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Full Length Article

Neem Coated Urea Improves the Productivity, Nitrogen Use Efficiency and Economic Return of Wheat Crop

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Abstract

Neem coating of urea is considered as imperative strategy to improve nitrogen (N) use efficiency (NUE) and reduce N losses. Similarly, sowing methods (SM) also fundamentally influence the growth, yield and NUE of wheat. Therefore, the current investigation was aimed to determine the impact of normal and neem coated urea, on the yield performance of the wheat crop, and NUE under different SM in Pakistan. The study comprised different levels of urea, *i.e.*, control (no urea), 100% recommended normal urea (100% RU), 100% recommended neem coated urea (100% RNCU) 75% recommended neem normal urea (75% RU), and 75% recommended neem coated urea (75% RNCU), in a factorial combination with four SM; line sowing (LS), broadcast sowing (BC), broadcast augmented with furrow sowing (BCAF), and bed sowing (BS). The application of 100% RNCU resulted in maximum productive tillers, grain yield, harvest index, nitrogen (N), phosphorus (P), and potassium (K) uptake; however, all these traits held same with 75% RNCU. Moreover, 100% RNCU resulted in maximum agronomic use efficiency (AUE) (17.33 and 21.30 kg/kg), NUE (30.31 and 31.75 kg/kg), nitrogen uptake efficiency (NUptE) (1.04 and 1.09 kg/kg) and nitrogen productive efficiency (NPE) (37.50 and 39.75 kg/kg). Among sowing methods; BS performed well and resulted in maximum productive tillers, grain yield, harvest index, N, P and K uptake and AUE, NUE, NUptE and NPE, compared to the other three SM. Additionally, 75% RNCU achieved maximum resource use efficiency and economic return, and 100% RNCU were not statistically differentiated. BS also gave the maximum RUE and economic return compared to the other SM. Therefore, it appears that 100% neem coated urea (150 kg ha^{-1}) and bed sowing proved to be better for improving wheat productivity, NUE, and economic return in warm semi-arid conditions. © 2021 Friends Science Publishers

Keywords: Nitrogen use efficiency, Nitrification, Neem coating, Productivity, Urea, Wheat

Introduction

The world's population is continuously soaring up and an increase in agricultural production remains a most challenging task to feed the 9.8 billion people by the end of 2050 (Alexandratos and Bruinsma 2012; Hassan *et al.* 2020a). Plants need sixteen nutrients for optimum growth and productivity, nonetheless, nitrogen (N) is mostly used nutrient by the plants. Thus, N is critical component of agriculture and accounts for 50% world's food production to meet food challenges (Zhang *et al.* 2016). Nitrogen is essential for normal plant growth and development, as it is a structural component of different enzymes, proteins, and chlorophyll (Chattha *et al.* 2017a; Guo *et al*. 2019). Photosynthesis, assimilates production, and leaf area are duration increases with the optimum N supply (Asibi *et al.* 2019) which in turn improves the grain productivity (Rafiq *et al.* 2010). Nonetheless, losses from N fertilizers are 50% which is main source of lower NUE (Coskun *et al.* 2017; Bindraban *et al.* 2020). Additionally, N losses also increase

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the negative environmental footprints by increasing the greenhouse gases emission and polluting the underground water (Coskun *et al*. 2017; Conijn *et al.* 2018).

Urea (46% N) is the most commonly used N fertilizer across the globe owing to its cost-effectiveness. In Pakistan, 70% of applied urea is lost into the environment and becomes unavailable for a plant which is a challenging task, and these N losses adversely affect ecosystem, climate and degrading the natural resources (Raza *et al*. 2018). Therefore, to reduce these impacts on our environment, there is a dire need to increase the fertilizer use efficiency and prolong the N availability for optimum plant growth and development. The use of slow releasing fertilizers is adopted to increase fertilizer use efficiency and reduce N losses (Guo *et al.* 2019). The slow releasing fertilizers have layers of different substance (oils, nutrients) which decreases the rapid hydrolysis of applied fertilizer and therefore prolong the nutrient availability and consequently increases crop yield (Naz and Sulaiman 2016). Neem coated urea possesses an excellent nitrification inhibition properties to increase crop yield and NUE (Khandey *et al.* 2017; Ghafoor *et al.* 2021). The neem coated based nitrification inhibitors are degradable and environmentally friendly and possess an appreciable potential to improve the NUE (Dimkpa *et al.* 2020). Several authors reported promising potential of nitrification inhibition in different plant parts and byproducts (oil) of neem to increase the crop yield and NUE under conventional sowing methods (Patra *et al.* 2006; Khandey *et al.* 2017; Ali *et al.* 2020; Ghafoor *et al.* 2021). However, no information is available linked with use of neem coated urea to improve NUE and crop yield under BS and BCAF sowing.

Well-developed plant root system is necessary for the better plant growth and nutrient uptake. The conventional sowing methods are the major reason behind the lower crop productivity owing to reduction in utilization efficiency of applied inputs (Khan *et al*. 2012; Chattha *et al.* 2020). Conventional sowing method (broadcasting) leads to poor stand establishment and increases nutrient and water loss (Gathala *et al.* 2011). Therefore, in this context improved sowing methods including ridge and bed sowing can play a significant role to improve crop productivity, nutrient use, and water use efficiency. Ridges and beds provide the loose layer of soil that ensures better root growth, root proliferation, and increases water and nutrient uptake, ultimately increases final production (Khan *et al.* 2012; Hassan *et al.* 2019; Iqbal *et al.* 2020). Wheat is an imperative crop cultivated across the globe as imperious sources of nutrients, carbohydrates and calories (Chattha *et al.* 2017b; Hassan *et al.* 2019, 2021; Muhsin *et al.* 2021). Although many studies were performed to improve the wheat crop yield and NUE through neem coated urea under conventional BC and LS sowing method. Nonetheless, no information is available related to effect of neem coated urea on NUE and performance of wheat crop under BS and BCAF sowing methods. Thus, we hypothesized that neem coated urea may improve wheat productivity and NUE through nitrification inhibition and slow N release under different sowing methods. Therefore, this study was conducted to determine best rate of neem coated urea for improving the wheat productivity and NUE under different sowing methods in warm semi-arid conditions.

Materials and Methods

Experimental site and soil

This study was conducted in 2018–2019 and 2019–2020 at Agronomy Research Farm, University of Agriculture Faisalabad, Pakistan. The studied site has a warm semi-arid climate (Hassan *at al.* 2018, 2020b) and weather conditions during the growing seasons are given in Fig. 1. The soil samples from diverse parts of the experimental field were collected with the help of augar and mixed to prepare composite samples and subjected to determine different physico-chemical. The soil pH and organic matter was determined by methods of Prasad *et al.* (2006) and Walkley and Black (1934), whilst, nitrogen (N), phosphors (P) and potassium (K) were determined by methods of AOAC (1990), Olsen *et al.* (1954) and Hanway and Heidel (1952) respectively. The soil was sandy loam with pH 7.82, organic matter 8.8 g kg^{-1}, %, available P 4.78 mg kg^{-1}, available K 170 mg kg^{-1} and total N 0.3 g kg^{-1}.

Experimental details

The experiment was laid out in randomized complete block design with a factorial arrangement having three replications. The experiment comprised five levels of urea application: control (no urea), 100% recommended normal urea (100% RU), 100% recommended neem coated urea (100% RNCU), 75% recommended normal urea (75% RU) and 75% recommended neem coated urea (75% RNCU). This was cross combined with four sowing methods (SM): line sowing (LS), broadcast sowing (BC), broadcast augmented with furrow sowing (BCAF), and bed sowing (BS). With urea and neem coated urea, in 100% recommended urea fertilizer, N was applied at the rate of 150 kg ha^{-1}, while in 75% recommended urea application N was applied at the rate of 112.5 kg ha^{-1}. The seeds of neem were collected from different trees and dried. After that they were crushed to extract the oil. 1000 mg neem oil was used to coat one kg of urea. The net plot size of 4.5 × 10 m was kept during both years of study. The experimental field was cultivated twice, followed by planking to prepare the final seed bed for sowing. The crop was sown on 25th and 27th November, during the respective 2018–2019 and 2019–2020 growth seasons, by using a seed rate of 125 kg ha^{-1}. In broadcasting (BC), wheat seeds were broadcasted in the field, while in line sowing (LS), the seeds were sown in 23 cm apart rows. In broadcast augment with furrow (BCAF), the seeds were

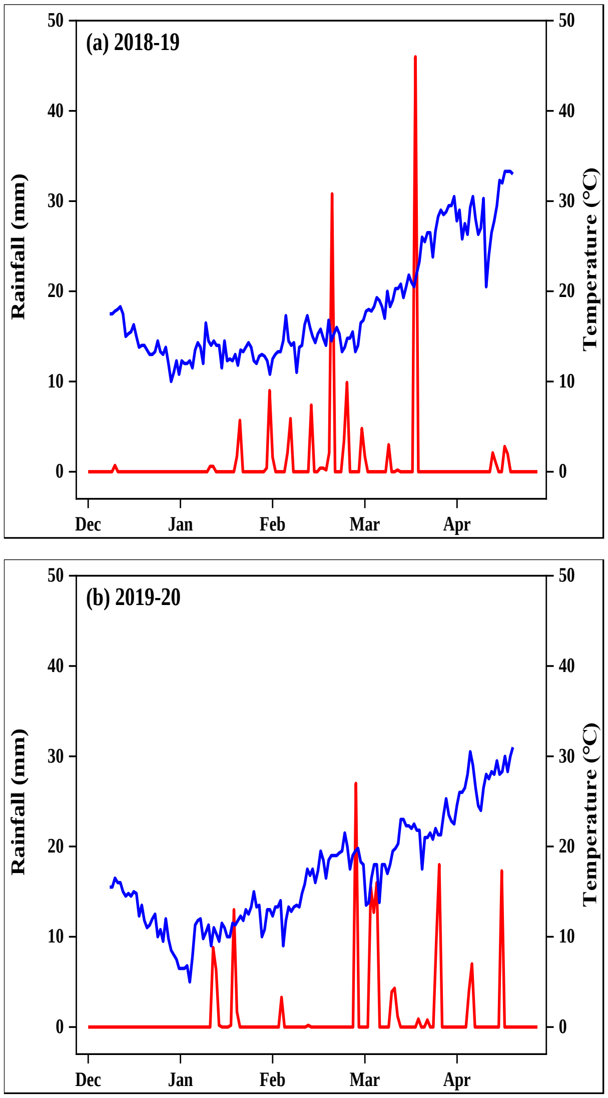

Fig. 1: Mean temperature and rainfall (mm) during the 2018-2019 and 2019-2020

broadcasted in the field and 75 cm apart ridges were made, whilst in bed sowing (BS) four lines of wheat were sown on each bed having 30 cm furrow. The P and K fertilizers were applied to the crop at the rate of 100 and 50 kg ha^{-1} of the two respective nutrients, in the form of di-ammonium phosphate (18% N, 46% P_2O_5) and sulphate of potash (50% K_2O) and N was applied in the form of urea (46% N) according to treatments. Complete quantity of P and K and half N was applied at sowing, while the rest of N was applied at first irrigation. In total, four irrigations were applied in each year. The first irrigation was applied post 21 days after sowing (DAS), and the remaining three irrigations were applied after 45, 85 and 110 DAS. The rest of the practices were kept consistent with the general recommendations for the wheat crop in the surveyed area.

Data collection

Destructive plant sampling was conducted to record the growth attributes including leaf area index (LAI) and crop growth rate (CGR). One meter long row in each plot was harvested and separated into leaves and stems. A sub-sample of leaves (5 g) was taken and leaf area was measured by a leaf area meter (CI-202, CID Bio-Science) and LAI was determined by given below formula as described by Watson (1947).

$$LAI = leaf\ area/ground\ area \qquad 1$$

Additionally, a sub-sample of plants (5 g) was taken from the harvested plants and oven-dried (75°C) until constant weight to determine the dry weight and CGR was determined by the method of Hunt (1978) with equation 2.

$$CGR = (W2 - W1)/(t2 - t1) \qquad 2$$

Here W2 and W1 show the dry matter at first and second harvesting, whereas T2 and T1 showing the time of second and first harvesting. The first LAI and CGR were determined at 30 DAS, and subsequent measurements were taken at 15-day intervals. Similarly, ten plants were selected and plant height was measured, spikelet and grains per spike were counted and averaged. At harvest maturity, the complete plots were harvested and sun-dried and weighed to determine the biological yield and later on threshed to determine grain yield and converted into t ha^{-1}. A sub-sample of 1000 grains were taken from the threshed grains and weighed to determine the thousand-grain weight (TGW). Additionally, the harvest index was assessed as the ratio of grain to biological yield.

Nutrients uptake and N efficiency assessments

The plant materials including the grains and straw (10 g) were oven dried (75°C) till constant weight. The N contents in straw were determined by the methods of Jackson (1962), whereas for N in grain, the percentage of protein contents (obtained by kernelyzer) was divided by 5.7 to get the percentage of N contents in grains (Herridge 2013). The dried grain and straw samples were wet digested ($HClO_4$: HNO_3 3:10 ratio) filtered and diluted with distilled water, and the P contents were determined by the inductively coupled plasma mass spectrometry, whereas the K contents were determined by flame photometer. The obtained values of nutrients were multiplied with the total dry matter to determine the NPK uptake (Fageria *et al.* 1997). For determination of NPK a set of three replicate was used for each treatment and later on average was taken. The agronomic use efficiency (AUE) was determined by this formula (Jadon *et al.* 2018):

$$AUE = grain\ yield\ fertilizer\ - grain\ yield\ control\ /N\ fertilizer\ applied \qquad (3)$$

The N uptake efficiency (NUptE) was determined by the following formula (Xu *et al.* 2020):

$$NUptE = N\ accumuation\ in\ plant\ /N\ fertilizer\ applied \quad (4)$$

The N use efficiency (NUE) was calculated by the following equation (Xu *et al.* 2020):

$$NUE = grain\ yield\ /N\ accumulation\ in\ plant \quad (5)$$

Lastly, N productive efficiency (NPE) was calculated by following formula (Xu *et al.* 2020):

$$NPE = grain\ yield\ /amount\ of\ applied\ N \quad (6)$$

Economic analysis and resource use efficiency

The economic analysis was performed to estimate the feasibility of diverse sowing methods and neem coated urea based on variable costs related to the different sowing methods and fertilizer applications (CIMMYT 1998). The cost of fertilizers, irrigation, herbicides, along with their application charges and cost of seeds were considered as a fixed cost. Moreover, the costs for different sowing methods, and normal and neem coated urea were treated as variable costs. The net benefit was calculated by subtracting the total cost from the gross income, while the net benefit-cost ratio was determined by dividing the gross income by total cost (CIMMYT 1998). Additionally, the resource use efficiency (RUE) was determined by the methods of Farooq and Nawaz (2014).

$$RUE = net\ benefit\ /total\ cost\ of\ production \quad 7$$

Statistical analysis

Data regarding growth, production, N accumulation and various N-efficiency parameters were analyzed by Fisher's analysis of variance (ANOVA) technique using STATISTIX 8.1 (Analytical Software, Inc., Tallahassee, FL, USA). The differences among treatments were separated using the least significant difference (LSD) test at 5% probability level (Steel *et al.* 1997). The data of each year was separately analyzed and therefore both years' data presented separately. The data set was also subjected to Pearson's correction to determine the reciprocal inter-relations among studied traits.

Results

Growth attributes

Plant growth parameters LAI, CGR and plant height were significantly influenced by the neem coated urea and sowing methods (Table 1). Initially, there was a non-significant difference among treatments in both years for LAI; however, the difference became wider when LAI reached maximum values at 75 days after sowing (DAS), before LAI started declining with senescence (Fig. 2). Highest paired LAI values at 75 DAS were recorded with the application of both (100 and 75% RNCU), while lowest paired LAI values were shown for urea at the two N doses (100 and 75% RU) (Fig. 2). Among SM; maximum LAI was noticed in bed sowing (BS) closely followed by line sowing (LS), while the lowest LAI in both growing seasons was noticed in BCAF. Crop growth rate also showed the same and reached a peak at 75–90 DAS, and afterward, it started decreasing (Fig. 3). Maximum CGR in both seasons was noted with 100% RNCU that remained similar with75% RNCU, while lowest CGR was recorded with the application of 100% RU (Fig. 3). Similarly, maximum plant height was recorded in 100% RNCU, followed by 75% RNCU that was at par statistically with 100% RU and minimum plant height was recorded with 75% RU in both years (Table 4).

Yield and yield components

The yield contributing traits showed a significant response to neem coated urea and SM (Table 1 and 2). In both study years, the maximum number of productive tillers and spikelet/spike was obtained with 100% RNCU followed by 75% RNCU, whereas the lowest number of tillers and spikelet/spike was obtained with 75% RU (Table 4). Among SM, maximum number of tillers and spikelet/spike was recorded in BS, while lowest number of tillers and spikelet/spike was recorded in BCAF (Table 4). The maximum number of grains/spike was also recorded in 100% RNCU, quite closely followed by 75% RNCU, while the lowest number of grains/spike was obtained at par in 100 and 75% RU (Table 4). Bed sowing performed best in terms of grains/spike, followed by LS; conversely, the two broadcast sowing methods (BC and BCAF) performed worst in terms of grains/spike during both seasons (Table 4).

The application of 100% RNCU passed all treatments and resulted in highest thousand-grain weight (TGW), whereas lowest TGW was reported in 75% RU (Table 5). There were also significant differences in TGW among SM; BS remained at top with maximum TGW, followed by LS, while BCAF remained at lowest ranking with minimum TGW (Table 5). Likewise, in both seasons maximum grain yield was recorded with 100% RNCU followed by 75% RNCU, while lowest grain yield was recorded in 75% RU (Table 5). The same ranking was shown in biological yield, whereas in harvest index higher values were observed, in general, for the full dose of N (100% RNCU and 100 RU) (Table 5). Amid SM, maximum grain yield was recorded in BS and the overall trend was BS > LS > BC > BCAF (Table 5). BS also resulted in maximum biological yield and HI, and the same overall trend (BS > LS > BC > BCAF) was observed (Table 5).

Nutrients uptake and nitrogen use efficiency

The nutrient (NPK) uptake was significantly affected by

Table 1: Analysis of variance for the effect different sowing methods and rates of neem coated urea yield traits of wheat crop

Treatments	Plant height (cm)		Productive tillers/m^2		Spikelet/spike		Grains/spike	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
Sowing methods (SM)	571.75**	822.95*	3236.40*	2898.98**	8.89*	5.37**	91.39**	97.91**
Urea application (UA)	510.22*	232.76*	2371.19*	3237.73**	6.71*	5.47**	60.44*	96.76**
SM × UA	7.99^{NS}	10.36^{NS}	356.69^{NS}	411.42*	0.87^{NS}	1.37^{NS}	5.79^{NS}	10.52*

**: highly significant, *: significant, NS: non-significant

Table 2: Analysis of variance for the effect different sowing methods and rates of neem coated urea on yield and yield traits of wheat crop

Treatments	1000 grain weight		Grain yield (g/plant)		Biological yield (g/plant)		Harvest index (%)	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
Sowing methods (SM)	60.03**	64.18**	5.563*	2.57**	5.19*	7.00**	148.20**	35.26**
Urea application (UA)	100.978	134.06**	7.28*	12.30**	16.84**	26.24*	128.31**	247.69**
SM × UA	3.81^{NS}	3.52*	0.32^{NS}	0.15^{NS}	0.11^{NS}	2.33*	25.21^{NS}	19.76^{NS}

**: highly significant, *: significant, NS: non-significant

Table 3: Analysis of variance for the effect different sowing methods and rates of neem coated urea on nutrients uptake and nitrogen use efficiency parameters wheat crop

Treatments	N uptake		P uptake		K uptake		AUE		NUptE		NUE		NPE	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
Sowing methods (SM)	603.40*	816.91*	1.57*	3.59**	363.08*	308.29**	6.65**	2.98**	0.013**	0.010**	10.07**	9.16**	22.29**	16.86**
Urea application (UA)	3700.44*	4401.4*	4.67*	6.58**	539.04*	1151.85*	0.75**	0.42*	0.004**	0.015**	3.83**	6.68*	24.64**	20.39**
SM × UA	5.83^{NS}	20.25^{NS}	0.034^{NS}	0.16^{NS}	8.24^{NS}	10.32^{NS}	0.01^{NS}	0.04^{NS}	0.002^{NS}	0.001^{NS}	0.24^{NS}	0.27^{NS}	0.33^{NS}	0.24^{NS}

**: highly significant, *: significant, NS: non-significant, N: nitrogen, P: phosphorus, K: potassium, AUE: agronomic use efficiency, NUptE: nitrogen, uptake efficiency, NUE: nitrogen use efficiency, NPE: nitrogen productive efficiency

Table 4: Effect of different sowing methods and rates of neem coated urea on the yield traits of wheat crop

Urea application	Plant height (cm)		Productive tillers/m^2		Spikelet/spike		Grains/spike	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
No urea	84.83 D	94.67D	265.00D	266.67E	12.43B	13.08E	37.42D	38.16D
100% RU	96.83BC	100.17BC	282.58BC	290.00C	13.46B	14.04C	40.33BC	42.67C
100% RNCU	102.58A	106.83A	301.67A	309.33A	14.33A	14.88A	43.25A	45.67A
75% RU	95.33B	99.17C	276.58C	283.67C	12.71C	13.67D	39.92C	42.17C
75% RNCU	97.58B	101.75B	291.83AB	301.00B	13.49B	14.32B	41.16AB	44.33B
LSD ($P \leq 0.05$)	2.14	2.17	5.23	6.06	0.17	0.17	1.09	0.39
Sowing methods								
LS	96.87B	102.00B	285.73B	292.93B	13.25B	14.10B	41.67B	43.33B
BC	91.20C	95.07C	282.73B	285.93C	13.20B	13.79C	39.36C	41.80C
BCAF	89.67C	94.60C	264.93C	274.20D	13.22C	13.34D	38.00C	39.60D
BS	103.00A	110.40A	300.73A	307.47A	14.27A	14.77A	43.54A	45.67A
LSD ($p \leq 0.05$)	3.83	2.17	7.72	1.51	0.19	0.05	0.70	0.60

Means with different letters differed at 0.05 *P* level. 100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing.

Table 5: Effect of different sowing methods and rates of neem coated urea on yield traits and yield of wheat crop

Urea application	1000 grain weight (g)		Grain yield (t ha^{-1})		Biological yield (t ha^{-1})		Harvest index (%)	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
No urea	35.31D	36.32D	3.14D	3.17D	10.26D	10.74D	30.74B	29.63C
100% RU	38.48C	41.29C	4.70C	5.43B	12.27B	13.26BC	37.69A	39.55AB
100% RNCU	42.95A	45.27A	5.09A	5.56A	13.24A	14.55A	37.00A	38.46B
75% RU	37.57C	40.50C	4.50D	5.11C	11.90C	12.91C	38.25A	40.98A
75% RNCU	40.47B	43.19B	4.94B	5.48AB	13.03A	14.11AB	38.36A	39.36AB
LSD ($P \leq 0.05$)	0.55	0.43	0.055	0.047	0.137	0.537	0.655	1.03
Sowing methods SM)								
LS	39.61B	42.23AB	4.66B	5.01B	12.28B	13.56A	37.67B	36.87BC
BC	38.20C	40.97B	4.39C	4.94B	11.91C	12.95AB	36.73B	37.86B
BCAF	36.58D	38.16C	3.69D	4.42C	11.49D	12.22B	32.22C	36.04C
BS	41.31A	43.45A	5.15A	5.42A	12.88A	13.72A	39.65A	39.61A
LSD ($P \leq 0.05$)	1.27	1.76	0.059	0.063	0.132	0.515	1.33	0.647

Means with different letters differed at 0.05 P level. 100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing.

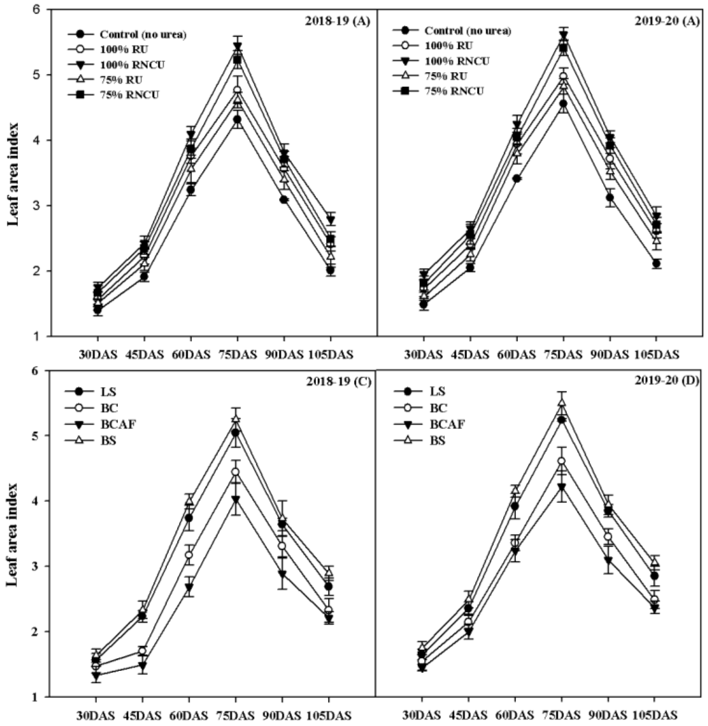

Fig. 2: Effect of neem coated urea (**A** and **B**) and sowing methods (**C** and **D**) on the leaf area index of wheat crop during 2018-19 and 2019-20. 100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing.

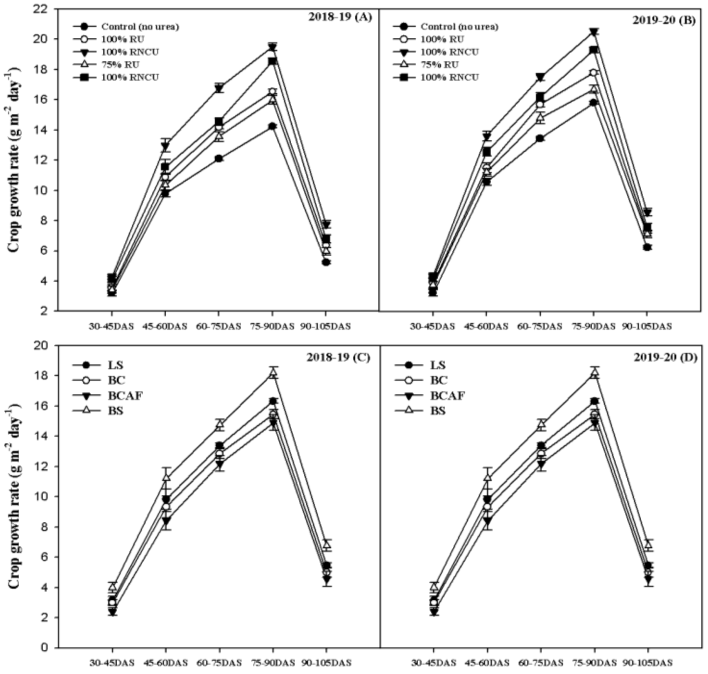

Fig. 3: Effect of neem coated urea (**A** and **B**) and sowing methods (**C** and **D**) on crop growth rate of wheat crop during 2018-19 and 2019-20. 100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing.

both nitrogen application and SM (Table 3). In both years the highest N, P and K uptake was shown with 100% RNCU while the lowest N, P and K uptake was observed with 75% RU (Table 6). There were significant differences among SM for nutrient uptake; BS determined the highest uptake of the three elements; LS ranked second, followed by BC and lastly BCAF (Table 6). The two factors nitrogen application and SM had a significant impact on nitrogen efficiency traits in both years (Table 3). In both years the highest agronomic use efficiency (AUE), nitrogen use efficiency (NUE), N uptake efficiency and N productive efficiency were evidenced by100% RNCU, followed by 75% RNCU; conversely, the lowest levels of the four traits were shown by 75% RU-U (Table 7). Sowing methods also exhibited significant differences for AUE, NUE, N uptake and productive efficiency; again, BS achieved the highest levels, followed by LS, BC and lastly BCAF (Table 7).

Economic analysis and resource use efficiency

Maximum net benefit and benefit-cost ratio (BCR) was achieved with the application of 75% RNCU followed by 100% RNCU, while lowest net benefit and BCR was obtained with application of 75% RU (Table 8). Among SM, maximum net benefit and BCR were recorded in BS, whereas minimum net benefit and BCR were noted in BCAF (Table 5). Similarly, resource use efficiency (RUE) remained highest in 75% RNCU, followed by 100% RNCU-NCU, while the lowest RUE was recorded in 75% RU (Table 8). Moreover, in the case of SM, BS resulted in maximum RUE, followed by LS and BC, while minimum RUE was recorded in BCAF (Table 8).

Pearson's correlation

Pearson's correlations showed a significant positive association among most of the studied traits (Fig. 4). The values indicate a positive correlation among productive tillers, thousand grain weight, spikelets/spike, and grain yield. Similarly, a positive association was also observed between nitrogen efficiency traits and grain yield, which is consistent with meaning of these traits (Fig. 4).

Discussion

The current findings support the hypothesis that neem coated urea would improve wheat N efficiency, productivity and net economic returns under varying sowing methods. Neem coated urea considerably enhanced wheat growth, as shown by the functional growth traits leaf area index (LAI) and crop growth rate (CGR) (Fig. 1 and 2) and the morphological traits plant height (Table 4). Neem coating ensures slower release of N and increases N availability for a longer period (Sannagoudra *et al.* 2012; Ghafoor *et al.* 2021), which in turn improves assimilates production and resultantly leads to a marked improvement in growth traits. LAI has a direct association with the number of leaves; therefore, the observed increase in LAI by neem coated urea was due to an increase in leaves/plants. Similarly, larger leaves ensure better light-harvesting, which in turn improves dry matter production and resultantly increases CGR (Fig. 3) and final production (Hassan *et al.* 2019). Diverse sowing methods also had a significant impact on LAI, CGR and plant height; however, bed sowing (BS) performed significantly better compared to other methods. The sowing on beds and ridges ensures the provision of loose fertile soil which provides a better environment for root growth and favors a better nutrient and water uptake and therefore, facilitates better assimilation and dry matter production (Fig. 3) and resultantly leads to the production of taller plants with higher LAI and CGR (Hassan *et al.* 2019; Chattha *et al.* 2020).

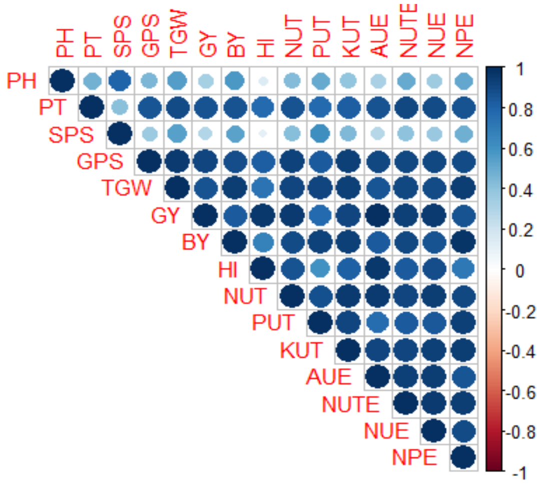

Fig. 4: Pearson's correlations between the studied traits. PH: plant height, PT; productive tillers, SPS: spikelet's per spike, GPS: grains per spike, TGW: thousand grain weight; GY: grain yield, BY: biological yield, HI: harvest index, NUT: nitrogen uptake, PUT: phosphorus uptake, PUT: potassium uptake, AUE: agronomic use efficiency, NUTE: nitrogen uptake efficiency, NUE: nitrogen use efficiency, NPE: nitrogen productive efficiency.

Neem coated urea significantly increased grain yield and its components in both seasons (Table 4 and 5). Neem coating induces slower release of N and reduces potential N losses, which in turn ensures a better N availability to the benefit of yield and yield contributing traits (Zhang *et al.* 2019). Additionally, neem coating also reduces NO^{3-} availability for denitrifying bacteria, which in turn increases nitrogen efficiency and consequently leads to an increase in both grain and biomass yield (Kundu *et al.* 2013; Alonso-Ayuso *et al.* 2016). Significant increase in yield components, grain and biological yield was observed in bed sowing compared to other methods (Table 4 and 5). Favorable soil conditions created in BS ensured efficient nutrient and water uptake, which might be the reason for

Table 6: Effect of different sowing methods and rates of neem coated urea on nutrients uptake

Urea application	Nitrogen uptake (kg ha^{-1})		Phosphorus uptake (kg ha^{-1})		Potassium uptake (kg ha^{-1})	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
No urea	76.92D	78.58D	11.44B	11.52C	120.42D	122.50D
100% RU	114.67B	118.83B	12.83A	13.06AB	132.50B	137.58B
100% RNCU	119.67A	124.17A	13.00A	13.39A	137.25A	147.08A
75% RU	110.17C	116.42C	12.56A	12.80B	128.50C	133.58C
75% RNCU	117.08AB	123.00A	12.86A	13.18A	135.50A	144.75A
LSD ($P \leq 0.05$)	1.31	1.04	0.247	0.18	1.14	1.27
Sowing methods						
LS	109.20B	116.13B	12.63AB	12.94B	132.67B	139.47B
BC	106.20B	108.40C	12.44B	12.60C	129.47C	134.33C
BCAF	100.20C	104.40D	12.10C	12.23D	124.80D	131.93D
BS	115.40A	120.73A	12.87A	13.38A	136.40A	142.07A
LSD ($P \leq 0.05$)	1.82	0.811	0.130	0.91	0.83	0.96

Means with different letters differed at 0.05 *P* level. 100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing

Table 7: Effect of different sowing methods and rates of neem coated urea on agronomic, N uptake, N use and N productive efficiencies

Urea application	Agronomic use efficiency (kg/kg)		N uptake efficiency (kg/kg)		N use efficiency (kg/kg)		N productive efficiency (kg/kg)	
	2018–2019	2019–2020	2018–2019	2019–2020	2018–2019	2019–2020	2018–2019	2019–2020
No urea	--	--	--	--	--	--	--	--
100% RU	13.86B	15.45C	0.79B	0.82C	29.68AB	30.67BC	35.76B	38.27B
100% RNCU	17.33A	21.30A	1.04	1.09A	30.31A	31.75A	37.50A	39.47A
75% RU	9.05D	12.97D	0.76D	0.79C	28.95B	30.09C	34.33C	36.50C
75% RNCU	11.99C	20.15B	0.97B	1.03B	29.86AB	31.42AB	37.09A	38.99AB
LSD ($P \leq 0.05$)	0.33	0.37	0.021	0.006	0.92	0.84	0.93	1.03
Sowing methods								
LS	12.41B	14.80B	0.72B	0.77B	30.08AB	31.17B	31.72B	38.75B
BC	8.83C	14.31B	0.70B	0.72C	29.58B	30.61BC	35.44C	37.67C
BCAF	5.08D	10.67C	0.66C	0.69D	28.50C	30.05C	34.72C	37.06C
BS	15.46A	16.94AA	0.77A	0.80A	30.66A	32.10A	37.80A	39.75A
LSD ($P \leq 0.05$)	0.34	0.52	0.011	0.02	0.85	0.87	0.91	0.74

Means with different letters differed at 0.05 *P* level. 100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing.

Table 8: Economic analysis and resource use efficiency for the effect of different sowing methods and different rates of neem coated urea

Sowing methods	Urea application	GY	AGY	SY	ASY	GV	SV	GI	PC	VC	TC	NB	BCR	RUE
LS	No urea	3.12	2.81	10.50	9.45	552.86	261.67	814.53	474.26	65.66	539.92	274.60	1.51	0.51
	100% RU	4.97	4.47	12.56	11.31	878.85	313.05	1191.90	479.22	65.66	544.88	647.02	2.19	1.19
	100% RNCU	5.38	4.84	15.23	13.71	951.43	379.55	1330.97	458.98	65.66	524.65	806.33	2.54	1.54
	75% RU	5.24	4.72	13.10	11.79	928.12	326.34	1254.46	462.70	65.66	528.36	726.10	2.37	1.37
	75% RNCU	5.50	4.95	13.63	12.27	972.96	339.71	1312.68	443.84	65.66	509.50	803.18	2.58	1.58
BC	No urea	3.19	2.87	10.93	9.84	564.96	272.39	837.34	474.26	62.50	536.76	300.58	1.56	0.56
	100% RU	4.65	4.19	12.38	11.14	823.68	308.40	1132.08	479.22	62.50	541.72	590.36	2.09	1.09
	100% RNCU	5.18	4.66	13.16	11.85	916.91	328.00	1244.91	458.98	62.50	521.48	723.43	2.39	1.39
	75% RU	5.05	4.55	12.39	11.15	894.49	308.85	1203.34	462.70	62.50	525.20	678.14	2.29	1.29
	75% RNCU	5.26	4.73	13.30	11.97	930.48	331.36	1261.84	443.83	62.50	506.33	755.52	2.49	1.49
BCAF	No urea	3.08	2.78	9.39	8.45	545.78	233.88	779.66	474.26	75.16	549.42	230.24	1.42	0.42
	100% RU	4.09	3.68	11.66	10.49	723.08	290.54	1013.62	479.22	75.16	554.37	459.25	1.83	0.83
	100% RNCU	4.40	3.96	12.74	11.46	779.14	317.45	1096.59	458.98	75.16	534.14	562.45	2.05	1.05
	75% RU	4.29	3.86	12.39	11.15	759.96	308.77	1068.73	462.70	75.16	537.85	530.88	1.99	0.99
	75% RNCU	4.42	3.98	13.13	11.82	782.97	327.21	1110.18	443.84	75.04	518.88	591.30	2.14	1.14
BS	No urea	3.22	2.90	11.20	10.08	569.97	279.03	849.00	474.26	70.41	544.67	304.33	1.56	0.56
	100% RU	5.52	4.97	13.03	11.73	977.39	324.80	1302.19	479.22	70.41	549.63	752.56	2.37	1.37
	100% RNCU	5.90	5.31	14.05	12.64	1044.36	350.01	1394.37	458.98	70.41	529.39	864.98	2.63	1.63
	75% RU	5.68	5.12	13.21	11.89	1006.00	329.12	1335.13	462.70	70.41	533.11	802.02	2.50	1.50
	75% RNCU	6.14	5.52	14.65	13.18	1085.95	365.01	1450.96	443.84	70.41	514.25	936.71	2.82	1.82

100% RU: 100% recommended normal urea, 100% RNCU: 100% recommended neem coated urea, 75% RU: 75% recommended normal urea 75% RNCU: 75% recommended neem coated urea. LS: Line sowing, BC: broadcast sowing, BCAF: broadcast augmented with furrow, BS: Bed sowing. GY: grain yield, AGY: adjusted grain yield, SY: straw yield, ASY: adjusted straw yield, GV: grain value, SV: straw value, GI: gross income, PC: permanent cost, VC: variable cost, TC: total cost, NB: net benefit, BCR: benefit cost ration, RUE: resource use efficiency.

improved yield and its components. The vigorous stand establishment, higher LAI, CGR, tillers, grains/spike and grain yield are the reflection of higher nutrient and water uptake in BS (Mahmood *et al.* 2013; Iqbal *et al.* 2020). Likewise, maximum biological yield in BS was due to positive conditions created by the bed sowing resulting in better root growth that enabled the plants to take up more nutrients and water to produce higher LAI and CGR and consequently higher biomass production (Table 5).

The results indicate that N, P, and K uptake was significantly increased with neem coated urea (Table 6). The increase in uptake of N by neem coated can be due to the fact that neem coating increased the synchronization between plant N demand and fertilizer release throughout the growing period (Wang *et al.* 2015) by reducing the nitrification speed that is not limiting in the warm climate of Punjab, Pakistan. Moreover, neem coated urea also promoted P and K uptake (Table 6). Nitrogen application increases root branching closer to the soil surface where the nutrient level is higher (Postma *et al.* 2014); therefore, the observed increase in P and K uptake by neem coated urea was due to an increase in root growth. Neem coated urea also significantly improved, AUE, N uptake efficiency (NUptE), NUE and N productive efficiency (NPE) compared to the normal urea (Table 4). The recovery efficiency in neem coated urea increased due to inhibition of nitrification and retaining of NH_4^+-N that can be used by plants for a longer period, in turn improving the overall utilization efficiency of applied fertilizers. Moreover, in neem coated urea, rate of N availability becomes slow and N uptake is increases, which in turn reduces the N losses and increases AUE, NUE, and N uptake efficiency (Ning *et al.* 2012; Jadon *et al.* 2018). Bed sowing resulted in maximum improvement in nutrient uptake and N utilization compared to other sowing methods (Table 6 and 7). Bed and ridge sowing provide a better growing environment to roots compared to other methods of sowing, thanks to reduced risk of flooded wheat plants in case of unusually wet periods. This suggested that sowing on beds enabled the plants to utilize the applied nutrients more efficiency compared to flat sowing (Rehman *et al.* 2011), which therefore improves AUE, NUptE and NUE.

Conclusion

The application of neem coated urea (150 kg N ha^{-1}) significantly improved wheat growth, yield, nutrient uptake, and nitrogen use efficiency through extended N availability. However, it was practically at par with 75% recommended neem coated urea (122 kg ha^{-1}), which performed generally better than the 100 and 75% normal urea. Moreover, among sowing methods, bed produced the maximum yield and resulted in maximum nutrient uptake, nitrogen use efficiency and economic returns than other sowing methods. Therefore, higher yield, nutrient uptake, nitrogen use efficiency and economic returns, jointly imparted by neem coated urea and bed sowing appears a promising approach to improve wheat productivity in warm, semi-arid regions at low latitudes.

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Author Contributions

MUC and IK planned the experiment, AR conducted the experiment and interpreted the results, MTA helped in data collection, AR, MUC, MBC, MN, MUH made the original draft, MAA, MMI, FH, FA, FAK and MK reviewed and edited final draft.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

Not applicable.

Ethics Approval

Not applicable.

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