increased with increasing temperature and moisture. The NOCU applied at 75% of the recommended conventional urea provided the best yield response and increased NUE, straw and grain N concentration, and total soil N under both irrigated and rainfed conditions. Therefore, coating urea with neem oil and its subsequent application at the rate of 75% of recommended urea can effectively improve urea utilization efficiency and improve crop yield in economical and eco-friendly manner under both irrigated and rain fed conditions.

Materials and methods

Preparation of coated urea in the laboratory

Coating of neem oil and potassium ammonium phosphate compound was carried out in the laboratory of department of soil and environmental sciences, UOS-Sargodha. Controlled conditions were maintained to avoid any contamination during these activities. The urea was coated using a rotary pan made of stainless steel. Granules of urea were weighed and added to the rotary pan. The coating ingredients (neem oil and potassium ammonium phosphate) were weighed out individually before being combined. Figure 6 indicates the water mist being supplied to the bed surface after the coating material and urea granules were mixed in rotary pan. This process was repeated until all the coating material and urea had been consumed. Finally, the urea granules were collected after being dried with a tiny fan and placed on a vibration tray. The ideal temperature for storing coated urea was 25 °C.

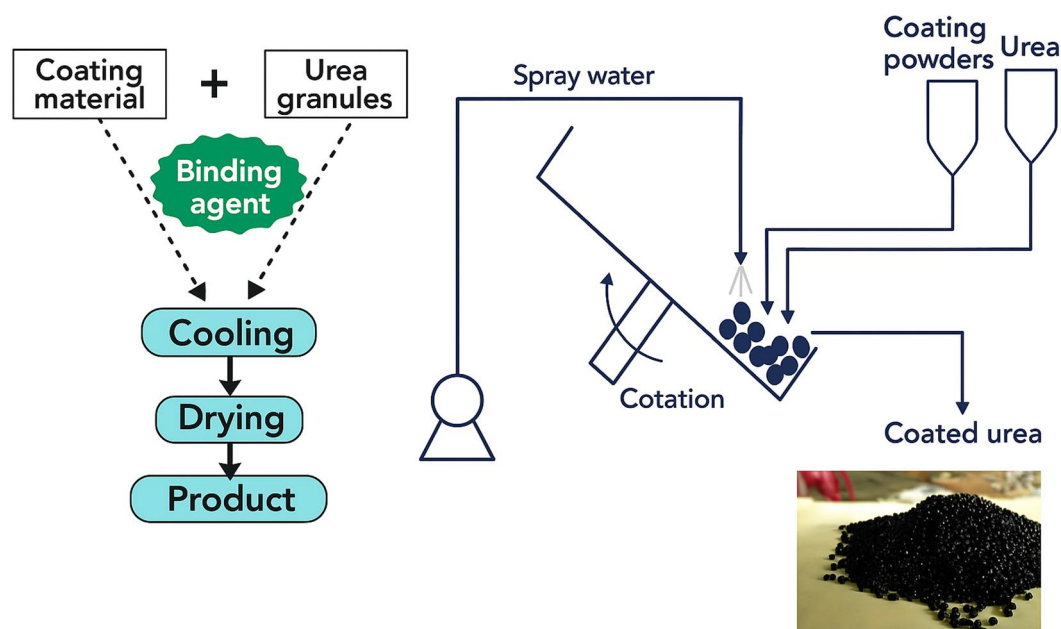


Fig. 6. Flow chart diagram of coating on urea granules with the help of urea coating machine.

Properties	Units	Sargodha	Chakwal
Textural class	–	Sandy clay loam	Sandy loam
Moisture %	%	30	35
ECe	dS m ⁻¹	1.85	2
pH	–	7.8	7.6
CEC	cmol _c kg ⁻¹	4.27	4.10
Organic matter	%	0.65	0.7
Total N	%	0.14	0.15
K	mg kg ⁻¹	106	95
P	mg kg ⁻¹	6.5	7

Table 3. Analysis of experimental soils.

Soil sampling and analysis

Soil samples were collected from the research area of COA, UOS by using the soil auger (0–15 cm depth). Random sampling was followed to collect 30 sub samples to make composite samples. These samples were prepared (dried, ground and sieved). Table 3 presents the analytical features of soils. Soil textural class was determined with the help of a hydrometer method⁸¹. The saturated soil paste was prepared and percentage of saturation was determined⁸². The pH of soil saturated paste was determined with the help of a pH meter (JENWAY 3510)⁸³. Pure extract of previously mentioned paste was taken using a vacuum pump extractor. By using the conductivity meter (JENWAY 4510), the electrical conductivity of extract was noted. Meter was calibrated by using the solution of 0.01 N KCl 83⁴⁵. For estimation of total N, protocol suggested by Jackson⁸⁴ was followed. Available phosphorus (P) was recorded on a spectrometer (T80 UV / VIS Spectrometer) using a wavelength of 880 nm⁸⁵. Similarly, a flame photometer (Jenway PFP-7) was used to analyze the K⁸⁶.

Laboratory incubation studies

The laboratory incubation studies were conducted at departmental laboratory of soil science using to check the effect of soil moisture content (30, 60 and 90% of field moisture capacity) and temperature regimes (25, 35 and 40 °C) on the performance of coatings material [NOCU (1.0% release), and PAPCU (1.5% release)] in optimizing urea hydrolysis and nitrification. Experiment was designed according to a completely randomized design (CRD) factorial design with three repeats. Three sets of treatments were run for the determination of NH₄⁺ and NO₃⁻ release at 10, 20 and 30 days intervals.

Field moisture capacity was established using retention curve method and soil moisture content was determined by the gravimetric method⁸⁷. Urea fertilizer were added in cups manually. Distilled water is used to maintain the weight of cups that have been filled with soil, fertilizer, and water. During the incubation, soil moisture content was maintained at field capacity after 24 h, NH_4^+ and NO_3^- release was measured after 10, 20 and 30 days of incubation through indophenol blue method and phenol disulphonic acid method⁸⁸.

Field experiment

Field experiments were performed using two factorial randomized complete block design (RCBD) with three replicates to further explore the performance of best coating agent (N0, 100% conventional urea, 75, 50 and 25% of the recommended NOCU) under irrigated and rainfed conditions using Akbar-2019 and Barani-2017 wheat cultivars respectively. The purpose of the field experiments was dose optimization of newly generated coated urea for wheat variety sown at particular location. The field experiment was performed at two locations. Location one was situated at experimental farm of the College of Agriculture, University of Sargodha, Sargodha (32.0740° N, 72.6861° E) where an irrigated wheat variety (Akbar-2019) was used as a test crop. Soil of the location one was taxonomically aridisols, haplargid, ustic, and hyper thermic. Maximum summer temperature is recorded as 50 °C (122 °F) and the lowest temperature at about freezing point in winter with an average temperature of about 24 °C, and annual average rainfall is about 410 mm⁸⁹. Similar experiment was established at location two situated at Naeem Zari farm Pind Dadan Khan, Chakwal (32.8322° N, 72.6151° E) where rainfed wheat cultivar (Barani-2017) was grown as test crop. The maximum summer temperature of location two was 40 °C and the lowest winter temperature of 4 °C. The average annual rainfall is ranging between 558 and 635 mm. Soil of location two was taxonomically alfisols, ustalfs, haplustalfs, aridic, and hyperthermic⁹⁰.

Urea was used as N source while single super phosphate (SSP) and potassium sulphate (SOP) were used as P and potassium (K) sources at the rate of 120: 90: 60 kg ha⁻¹ (N: P: K). P and K fertilizers were added as basal, while urea was applied in split doses. The method of application of coating materials in soil is manually broadcast. Flood irrigation method used in the experiment. Weeds were removed by manual hoeing. Plants were harvested and data regarding plant fresh, grain and biological yield were recorded. After the wet digestion, N content in different plant parts was measured using a Kjeldahl apparatus⁸⁸. NUE was calculated using following formula⁹¹.

$$\text{NUE} = \frac{(\text{Yield in fertilizer plot kg ha}^{-1}) - (\text{Yield in control plot kg ha}^{-1})}{\text{Quantity of applied N (kg ha}^{-1})}$$

Chlorophyll content was recorded using soil plant analysis development (SPAD) meter (Spad-502 chlorophyll meter, Konica Minolta Optics, Japan)⁹².

Statistical analysis

The data was analysed statistically following the Fisher's analysis of variance for CRD and the LSD test for comparison of treatment means⁹³.

Data availability

All data collected/used during this study are included in this published article.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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