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Subsurface-Applied Coated Nitrogen Fertilizer Enhanced Wheat Production by Improving Nutrient-Use Efficiency with Less Ammonia Volatilization

Muhammad Yaseen [1], Adeel Ahmad [1], Muhammad Naveed [1,*], Muhammad Asif Ali [2], Syed Shahid Hussain Shah [2], Muhammad Hasnain [2], Hayssam M. Ali [3], Manzer H. Siddiqui [3], Mohamed Z. M. Salem [4] and Adnan Mustafa [5,*]

1 Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad 38000, Pakistan; dryaseenuaf@yahoo.com (M.Y.); Adeelgujjar046@yahoo.com (A.A.)
2 Engro Fertilizers Limited, The Harbor Front Building, HC-3, Marine Drive, Block-4, Clifton, Karachi 75600, Pakistan; masifali@engro.com (M.A.A.); sshshah@engro.com (S.S.H.S.); muhasnain@engro.com (M.H.)
3 Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 2455, Saudi Arabia; hayhassan@ksu.edu.sa (H.M.A.); mhsiddiqui@ksu.edu.sa (M.H.S.)
4 Forestry and Wood Technology Department, Faculty of Agriculture (EL-Shatby), Alexandria University, Alexandria 21545, Egypt; zidan_forest@yahoo.com
5 Biology Center CAS, SoWa RI, Na Sadkach 7, 370-05 České Budějovice, Czech Republic
* Correspondence: muhammad.naveed@uaf.edu.pk (M.N.); adnanmustafa780@gmail.com (A.M.)

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Abstract: Nitrogen (N) is an essential plant nutrient, therefore, N-deficient soils affect plant growth and development. The excessive and unwise application of N fertilizers result in nutrient losses and lower nutrient use efficiency that leads to the low crop productivity. Ammonia volatilization causes a major loss after N fertilization that causes environmental pollution. This experiment was conducted to evaluate the effectiveness of coating and uncoating N fertilizer in enhancing yield and nutrient-use efficiency with reduced ammonia emissions. The recommended rate of nitrogen and phosphorus, urea and di-ammonium phosphate (DAP) fertilizers were coated manually with 1% polymer solution. DAP (coated/uncoated) and potassium were applied at the time of sowing as subsurface application. While urea (coated/uncoated) was applied as surface and subsurface application. Results showed that nutrient use efficiencies of wheat were found to be maximum with the subsurface application of coated N fertilizer which increased nutrient-use efficiency by 44.57 (N), 44.56 (P) and 44.53% (K) higher than the surface application of uncoated N fertilizer. Ammonia emissions were found the lowest with subsurface-applied coated N fertilizer. Thus, coated fertilizer applied via subsurface was found the best technique to overcome the ammonia volatilization with an improvement in the yield and nutrient-use efficiency of wheat.

Keywords: N fertilizer; subsurface application of N; surface application of N; polymer coated fertilizer; ammonia volatilization; nutrient use efficiencies; yield of wheat

1. Introduction

Synthetic nitrogen (N) fertilizer application in croplands changes greenhouse gas emissions, water quality, the global nutrient budget, and feedback to the climate system, in addition to increasing agricultural output. However, existing Earth system and land surface modelling studies must disregard or employ oversimplified data (e.g., static, spatially uniform fertilizer use) to characterize agricultural N input across decadal or century-long periods due to a lack of geographic fertilizer input data [1]. Nitrogen fertilizer is widely used to increase crop production in arable land [2,3]. N supply in excess of the crop's demand leads to N losses as $NO_3^- - N$ leaching [4–6], NH_3 volatilization [7,8], $N_2O/NO/N_2$ emission [9,10], etc., resulting in non-point-source pollution [11] global warming [12] and other negative environmental impacts. Among these losses, major N loss is via ammonia volatilization [13–15]. Therefore, it's critical to improve strategies in order to reduce negative environmental effects while sustaining crop yields [16].

Wheat (*Triticum aestivum* L.) is the most widely grown crop in temperate climates, and used for both human and cattle feed. Wheat provides the human diet with important vitamins, minerals, and amino acids, as well as beneficial dietary fiber and phytochemicals, which are particularly abundant in whole-grain products [17]. Wheat production feeds millions of people around the world and is largely reliant on adequate nitrogen supply. Nitrogen is a major nutrient that restricts the productivity of wheat [18]. There is also a lot of variation in how wheat cultivars acquire and use nitrogen to produce higher yields [19]. Thus, applying the correct rate of nitrogen fertilizer is regarded as a main means of raising wheat grain yield, enhancing N uptake and use efficiency, but N-losses due to volatilization leads to reduced yield and nutrient-use efficiency of wheat [20].

To enhance nitrogen-use efficiency (NUE) and minimizing N losses effectively, several strategies have been employed in recent years [21]. Use of urease and nitrification inhibitors is an effective technique in minimizing the N losses [22], but urease and nitrification inhibitors are too expensive for common farmer [23]. Breeding approaches are also employed for enhancing nitrogen fixation but this is a time-consuming process [24]. To avoid the negative environmental consequences of urea application, it is recommended to use controlled release urea (CRU). At soil pH $\geq$ 6.0, CRU effectively reduces N_2O emissions and NH_3 volatilization [25]. Blending urea reduces the ammonia volatilization losses very effectively up to 17–20% as compared to the uncoated urea [26]. Polymer coating of urea is a cheaper and effective technique to lower the N losses, and for enhancing the nitrogen-use efficiency [27,28]. Polymer coated urea significantly enhanced the corn yield and nitrogen-use efficiency by lowering the N losses [29].

The NH_3 loss is significantly decreased when administered at planting or as a side-dress in comparison to broadcasting [30]. Deep placement of urea is also an effective technique in lowering N losses and enhancing nitrogen-use efficiency [31], but the subsurface application of polymer-coated urea has not been examined so far. At high temperature conditions, the efficiency of surface-applied N fertilizers is affected [32]. So, under such conditions, subsurface application of polymer coated N fertilizer could be a much more beneficial approach. Based on these facts the present study hypothesized that coated nitrogen fertilizer along with the right application method might be effective in influencing the yield and nutrient-use efficiency of wheat by lowering ammonia emission losses. The objective of the study was to reduce the ammonia-volatilization-induced N losses with an increase in the yield and nutrient-use efficiency of wheat by applying coated fertilizer via surface and subsurface application.

2. Materials and Methods

2.1. Experimental Site and Treatments

The present experiment was conducted during 2020–2021 at the research area (situated at latitude 30°30′ and 32°0′ N and longitude 72°0′ and 73°45′ E) of Institute of Soil and Environmental Sciences (ISES), University of Agriculture, Faisalabad (UAF) with the collaboration of Engro Fertilizer Company (Pvt.) Ltd. (Clifton Karachi, Pakistan). The experiment was designed following randomized complete block design (RCBD) under field conditions keeping plot size 8 $\times$ 9 m. Treatment plan consisted of: control (without fertilizer), surface-applied uncoated N fertilizer, surface-applied coated N fertilizer, subsurface-applied uncoated N fertilizer, and subsurface-applied coated N fertilizer. All treatments were replicated thrice. Coating of commercial urea and di-ammonium phosphate (DAP) fertilizers was performed at Soil Fertility and Plant Nutrition Laboratory (SFPNL), ISES, UAF as described by Noor et al. [33] and Khalid et al. [34]. For coating, polymer solution (polycarbonyldiamide; 1%) in distilled water was prepared and blended with the fertilizer manually and dried under the laboratory conditions. The used polycarbonyldiamide is an ecofriendly copolymer and also a good absorbent of water.

Therefore, when exposed to moisture, the size of the fertilizer granule increases to facilitate diffusion absorption.

2.2. Field Experiment and Crop Management

Soil samples were collected from the field and analyzed for physiochemical properties (Table 1). After land preparation with cultivator and planker, seeds of wheat CV 'Faisalabad 2008' were sown using a drill at the seed rate of 100 kg ha^{-1}. The recommended dose of phosphorus at the rate of 90 kg P_2O_5 ha^{-1} was applied via DAP (both coated and uncoated forms) while subsurface application potassium (K) at the rate of 60 kg K_2O ha^{-1} (sulphate of potash) was applied at sowing time as. Each treatment received the same dose of potassium. The remaining N dose over DAP was applied through urea (both coated and uncoated forms) as surface and subsurface application following the treatment plan at the rate of 120 kg N ha^{-1}. Subsurface fertilizer application was done 3 to 4 cm below the soil surface. Coated and uncoated urea was applied at 20 days with first irrigation after sowing the crop. Subsurface urea was applied along with P and K sources, thus, no additional cost was required. In total, five irrigations were applied to the wheat crop at 25, 45, 65, 85 and 105 days after sowing. All irrigations were applied up to 3 acre inches. All other recommended agronomic practices were adopted as per need.

Table 1. Pre-analysis of the tested soil.

Properties	Unit	Readings
Sand	%	49.03 ± 2.07
Silt	%	27.40 ± 1.62
Clay	%	23.57 ± 1.56
Texture	-	Sandy Loam
Saturation Percentage	%	30 ± 2
ECe	dS m^{-1}	1.94 ± 1.1
pHs	-	7.87 ± 0.9
CEC	$cmol_c$ kg^{-1}	13.5 ± 1.09
Ca^{2+} + Mg^{2+}	me L^{-1}	10.11 ± 1.15
$SO_4{}^{-2}$	me L^{-1}	9.86 ± 0.82
Cl^{-1}	me L^{-1}	12.70 ± 2.01
$HCO_3{}^{-1}$	me L^{-1}	2.49 ± 0.67
$CO_3{}^{-2}$	me L^{-1}	0.31 ± 0.21
Organic matter	%	0.78 ± 0.77
Soluble Na	me L^{-1}	16.86 ± 2.1
Extractable P	mg kg^{-1}	6.10 ± 0.95
Soluble K	me L^{-1}	0.04 ± 0.01

2.3. Measurement of Ammonia Emission

Static chambers were installed in each plot for the measurement of ammonia gas. Sulfuric acid (0.5 N) traps were placed in the chambers for trapping ammonia that was later analyzed with Kjeldahl apparatus after 20 days interval following the method of Bremner and Douglas [35]. The traps in chambers were changed after every 20-day interval.

2.4. Evaluation of Growth, Yield and Nutrient Use Efficiencies of Wheat

At the crop's physiological maturity, the chlorophyll contents were recorded using a SPAD meter. Plant height and spike length were measured using a meter rod. After harvesting of wheat crop, number of fertile, unfertile and total tillers per meter square area were counted and yield components (grain yield, straw yield and biological yield weighed using a weighing balance) of wheat were noted. Nutrient agronomic use efficiencies were calculated using the following formulae:

$$\text{N agronomic use efficiency} = \frac{\text{Yield of N fertilized plot}\left(\text{kg ha}^{-1}\right) - \text{Yield of control plot}\left(\text{kg ha}^{-1}\right)}{\text{Amount of N applied}\left(\text{kg N ha}^{-1}\right)}$$

$$\text{P agronomic use efficiency} = \frac{\text{Yield of P fertilized plot}\left(\text{kg ha}^{-1}\right) - \text{Yield of control plot}\left(\text{kg ha}^{-1}\right)}{\text{Amount of P applied}\left(\text{kg P ha}^{-1}\right)}$$

$$\text{K agronomic use efficiency} = \frac{\text{Yield of K fertilized plot}\left(\text{kg ha}^{-1}\right) - \text{Yield of control plot}\left(\text{kg ha}^{-1}\right)}{\text{Amount of K applied}\left(\text{kg K ha}^{-1}\right)}$$

2.5. Plant Analysis and Nutrient Recoveries

Chemical analysis for N, P and K concentrations in the grain, straw and roots were performed at SFPN, ISES, UAF. Grain, straw and root samples were digested following method proposed by Wolf [36] by using sulfuric acid and hydrogen peroxide. Nitrogen concentration from digested plant samples was estimated following the Kjeldahl method [37]. Phosphorus and potassium were determined using methods described by Olsen [38] and Chapman and Pratt [39], respectively. Nutrient recovery use efficiencies were calculated using following Equations.

$$\text{N recovery use efficiency} = \frac{\text{N uptake by fertilized grains} - \text{N uptake by unfertilized grains}}{\text{Amount of N applied}\left(\text{kg N ha}^{-1}\right)}$$

$$\text{P recovery use efficiency} = \frac{\text{P uptake by fertilized grains} - \text{P uptake by unfertilized grains}}{\text{Amount of P applied}\left(\text{kg P ha}^{-1}\right)}$$

$$\text{K recovery use efficiency} = \frac{\text{K uptake by fertilized grains} - \text{K uptake by unfertilized grains}}{\text{Amount of K applied}\left(\text{kg K ha}^{-1}\right)}$$

Here nutrient uptake for N, P and K were calculated using following Equation.

$$\text{Nutrient uptake by grains} = \frac{\text{Nutrient concentration in the grain} * \text{Grain yield}}{100}$$

2.6. Statistical Analysis

All the collected data were analyzed using Statistics 8.1 software and mean comparison was conducted following the least significant difference (LSD) test at alpha = 0.05 for homogeneous groups.

3. Results

3.1. Agronomic Traits

Table 2 explained the changes in plant height, spike length, number of spikelets per spike and tiller count per square meter area of wheat in response to coated and uncoated fertilizers applied via surface and subsurface application methods. In comparison to control (no fertilizer applied) all treatments significantly enhanced plant height, spike length and number of spikelets per spike. Among surface and subsurface application methods of N fertilizer, subsurface application of coated urea resulted in 3, 4 and 5% higher plant height, spike length and number of spikelets per spike than surface-applied coated urea, respectively, while, over traditional N fertilizer application (surface-applied uncoated N fertilizer), subsurface-applied coated N fertilizer yielded 6, 18 and 28% higher plant height, spike length and number of spikelets per spike, respectively.

The number of fertile, unfertile and total tillers were recorded in an area of meter square for plots treated with coated and uncoated fertilizers as surface and subsurface (Table 2). The highest number of unfertile tillers (18.33) was recorded in treatment of subsurface-applied uncoated N fertilizer, while coated N fertilizers applied through same method significantly reduced this number. Total number of tillers and fertile tillers were slightly higher in treatments of coated N fertilizers applied in both methods of application. Number for total tillers and fertile tillers was 15 and 16%, respectively, higher with the subsurface application of coated N fertilizer than surface-applied uncoated N fertilizer.

Table 2. Impact of method of application of coated and uncoated N fertilizer on agronomic traits of wheat.

Treatment	**Agronomic Traits**					
	Plant Height (cm)	**Spike Length (cm)**	**Number of Spikelets per Spike**	**Tillers Count per Square Meter**		
				Total	**Unfertile**	**Fertile**
Control	77 ± 2.08 ^{B}	12.33 ± 0.88 ^{B}	14 ± 0.58 ^{C}	179 ± 10.23 ^{C}	9.33 ± 1.33 ^{B}	169.67 ± 9.22 ^{C}
Surface-applied UF	97.67 ± 0.88 ^{A}	14.67 ± 0.88 ^{AB}	15.67 ± 1.33 ^{BC}	336.33 ± 9.07 ^{B}	12.33 ± 0.88 ^{B}	324 ± 8.34 ^{B}
Surface-applied CF	100.33 ± 1.86 ^{A}	16.67 ± 1.2^{A}	19 ± 1.16 ^{A}	367.67 ± 12.68 ^{AB}	12.33 ± 1.45 ^{B}	355.33 ± 11.36 ^{AB}
Subsurface-applied UF	99.67 ± 1.45 ^{A}	15 ± 1.0 ^{AB}	16.67 ± 0.88 ^{B}	342.67 ± 5.7 ^{B}	18.33 ± 1.67 ^{A}	324.33 ± 4.92 ^{B}
Subsurface-applied CF	103.33 ± 2.61 ^{A}	17.33 ± 0.88 ^{A}	20 ± 1.0 ^{A}	388.33 ± 12.05 ^{A}	12.67 ± 0.88 ^{B}	375.67 ± 11.62 ^{A}

Note: UF = uncoated N fertilizer, CF = coated N fertilizer; Letters in superscript shows statistical significance among respective parameters.

3.2. Chlorophyll Contents

Chlorophyll contents in terms of SPAD values were significantly affected with the application of coated N fertilizers. In both surface and subsurface application methods, chlorophyll contents were 39 and 25% higher with coated N fertilizers than uncoated N fertilizers, respectively (Figure 1a). Comparing methods of application in uncoated and coated N fertilizers separately gave nonsignificant results.

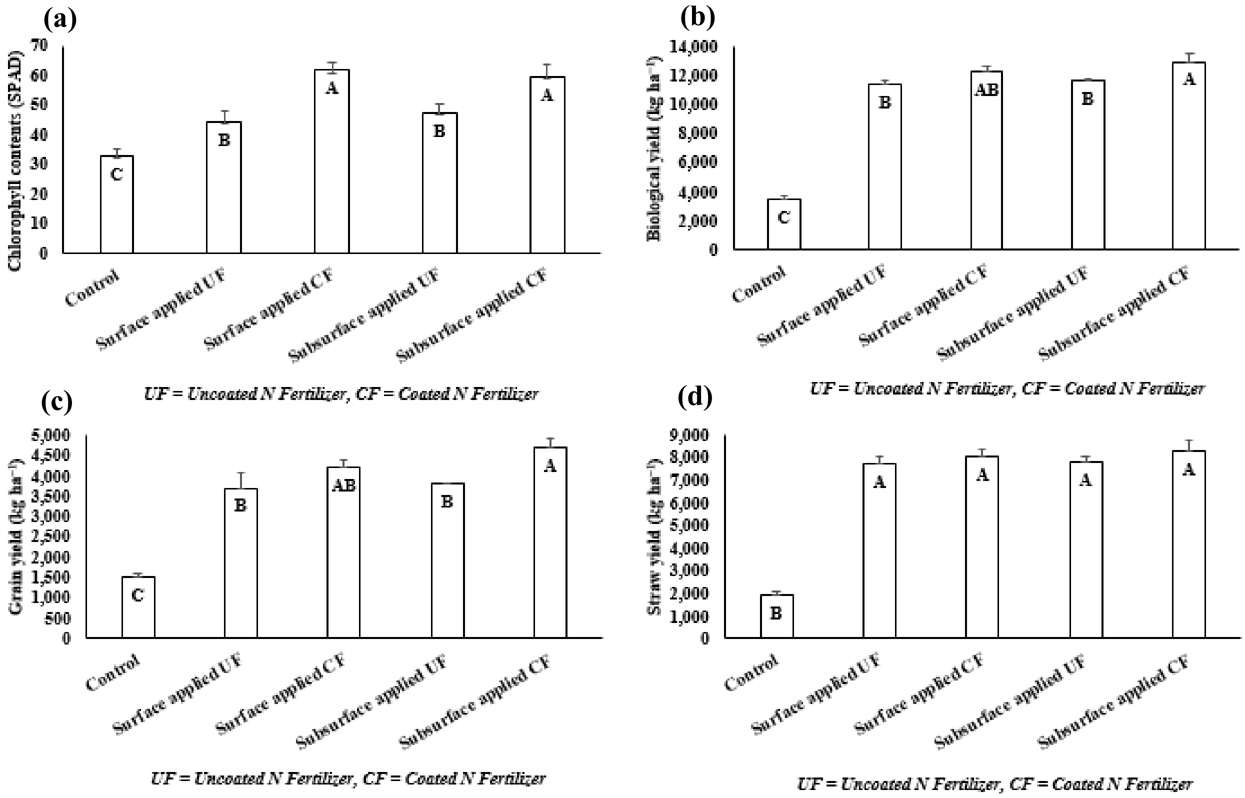

Figure 1. Impact of method of application of coated and uncoated N fertilizer on chlorophyll contents and yield attributes of wheat. (**a**) Shows chlorophyll contents, (**b**) shows biological yield, (**c**) shows grain yield and (**d**) shows straw yield of wheat. Letters shows statistical significance among respective parameters.

3.3. Crop Yield

Figure 1b–d indicate the influence of method of application for coated and uncoated N fertilizers on biological yield, grain yield and straw yield of wheat. The subsurface-applied coated N fertilizers resulted in 13, 26 and 7% higher biological, grain and straw yield values than the surface-applied uncoated N fertilizer. The surface-applied coated N fertilizer gave 7, 14 and 4% higher biological, grain and straw yield than surface-applied uncoated fertilizer, respectively. Differences among treatments were small in terms of straw yield that gave nonsignificant results but grain yield and biological yield were significantly affected by the treatment sets. However, the control gave the lowest values for all yield components.

3.4. Nutrient Concentration in the Plant Parts of Wheat

Table 3 shows N concentration in the grain, straw and roots of wheat plants fertilized with different methods of application for coated and uncoated N fertilizers. Minimum concentration of N was detected in all parts of plants treated with no fertilizer (control). Coated N fertilizer showed a significant influence on N concentration in both methods of fertilizer application over uncoated N fertilizer by enhancing N concentration in wheat grain, straw and root up to 33, 46 and 34% over surface-applied and 26, 43 and 47% over subsurface-applied uncoated N fertilizer, respectively. However, the highest N concentration in wheat grain, straw and root was observed where coated N fertilizer was applied via the subsurface application that was 57, 59 and 65% in grain, straw and root respectively over surface-applied uncoated N fertilizer.

Methods of application of coated N fertilizer showed a significant influence on the P concentration in grain, straw and roots of wheat (Table 3). The highest P concentration in the grain, straw and roots was observed when wheat plants received coated N fertilizer through subsurface application. The concentration of P in the grain, straw and roots was 40, 35 and 6% higher over subsurface-applied uncoated N fertilizer, respectively. In grains, P concentration with subsurface-applied coated N fertilizer was 24% higher over all other treatments including surface-applied coated N fertilizer. While in straw and roots the difference between P concentration from surface-applied and subsurface-applied coated N fertilizer was nonsignificant, although a slight difference was found. In roots, P concentration was nonsignificant among subsurface-applied uncoated and coated N fertilizer.

Potassium concentration in the wheat grain, straw and root was found to be maximum where the subsurface application of coated N fertilizer was ensured. In wheat straw, K concentration was nonsignificant among surface-applied uncoated N fertilizer, surface-applied coated N fertilizer, subsurface-applied uncoated N fertilizer and subsurface-applied coated N fertilizer, though small differences were observed. While in case of grain and root, K concentration was significantly different among all treatments (Table 3). Surface applied coated N fertilizer significantly enhanced K concentration in wheat grain and root up to 19 and 18%, respectively, over surface-applied uncoated N fertilizer. While subsurface-applied coated N fertilizer improved K concentration in grain and root of wheat up to 18 and 22% than subsurface-applied uncoated N fertilizer, respectively. Overall, subsurface-applied coated N fertilizer induced 29, 12 and 32% more K in wheat grain, straw and root, respectively than surface-applied uncoated N fertilizer.

Table 3. Impact of method of application of coated and uncoated N fertilizer on N, P and K concentrations in different parts of wheat plants.

Treatment	N Concentration in the Plant Part (%)			P Concentration in the Plant Part (%)			K Concentration in the Plant Part (%)		
	Grain	**Straw**	**Root**	**Grain**	**Straw**	**Root**	**Grain**	**Straw**	**Root**
Control	0.31 ± 0.03 ^{D}	0.24 ± 0.01 ^{E}	0.44 ± 0.01 ^{E}	0.33 ± 0.03 ^{D}	0.39 ± 0.02 ^{D}	0.52 ± 0.04 ^{C}	0.47 ± 0.003 ^{E}	0.58 ± 0.04 ^{B}	0.62 ± 0.007 ^{E}
Surface-applied UF	0.86 ± 0.06 ^{C}	0.61 ± 0.01 ^{D}	0.85 ± 0.01 ^{D}	0.82 ± 0.03 ^{C}	0.76 ± 0.01 ^{C}	1.97 ± 0.06 ^{B}	0.77 ± 0.006 ^{D}	1.75 ± 0.05 ^{A}	2.03 ± 0.003 ^{D}
Surface-applied CF	1.05 ± 0.02 ^{B}	0.89 ± 0.01 ^{B}	1.14 ± 0.03 ^{B}	0.95 ± 0.02 ^{B}	0.87 ± 0.01 ^{AB}	2.18 ± 0.03 ^{A}	0.92 ± 0.01 ^{B}	1.91 ± 0.06 ^{A}	2.41 ± 0.06 ^{B}
Subsurface-applied UF	1.04 ± 0.03 ^{B}	0.68 ± 0.01 ^{C}	0.95 ± 0.01 ^{C}	0.83 ± 0.03 ^{C}	0.77 ± 0.01 ^{BC}	2.15 ± 0.06 ^{A}	0.84 ± 0.003 ^{C}	1.87 ± 0.05 ^{A}	2.195 ± 0.02 ^{C}
Subsurface-applied CF	1.35 ± 0.03 ^{A}	0.97 ± 0.01 ^{A}	1.40 ± 0.06 ^{A}	1.18 ± 0.03 ^{A}	0.97 ± 0.07 ^{A}	2.18 ± 0.03 ^{A}	0.99 ± 0.006 ^{A}	1.96 ± 0.11 ^{A}	2.68 ± 0.03 ^{A}

Note: UF = uncoated N fertilizer, CF = coated N fertilizer; Letters in superscript shows statistical significance among respective parameters.

3.5. Nutrient Use Efficiencies

3.5.1. Agronomic Nutrient Use Efficiencies

Coated N fertilizers enhanced the agronomic nitrogen-use efficiency of wheat as compared to their respective uncoated fertilizer application. Subsurface-applied N fertilizers proved best by giving 4.58% higher agronomic nitrogen-use efficiency value than the standard surface application method of uncoated N fertilizer. Surface- and subsurface-applied coated N fertilizer enhanced agronomic N-use efficiency up to 23.35 and 44.57% as compared to the surface-applied uncoated N fertilizer, respectively (Figure 2a). A similar trend was also seen for phosphorus and potassium agronomic use efficiencies in (Figure 2b,c). Subsurface application of coated N fertilizer showed a strong influence on the agronomic use efficiencies of phosphorus and potassium in addition to nitrogen. As the highest agronomic use efficiencies of phosphorus (35.33 kg kg^{-1}) and potassium (53 kg kg^{-1}) were noted with subsurface-applied coated N fertilizers. Surface applied coated N fertilizer improved phosphorus and potassium agronomic use efficiencies up to 23.36 and 23.32% as compared to the surface-applied uncoated N fertilizer.

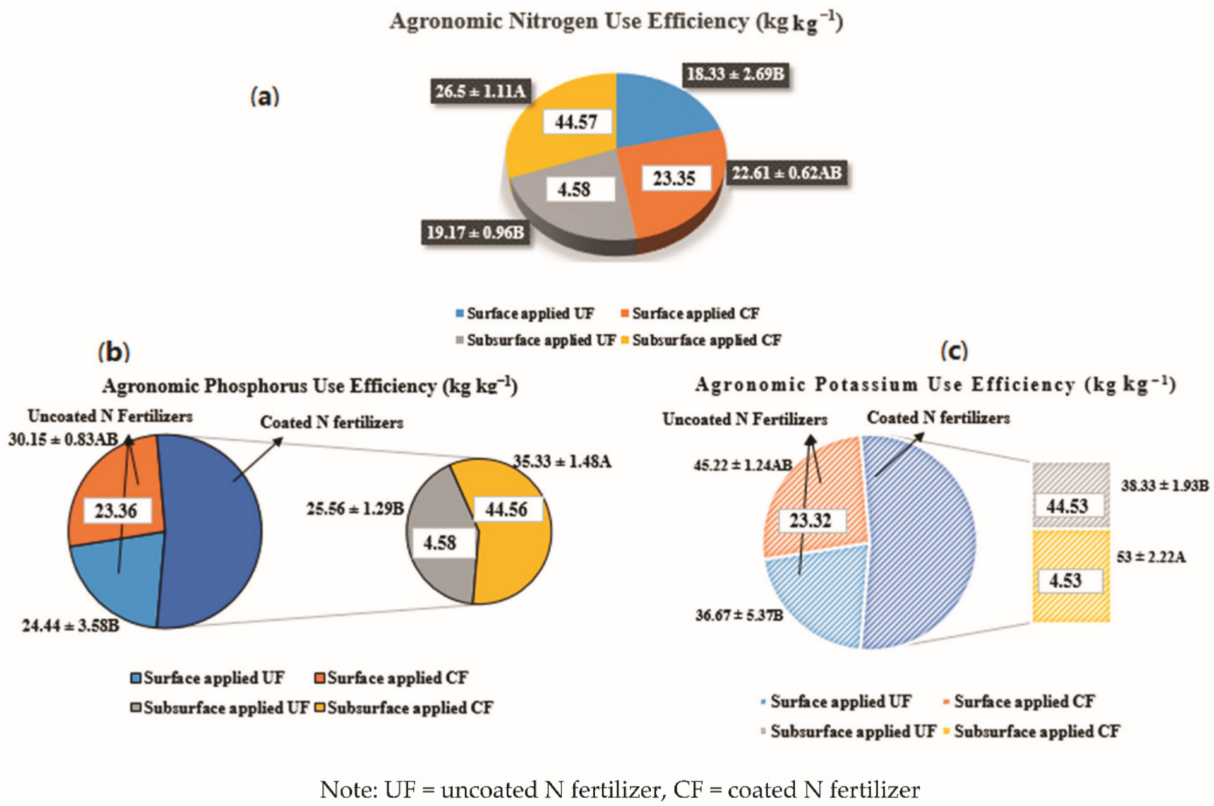

Figure 2. Impact of method of application of coated and uncoated N fertilizer on agronomic nutrient use efficiencies (kg kg^{-1}) of wheat. (**a**) Shows agronomic nitrogen-use efficiency, (**b**) shows agronomic phosphorus-use efficiency, (**c**) shows agronomic potassium-use efficiency. The figure also illustrates percent increase in agronomic nutrient use efficiencies due to proposed approaches for N application over standard N application 'surface-applied uncoated N fertilizer'. Letters shows statistical significance among respective parameters.

3.5.2. Recovery Nutrient Use Efficiencies

Recovery nitrogen-use efficiency in the wheat grains was directly influenced by the methods of coated and uncoated N fertilizer application (Figure 3a). Recovery N-use efficiency was the lowest with surface-applied uncoated N fertilizer that was significantly improved by subsurface application of uncoated N fertilizer (37%). Coated N fertilizer applied via surface and subsurface application further improved the recovery of N (64 and 124%, respectively) in wheat grains. As depicted in Figure 3b, recovery P-use efficiency of wheat grains was also strongly influenced by the method of application of both coated and uncoated N fertilizer. The highest recovery P-use efficiency was observed with the subsurface application of coated N fertilizer (86% over subsurface-applied uncoated N fertilizer) followed by surface-applied coated N fertilizer (39% over surface-applied uncoated N fertilizer). Among uncoated fertilizers, subsurface-applied N fertilizer gave nonsignificant results to that of surface-applied. Figure 3c shows recovery potassium-use efficiency of wheat grain. Though uncoated N fertilizer applied via surface and subsurface method showed nonsignificant results, coated N fertilizers improved recovery K-use efficiency significantly over uncoated N fertilizer in both application methods. Even, subsurface application of coated N fertilizer further improved recovery K-use efficiency (83% over surface-applied uncoated N fertilizer).

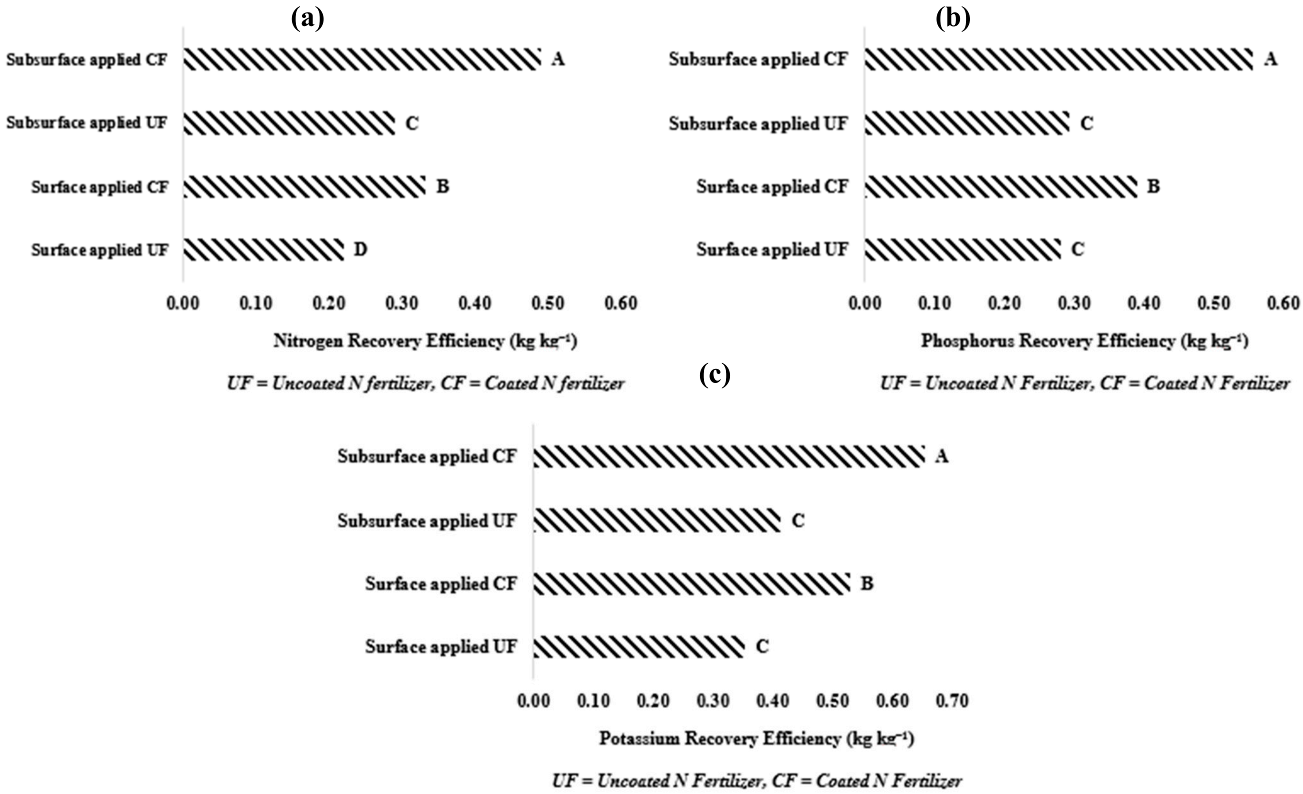

Figure 3. Impact of method of application of coated and uncoated N fertilizer on nutrient recovery-use efficiency (kg kg^{-1}) of wheat. (**a**) Shows recovery nitrogen-use efficiency, (**b**) shows recovery phosphorus-use efficiency, (**c**) shows recovery potassium-use efficiency. Letters shows statistical significance among respective parameters.

3.6. Ammonia Emission

Volatilization of the ammonia gas from all treatments at all intervals is indicated in (Figure 4). Ammonia emission was recorded the highest when surface uncoated N fertilizer applied at the first interval, which was reduced significantly at the latter intervals but was still much higher in comparison to the coated N fertilizer treatments. At the first interval second-highest ammonia emission was noted with subsurface-applied uncoated N fertilizer. Coated N fertilizers significantly reduced the ammonia emission at all intervals with both methods of application. However, ammonia emission was noted lowest with the application of subsurface coated N fertilizer after control (no fertilizer) at all intervals. The trend line indicates that ammonia emission was reduced with the application of uncoated N fertilizers at later intervals but was still much higher than coated N fertilizer treatments.

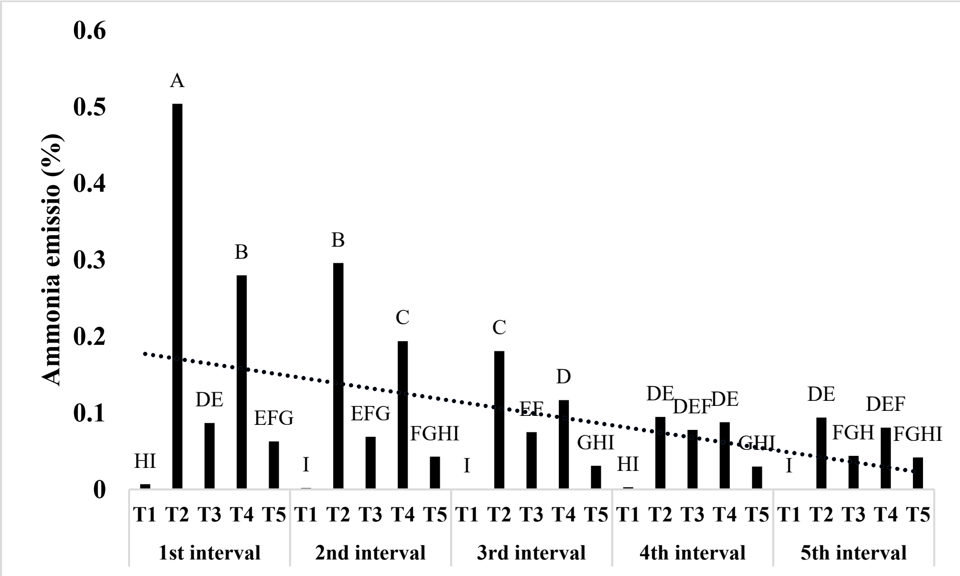

Figure 4. Impact of method of application of coated and uncoated N fertilizer on ammonia emission (%) every 20 days up to 100 days. Coated and uncoated urea applied at 20 days with first irrigation after sowing indicated impact on ammonia emission at first and onward intervals. The line showed more or less decreasing trend in ammonia emission with time due to effect of treatments (T1 = control (without fertilizer), T2 = surface-applied uncoated N fertilizer, T3 = surface-applied coated N fertilizer, T4 = subsurface-applied uncoated N fertilizer, T5 = subsurface-applied coated N fertilizer. Letters shows statistical significance among respective parameters.

4. Discussion

Ammonia is a principal two nitrogen-containing compound that is lost from applied fertilizer due to ammonia volatilization, resulting in environmental pollution as well as lower yields and crop nutrient-use efficiency [40]. Various methods have previously been used to reduce nitrogen losses and improve nutrient utilization efficiency [41]. Polymer coating of the conventional N fertilizers is one of the most effective techniques for reducing N losses and enhancing nitrogen-use efficiency [42]. Benlamlih et al. [43] described that biodegradable polymer coated N fertilizers reduced N_2O and leaching losses of N under heavy rain fall events.

The use of coated N fertilizers, both as surface and subsurface applications, dramatically reduced ammonia emissions (Figure 4). The reduction in ammonia emissions with the use of coated N fertilizer could be attributed to the ammoniacal N being exposed to the atmosphere less. The ammonium produced from applied N fertilizer undergoes four different processes: it is (1) taken up by the plant, (2) converted to nitrate through nitrification, (3) fixed in the soil colloids, and (4) volatilized in the form of ammonia [44]. When there is maximum utilization of applied N fertilizer by the crop plants, there is least chance for other fates. As in our study we observed a higher recovery use efficiency of applied coated N fertilizer in accordance with the results of several researchers, the least ammonia emission might be an outcome of this maximal utilization of N. Ammonia emission was significantly reduced by coating the N fertilizer due to maximum utilization of applied N [45]. Subsurface application of coated N fertilizer further reduced the ammonia volatilization (Figure 4), as N utilization by plants was also increased with this application method. So, the protection from atmospheric interaction induced by subsurface application of coated N fertilizer might have protected ammonium from getting lost via ammonia volatilization. The subsurface placement of N fertilizer was the effective method to decline in the gaseous emission from N fertilizer under field conditions [46].

Our results show that the subsurface application of coated N fertilizers was found more effective in significantly improving plant growth attributes (plant height, spike length, number of spikelets per spike and tiller count per square meter) as compared to traditional surface-applied uncoated N fertilizer (Table 2). The long term N availability to plants is necessary to enhance the vegetative growth of the plants, as optimum N availability promotes the biosynthesis of carbohydrates that could be utilized for the development of top portion of the plants. Therefore, the subsurface application of coated N fertilizer might be the main reason for the long-term N availability to wheat plants, resulting in improved growth performance. Our results are in line with Ghafoor et al. [47] who reported higher number of tillers and subsequent yield of wheat with the application of controlled release N fertilizer. Subsurface application gave more promising results which might be due to the least interaction of released nutrient to the atmosphere. Other researchers have reported that deep placement of N fertilizer improved the growth and biomass of plants [48–50].

At the physiological maturity of wheat plants, chlorophyll contents in wheat leaves were found higher in coated N fertilizer treatments than uncoated fertilizer (Figure 1). Nitrogen is the structural part of the chlorophyll molecule, thus, a consistent supply of N is necessary for the proper development of the chlorophyll molecules. The controlled N release through coated N fertilizer might have influenced the synthesis of chlorophyll at physiological growth of wheat, as was observed in the present study. Consistent supply of N through coated N fertilizer and deep placement of N fertilizer enhanced the chlorophyll contents of wheat and fine rice, respectively [51,52].

Coated N fertilizer effectively improved the yield of wheat crop, as all yield components including grain yield, straw yield and biological yield were found significantly higher with subsurface application in comparison to the surface-applied N fertilizers (Figure 1). In the soil system, N goes for several interactions with other nutrients. The prevention of direct exposure of N fertilizer to the atmosphere through the application of subsurface-coated N fertilizer might have caused the lower losses of N, resulting in more N present in soil that caused synergistic interactions with other nutrients especially micronutrients that accounted for higher yield performance of crops. Nitrogen plays a role in the higher production of crops directly, but due to its synergistic interactions with other nutrients, its effect amplifies to a higher level. As DAP was also coated for estimating the ammonia emission from coated fertilizers, so the increase in yield could also be due to greater P availability from coated DAP. The gaseous emission from N fertilizer was reduced significantly by the deep placement of N fertilizer resulting in a higher yield of rice crop [31]. In the present study, use of coated N fertilizer as subsurface application further enhanced the yield of wheat possibly due to the least damage to seedling by closely placed N fertilizer grain. A toxic concentration of an essential nutrient present near the roots of the seedling might harm its growth, resulting in a decreased crop yield. The coating layer could protect the roots from direct contact to the higher concentration of nutrients leading to the more vigorous growth of plants. So, this might be the fact behind the increase in the yield by the application of coated N fertilizer. Similar to our findings, the maize yield was found to be significantly higher with the application of coated N fertilizers in comparison to the uncoated N fertilizers [53].

Nutrient uptake by the plant was also influenced by the application of coated N fertilizers, therefore N, P and K concentrations were found to be higher in different plant parts of the wheat in coated treatments than uncoated treatments (Table 3). The application method directly influences nitrogen uptake as was revealed in the present study. Surface application of uncoated N fertilizer showed the least N concentration in all tested parts of wheat plant while coated N fertilizer and subsurface application improved its concentration. Maximum N concentration in plant parts was seen with subsurface-coated N fertilizer. This could owe to more N availability in the root zone soil and minimum N losses to the surrounding environment. Folina et al. [54] reported higher uptake by the field crops with coated N fertilizers. Likewise, deep placement of N fertilizer also enhanced N uptake by the rice crop [55]. More interestingly, phosphorus and potassium concentrations in plant parts were also influenced by N fertilizer application, and their highest concentrations in plant parts were also seen with subsurface application of coated N fertilizer (Table 3). This might be due to the changes induced in the soil microenvironment under the influence of ion exchange mechanism between plant roots and available N in the soil. Plants usually use N to mobilize P from organic sources and fixed P complexes, as ammonium formed from applied N fertilizer is a cationic form of N [56]. When a plant uptakes the cationic form, it releases hydrogen ion in an exchange mechanism, which creates acidic conditions in the soil system. Moreover, the process of conversion of urea to ammonium also creates acidic conditions in the soil system [57]. So, this changed environment might undergo higher concentration of P in the plant parts by solubilizing the fixed P in the soil. The urea and ammonium nitrate fertilizer contributed to a decline in the soil pH [58]. Likewise, a decline in soil pH has an enormous impact on plant nutrition [59]. N also plays a role in the acquisition of K in higher plants, thus increase in the K concentration in plant parts might be the consequence of this interaction between N and K. Similar to our findings, Fageria and Oliveira [60] and Milford and Johnston [61] reported a synergistic interaction between N and K in rice, wheat and other field crops.

In the present study, agronomic and recovery nitrogen use efficiencies were found to be at their maximum with the subsurface application of coated N fertilizer (Figures 2 and 3), possibly due to the minimum N losses and maximum utilization of N released from fertilizer granule. The amount of accessible nitrogen in the soil causes the crop to absorb more nitrogen, which has a direct impact on the plant's physiological and metabolic processes. Plants with greater physiological and metabolical activities grow more vigorously, resulting in a higher yield. Similarly, higher N uptake leads to higher recovery nitrogen-use efficiency. Wu et al. [48] reported higher recovery use efficiency in rice due to the deep placement of N fertilizer. Similarly, in another study, slow-release N fertilizer improved the nitrogen-use efficiency of sunflower [62]. Phosphorus and potassium use efficiencies were also influenced by the method of application of coated and uncoated N fertilizer might be due to the activation of indigenous P and K solubilizing bacteria present indigenously in the soil. Polymer might be used as a food substrate for indigenous P and K solubilizing bacteria that lead to less fixation of P and K with counter ions and clay colloids. The improvement in the phosphorus-use efficiency could also be due to the long term availability of P in the soil from coated DAP, as coated DAP was applied along with coated urea. In line with our findings, Imran et al. [63] reported enhanced phosphorus-use efficiency due to glycine + polymer coated fertilizer in wheat. The use efficiencies of N, P and K were found higher with their simultaneous application in wheat and upland rice [60,64].

Overall, coated N fertilizers performed significantly better than uncoated N fertilizers under both the application methods. The coating material provides a physical barrier to the surrounding water and counter ion, protecting the internal contents from a reaction with these ions or water molecules. Thus, the performance of coated N fertilizers regarding increased growth, yield, nutrient use efficiencies and reduced ammonia emission might be due to this protection of nutrient induced by the coating layer. The slower release of N from the coated N fertilizer enhanced the nitrogen-use efficiency of wheat and other field crops [54,65]. In line with the method of N fertilizer application, the subsurface application was proved best for growth, yield and nutrient use efficiencies as compared to the surface-applied N fertilizer. Subsurface application might have caused minimum N losses by reducing the contact of nutrient to atmosphere, resulting better crop growth and nutrient use efficiencies. Gaseous loss of N was reduced with deep application of N fertilizer with an improvement in the biomass and yield of rice [66–68]. However, the combination of both techniques that involve the subsurface application of coated N fertilizer was found much fruitful in this study. Subsurface-applied coated N fertilizer ideally enhanced the growth, yield and nutrient-use efficiency with a significant reduction in the ammonia volatilization. The present strategy has the potential to not only improve the farmer's income and food quality but also protect the environment from toxic gasses emission like ammonia from the applied N fertilizers application.

5. Conclusions

The method of administration of coated and uncoated N fertilizer showed a strong influence on the growth, yield and nutrient use efficiencies of wheat in addition to the ammonia losses. Maximum reduction in the ammonia emission was observed with subsurface application of coated N fertilizer. Subsurface-applied coated N fertilizer not only maximized the nitrogen-use efficiency of wheat but also improved phosphorus and potassium use efficiencies maximally. Thus, subsurface application of coated N fertilizer was found to be the best approach to optimize the nutrient-use efficiency of crops. Moreover, subsurface application was also found more economical, as it was applied along with P and K at the time of sowing, avoiding split application during crop growth. However, the present experiment was a one-year study, and further studies are needed for a close insight to explore the exact mechanism at the biochemical and genetic levels. Studying the changes in the microbial population present in soil indigenously could further enhance the worth of this technique.

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