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Full Length Article

Optimizing Wheat *(Triticum aestivum)* Water Productivity and Nitrogen Use Efficiency in Sandy Soils Using Water Retention Polymers with Improved Nitrogen Fertilizers

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Abstract

A field experiment was carried out in the research area of Fertilizer Research Centre, Faisalabad, Pakistan, during 2022–2023 to explore ways to improve crop performance indicators *i.e*., water productivity and nitrogen use efficiency in sandy soils, which typically degraded to retain water. The study evaluated and compared the use of water retention polymers (WRPs) along with different types of nitrogen fertilizers, including standard urea and neem-coated urea (NCU) to investigate interactive effects of different treatments on water productivity and nitrogen use efficiency (NUE). Treatments were control (first treatment and second treatment), first treatment applied standard urea (SU; 185 kg ha^{-1}) without WRP, while second treatment applied NCU without WRP or SU with application of P: K (124:62 kg ha^{-1}) while remaining treatments were applied with SU combined with WRP at different amounts 12 kg ha^{-1} (third treatment), 16 kg ha^{-1} (fifth treatment), or 20 kg ha^{-1} (seventh treatment), and with Neem Coated Urea combined with WRP at different amounts 12 kg ha^{-1} (fourth treatment), 16 kg ha^{-1} (sixth treatment), or 20 kg ha^{-1} (eighth treatment) respectively. The study also assessed how varying rates of WRPs affected wheat yield and related traits, by statistical analysis using the Randomized Complete Block Design (RCBD). For an accurate assessment of the treatment's effect, Tukey's test was applied. Optimum water productivity and Irrigation Water Use Efficiency (IWUE) were recorded in eighth treatment (1.282 kg m^{-3} and 12.82 kg ha^{-1} mm^{-1}), but at the cost of reduction in yield. Optimum NUE was also obtained in fifth treatment (23.6). SU significantly improved yields compared to NCU, primarily due to nutrient leaching. SU combined with WRP outperformed NCU in NUE, IWUE, water productivity and yield performance, highlighting the importance of WRPs and nitrogen fertilizers in sandy soils. The study revealed that WRPs significantly improved soil moisture retention, reducing irrigation water demands, and thus, were helpful in decision making to achieve maximum yield under full water availability or maximum IWUE under water scarcity conditions.

Keywords: Neem coated urea; Water retention polymers; Irrigation water use efficiency; Water productivity; Nitrogen use effciency; Sandy soil

Introduction

The global food security challenge is met by more than 20% of the world's wheat production (FAO 2021). Increasing water productivity (WP) in wheat cultivation for sustainable agriculture is a vital concern (Ahmed *et al*. 2022). Pakistan's agriculture, primarily based on wheat, accounts for 19.3% of GDP. However, water availability for Rabi crops has declined by 19.6% from 2019–20 (GoP 2019–20). Pakistan is facing challenges in wheat crop production due to climate

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change, crop exhaustion, heat stress, soil conditions, lack of technology, certified seeds and water scarcity (Aslam 2016). Neem-coated urea (NCU) and water retention polymers (WRPs) are a potential solution to improve WP and nitrogen use efficiency (NUE). Understanding their interplay can reduce nitrogen leaching, improve nutrient availability, and enhance water use irrigation efficiency (IWUE) in water-limited areas (Kumar *et al*. 2023; Smith *et al*. 2024).

Among the most promising are advanced agronomic methods involving WRPs and slow-release fertilizers like NCU (Kumar *et al*. 2021). Studies showed that NCU can reduce nitrogen leaching by 50%; so, employing WRPs in combination with slow-release fertilizers can increase wheat yields by 20% (Iqbal *et al*. 2024). Studies showed that coated urea, such as NCU and nano-ZnO-coated urea, can reduce nutrient leakage in sandy soil in semi-arid areas with limited water supplies. WRPs improved nitrogen leaching, water consumption efficiency, and soil nutrient availability (Meena *et al.* 2021).

Regional solutions for national fertilization and water conservation are lacking, but combining WRPs and neem coated urea could boost wheat output (Fischer *et al*. 2022). However, separate assessments are insufficient to fully realize their combined impact on crop production, WP and water savings (Sharma and Kumawat 2019). Fertilizer application depends on crop, soil, water, manure, crop variety, potential yield and cultivation management. Nitrogen and polymer coated fertilizers are reported to improve wheat plant production on sandy soil (Zhang and Liang 2015; Shivay *et al.* 2016; Hegab 2018; Dey and Kumar, 2019; Ghafoor *et al.* 2021).

Field studies in semi-arid environments demonstrate WRPs augment water supply for growing crops when they need it most, producing stable yields during drought (Pereira and Marques 2021; Ali *et al*. 2022). Integrated application of WRPs and NCU may be feasible for resource use efficiency in wheat (Kaur *et al*. 2024). Agriculture is exploring the potential of WRPs to combat desertification and boost productivity by improving water retention in sandy soils, preventing drought stress, increasing irrigation duration, and influencing yield and plant developmental characteristics (Ostrand *et al*. 2020; Lal *et al.* 2021; Takahashi *et al*. 2023; Safdar *et al*. 2023). Quality of crops, length of irrigation interval, environmental safety such as reducing water loss using WRPs, control of runoff water, suppression of soil erosion, and improvements in irrigation efficiency (especially in wheat) by increasing the photosynthetic characteristics (Liu 2014; Liao *et al*. 2016; Ostrand *et al*. 2020; Hommadi *et al.* 2021; Sewhag 2022).

The present study evaluated (a) the effect of standard urea (SU) and NCU with WRPs on wheat yield and WP and (b) The effect of WRPs on soil-moisture dynamics and irrigation schedules, the improvement of water use efficiency (WUE), and reduction of nitrogen loss using NCU and the possibility for adopting these technologies together to improve the WP of wheat. It was hypothesized that NCU supplemented water retention polymers (WRPs) could be an effective option to increase WUE, NUE, and wheat productivity under arid environments, which may lead to sustainable agricultural practices. The study aimed to increase water and nutrient-use efficiencies of sustainable wheat production using WRPs, uncoated urea, and neem urea to improve productivity of water in wheat and develop sustaining agricultural practices in water-scarce areas.

Materials and Methods

Experimental area and weather conditions

A field experiment was conducted using the wheat variety Zincol-2016 during the winter season of 2022–23 at the Fertilizer Research Center, Millat Road, Faisalabad, Pakistan (Latitude 31.4312954°N, Longitude 73.0759443°E). Map of the experimental site is shown in (Fig. 1). This region experienced a hot climate in summer and a cold climate in winter, with a mean maximum temperature of 40.5°C in winter and a mean minimum of 26.9°C during summer. The annual average rainfall in the region was approximately 350 mm, with half occurring in July and August, and the average wind speed was about 3 ms^{-1} (Raza *et al*. 2021). Weather data for the duration period of this study is provided in Table 1.

Soil physico-chemical properties

The study involved obtaining soil samples from experimental plots in Faisalabad to determine physical and chemical parameters. The sieving method was used to determine soil texture, resulting in sandy loam. Chemical characteristics like pH, EC, organic matter, N, P and K were calculated. Moisture content was determined using the gravimetric method, and pH, EC, K and P were measured in a 1:5 soil suspension. Table 2 provides a summary of the chemical and physical properties of a soil sample. It identified pH (8.8) as a moderate alkaline soil, suggesting limited nutrient availability for plants. The total N and P contents were low while available K content was moderate. The EC value indicated that the soil was moderately saline, limiting water uptake and potentially affecting plant growth. The organic matter content (0.49%) was low. Field capacity (22%) was low, suggesting that the soil cannot hold much water. The permanent wilting point (8%) represented the minimum amount of water the soil can hold without becoming unavailable to plants. The difference between field capacity and permanent wilting point represented the available water holding capacity. pH 7.5 indicates alkaline soil; EC < 2 mS/cm suggests low salinity risk for most crops (USDA classification).

Organic matter content < 1% indicates low fertility; recommended for organic amendment.

Field capacity and permanent wilting point determined *via* pressure plate apparatus at -1/3 bar and -15 bar, respectively.

Nutrient levels: Low in N and P (below critical thresholds for wheat); moderate in K. Soil samples collected from 0–30 cm depth at 5 random locations, air-dried, sieved (<2 mm), and analyzed using standard protocols (Walkley-Black for OM; ammonium acetate extraction for K; Olsen method for P; glass electrode for pH; conductivity meter for EC).

Irrigation water analysis

The groundwater was utilized for irrigating wheat crops using a tube well and flood irrigation system. A water sample was collected from a running tubewell using a standard sampling method. The water analysis for pH, EC, SAR, RSC, total hardness, and TSS values revealed that it was ideal for irrigation generally, despite relatively moderate RSC EC values (Table 3).

Field preparation/tillage method and experimental design/layout

Wheat was grown using a conservation tillage technique, which improved field capacity, maintained soil moisture, and lowered energy costs. Compared to SU tillage techniques, this sustainable approach was less expensive. All eight treatments were replicated three times. The experimental design produced 24 treatment plots (Fig. 2). With rows representing replications and columns identifying treatments, including W/C for watercourse was 162 m^2 (18 m × 9 m). Total experimental area comprised 4046 m^2 (1 acre).

Treatments description and fertilizers application

Wheat grains were sown on November 30th and harvested on April 30th. The study aimed to evaluate the effects of WRPs combined with optimized fertilizer applications on soil moisture and water production in wheat farming. The trial consisted of eight treatments (first treatment to eighth treatment), distinguished by WRPs and fertilizer combinations. NCU is a nitrogen-rich fertilizer made from urea and neem derivatives provided by Fertilizer Research Center FFC Faisalabad. It contains compounds like azadirachtin, nimbin, and salannin, known for their natural pesticide and anti-nitrification effects. The neem oil, typically sourced from neem seeds, makes up 0.5% to 1% of the urea granule's total weight. This composition is balanced for environmental safety, crop compatibility, and ease of application, confirming to agricultural authorities' standards in large-scale farming applications (Singh 2016). Experimental treatment details are given in Table 4. In treatments first treatment, third treatment, fifth treatment, and seventh treatment, WRPs as hydrogels were utilized at varying rates (12 kg ha^{-1} for third treatment and fourth treatment, 16 kg ha^{-1} for fifth treatment and sixth treatment and 20 kg ha^{-1} for

Table 1: Meteorological data during the wheat crop season 2022–23

Month	Avg. maximum T (°C)	Avg. minimum T (°C)	Avg. RH (%)	Rainfall (mm)	Average sunshine (h)
November	26.3	12.8	55.4–82.2	3.0	5 h 19 min
December	17.0	6.0	40.0–67.0	7.0	3 h 23 min
January	17.3	5.5	40.–60.3	50.8	4 h 43 min
February	23.8	8.7	46.4–83.4	24.8	7 h 21 min
March	24.5	13.9	62.4–85.0	135	6 h 06 min
April	33.1	18.8	51.7–69.7	20.4	8 h 57 min

RH (%) = Relative Humidity ranges (min–max) represent daily observed values across the month; T (°C) = Temperature and rainfall (mm) data recorded at Pakistan Meteorological Department; Sunshine duration (h)

Table 2: Soil physico-chemical properties of the experimental site

Soil property	Value	Soil property	Value
pH	8.8	N (g/kg)	0.40
EC (mS/cm)	1.48	P (ppm)	6.6
Organic matter (%)	0.49	K (ppm)	143
Field capacity (%)	22	Permanent wilting point (%)	8

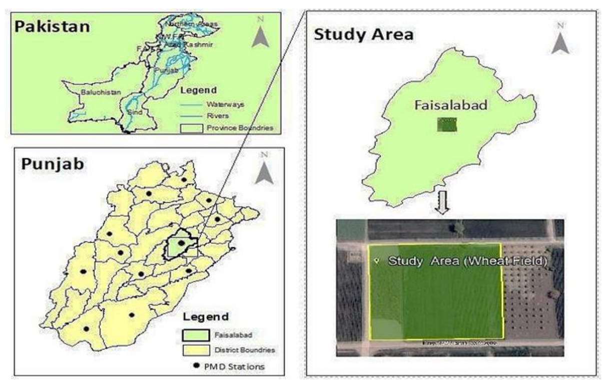

Fig. 1: Study area map of wheat crop

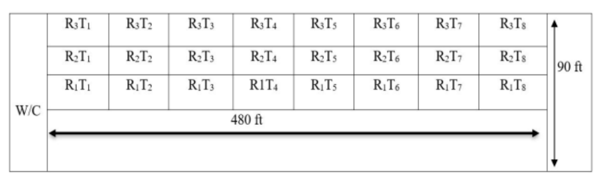

Fig. 2: Field layout

seventh treatment and eighth treatment) during each irrigation event. Therapies during the initial and subsequent waterings, first treatment, third treatment, fifth treatment, and seventh treatment were given the recommended dosage of urea (185 kg ha^{-1}), while second treatment, fourth treatment, sixth treatment, and eighth treatment were given urea coated with neem (185 kg ha^{-1}). Fertilizer inputs at planting were DAP (124 kg ha^{-1}), MOP (62 kg ha^{-1}) and micronutrients (zinc and boron). Border irrigation systems were used to water the plants. By including the fertilizer application ratios (N: P_2O_5:K_2O) and the quantity of NCU, the study sought to investigate the synergistic impacts of WRPs, different fertilizers, and NCU on crop performance.

Table 3: Irrigation water analysis

Irrigation water quality indicators	Value	Irrigation water quality Indicators	Value
pH	6.9	RSC (meq/L)	0.86
EC (dS/m)	1.85	Total hardness	295.2
SAR (meq/L)	6.1	TSS	1075.0

pH 6.5–8.4 EC Electrical Conductivity dS/m; SAR = Sodium Adsorption Ratio; RSC (Residual Sodium Carbonate); Total Hardness meq/L; TSS (Total Suspended Solids)

Table 4: Treatments description for the experiment

Treatment	WRP kg ha^{-1}	SU kg ha^{-1}	NCU kg ha^{-1}	P:K ratio kg ha^{-1}	Treatment Details
T1	Control	185	Control	124:62	Recommended dose of N (Standard Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With no water retention polymers application).
T2	Control	Control	185	124:62	Recommended dose of N (Neem Coated Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With no water retention polymers application).
T3	12	185	Control	124:62	Recommended dose of N (Standard Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With 75% of water retention polymers application).
T4	12	Control	185	124:62	Recommended dose of N (Neem Coated Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With 75% of water retention polymers application).
T5	16	185	Control	124:62	Recommended dose of N (Standard Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With 100% of water retention polymers application).
T6	16	Control	185	124:62	Recommended dose of N (Neem Coated Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With 100% of water retention polymers application).
T7	20	185	Control	124:62	Recommended dose of N (Standard Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With 125% of water retention polymers application).
T8	20	Control	185	124:62	Recommended dose of N (Neem Coated Urea), P (DAP) and K (MOP) fertilizers with 4 irrigations (With 125% of water retention polymers application).

WRPs = Water Retention Polymers; P = Phosphorus; K = Potassium; R1 = Replication-1; R2 = Replication-2; R3 = Replication-3

Irrigation scheduling and irrigation method

Farmers in irrigated agriculture assessed irrigation timing and quantity during the crop's growing season as part of their irrigation decision-making practice to optimize water timing, quantity, and crop response as well as when to water (Soomro *et al*. 2023). A tensiometer loaded with water, attached, and buried in the earth was used to find the moisture content at a depth of 0–30 cm. Measurements of moisture were taken using a gauge showing centibars before every watering. These measurements against the moisture characteristics curve helped one classify them as wet, optimum, semi-dry, or dry (Ansari *et al.* 2019).

Determination of total applied water, IWUE, NUE and WP, ET$_{crop}$/CWR and IWR for wheat

The following formulas were used to calculate total applied water, irrigation water use efficiency (IWUE), and WP as used by researchers in irrigation and crop water requirement and ET estimation (Doorenbos and Pruitt 1977; Jensen *et al.* 1990; Abd El-Wahed and Ali 2015).

$$\text{Net irrigation Depth (mm)} = \frac{\text{Field Capacity} - \text{M.C (\%)}}{100} \times \text{Root zone depth of plant (mm)} \quad (1)$$

$$\text{Gross irrigation Depth (mm)} = \frac{\text{Net Irrigation Depth (mm)}}{0.60} \quad (2)$$

Where Root zone depth of plant = 300 mm, 600 mm, 900 mm, 900 mm for first treatment, second treatment, third treatment, and fourth treatment irrigation respectively. The field capacity for sandy soil was 22% and PWP was 8%.

$$\text{Total water Applied} \left(\frac{\text{m3}}{\text{ha}}\right) = \frac{\text{Gross Irrigation Depth (mm)}}{1000} \times 1\text{ha} \times 10000\text{ m2} \quad (3)$$

$$\text{IWUE} \left(\frac{\text{kg}}{\text{ha mm}}\right) = \frac{\text{Yield} \left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Total Water Applied (mm)}} \quad (4)$$

$$\text{WP} \left(\frac{\text{kg}}{\text{m3}}\right) = \frac{\text{Yield} \left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Total Water Applied} \left(\frac{\text{m3}}{\text{ha}}\right)} \quad (5)$$

$$\text{Crop water requirement (CWR), ETc (mm)} = \text{Kc} * \text{ETo} \quad (6)$$

$$\text{Irrigation Water Requirement IWR (mm)} = \text{ETc} - \text{Effective rainfall (Pe)} \quad (7)$$

$$\text{Blaney Criddle Method ETo} = \text{p} \, (0.457 \text{ T mean} + 8.13) \quad (8)$$

$$\text{Pe} = 0.8\text{ P} + 25 \text{ if P} > 75 \frac{\text{mm}}{\text{month}} \text{ Pe} = 0.6\text{ P} + 10 \text{ if P} < 75 \text{ mm/month} \quad (9)$$

$$\text{NUE} = \frac{\text{Yield} \left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Fertilizer N Applied} \left(\frac{\text{kg}}{\text{ha}}\right)} \quad (10)$$

Where, Kc = Crop coefficient, ETo: Reference Evapotranspiration, p: mean daily percent of annual daytime hours T: mean air temperature in o C monthly, with P = rainfall or precipitation (mm/month), Pe =effective rainfall or effective precipitation (mm/month).

Crop data

The data from all the treatments was recorded for plant height, tillering efficiency, spike length, grains per spike, 1000 grain weight and overall yield.

Statistical analysis

Data were statistically analyzed using Statistix software version 10, with a randomized complete block design (RCBD) employed as the experimental design. Differences between treatment means were considered significant if they exceeded the least significant differences (*P < 0.05*). To assess the data's normality, the Shapiro-Wilk normality test was performed, and post-hoc comparisons between treatment groups were conducted using Tukey's Test.

Results

Effects of SU and NCU on wheat yield attributes

The results showed statistical significance and variability in crop performance when treated with SU versus NCU. The results indicated that NCU did not substantially outperform normal urea of important yield features such as plant height, spike length, grains per spike, 1000 grain weight, and overall yield. under-investigated conditions. Data revealed that the effect of NCU on plant height was statistically insignificant in comparison to standard urea. The F-value of 1.20 (*P = 0.3635*) indicated no significant difference between the two treatments at the 5% significance threshold. Tukey's test further substantiated this finding (*P = 0.4374*), indicating no significant difference in plant height among the treatments (Table 5a). A low coefficient of variation (CV = 1.54) showed a consistent response across treatments, so the variation in plant height was small and not influenced by the type of urea used (Fig. 3a).

Results revealed that NCU did not significantly alter spike length. The F-value of 1.68 (*P = 0.1926*) revealed no noticeable change over the treatments. A CV of 2.43 further indicated the smallest error variability. The relative efficiency of RCBD (1.18) showed that the experimental design was rather ineffective (Table 5a). Tukey's test further confirmed that there are no appreciable variations across the treatments (*P = 0.1881*), implying that the two treatments generate somewhat similar spike lengths (Fig. 3a).

Based on the F-value of 0.89 (*P = 0.542*), the data implied that NCU has also statistically non-significant effect on the count of grains per spike. However, there was some fluctuation in the data, as reflected by higher coefficient of variation (CV = 5.81), indicating variability in the number of grains per spike across replicates (Table 5a). While the results were non-significant, there appears to be a slight trend suggesting better performance with NCU, potentially due to its slow-release characteristics, which may improve nitrogen availability over time (Fig. 3a).

The analysis of 1000 grains weight data showed no significant difference between the treatments, as indicated by the F-value of 1.22 (*P = 0.3548*), which suggests that both NCU and regular urea resulted in similar outcomes for this parameter. However, the relatively high error variability, reflected by the mean square (MS) of 11.9166 and the coefficient of variation (CV = 8.73), indicates substantial fluctuation in the results (Table 5a). This fluctuation may be affected by ambient conditions or experimental errors, which could significantly change this character showing the absence of a definitive trend favoring either treatment (Fig. 3a).

The grain yield demonstrated no significant difference between treatments, evidenced by an F-value of 1.21 (*P = 0.3573*), indicating that the use of NCU did not substantially influence crop production relative to SU. The little effect on yield may result from various causes, including soil nutrient composition or the time of fertilizer application. The Shapiro-Wilk value (W = 0.9560) indicated that the residuals adhered to a normal distribution, so affirming the robustness of the statistical study (Table 5b). Fig. 3a illustrated that both procedures produce comparable results. Prominent trends encompass elevated RCBD relative efficiency for yield characteristics such as yield, spike length, and 1000-grain weight, signifying the design's robustness and efficiency (Fig. 3b).

Effects of WRP on moisture content, depth of water applied, crop water requirement CWR, IWR and irrigation scheduling

Tillering was improved by December and January's low temperatures. March and April suffered much rainfall, which helped to prevent extreme temperature changes and promoted improved grain development and growth. In total, 241 mm of rainfall throughout the wheat season. However, excessive precipitation had a detrimental effect on crops in the irrigated districts of upper Punjab. The application of WRPs significantly impacted soil moisture content, irrigation water requirements (IWR), and crop water requirements (CWR) across different treatments. The application of WRPs at varying rates (third treatment - eighth treatment) consistently resulted in higher soil moisture content compared to the control treatments (first treatment and second treatment), which did not receive any WRPs. This indicated that the polymers effectively enhanced the soil's ability to retain water, thus reducing the need for frequent irrigation. Fig. 4a further substantiated this association, illustrating an increase in soil moisture content with the incorporation of WRP. Plants' water needs grew as they developed, which raised irrigation levels in the first treatments. Application of Higher WRPs (seventh treatment and eighth treatment) however produced reduced irrigation depths since they reportedly maintained more soil moisture, so lowering the demand for more irrigation.

At varying application rates, the research demonstrated that WRPs significantly altered soil moisture levels, CWR, and irrigation water requirements (IWR). Lower irrigation resulted from higher application rates since the overall volume of irrigation water used dropped as the WRP application rate increased. It was good that WRPs raised soil moisture levels in arid situations. This suggested that by reducing the frequency and watering volume, they could assist in saving water. CWR of the WRPs-treated plots (third treatment –eighth treatment) was substantially less than that of the control treatments (first treatment and second treatment). By improving soil water retention, WRPs reduced the demand for further irrigation. Minimum crop

Table 5a: Statistical analysis on yield attributes

Trt#	Plant height (cm)			Spike length (cm)			Grains per spike (GPS)			1000 grains weight (g)			Yield (kg ha^{-1})		
	Mean ± SD	CV	SE	Mean ± SD	CV	SE	Mean ± SD	CV	SE	Mean ± SD	CV	SE	Mean ± SD	CV	SE
T1	100.80a ± 1.80	1.78	1.03	9.60a ± 0.26	2.75	0.15	52.50a ± 3.06	5.83	1.76	39.02a ± 6.15	15.76	3.55	1287a ± 203.05	15.77	117.23
T2	100.97a ± 0.95	0.94	0.54	9.80a ± 0.62	6.37	0.36	56.13b ± 3.65	6.51	2.11	38.04a ± 2.81	7.38	1.62	1255a ± 92.60	7.37	53.467
T3	101.40a ± 1.27	1.25	0.73	9.96a ± 0.11	1.15	0.06	53.60a ± 0.51	0.96	0.30	40.33a ± 1.0	2.49	0.58	1328a ± 30.19	2.27	17.43
T4	100.60a ± 1.64	1.63	0.95	9.90a ± 0.10	1.01	0.05	53.93a ± 4.82	8.93	2.78	40.30a ± 1.79	4.45	1.03	1329a ± 59.16	4.44	34.15
T5	103.53b ± 1.35	1.31	0.78	10.06b ± 0.11	1.14	0.06	52.73a ± 1.41	2.68	0.81	44.16b ± 4.84	10.97	2.79	1457b ± 160.0	10.98	92.38
T6	102.47ab ±1.19	1.16	0.68	10.16b ± 0.15	1.50	0.08	51.43a ± 3.08	6.00	1.78	39.70a ± 1.64	4.14	0.95	1309a ± 54.32	4.14	31.36
T7	102.13ab ±2.28	2.23	1.31	10.06b ± 0.11	1.14	0.06	52.63a ± 1.85	3.53	1.07	37.80c ± 1.86	4.92	1.07	1247a ± 61.30	4.91	35.39
T8	101.33a ± 2.88	2.84	1.66	10.03b ± 0.25	2.50	0.15	50.63a ± 2.55	5.05	1.47	37.14c ± 3.28	8.83	1.89	1225a ± 108.16	8.82	62.44

Means within each column followed by different superscript letters are significantly different at $P < 0.05$ (Tukey's HSD test after one-way ANOVA). SD = Standard Deviation; CV = Coefficient of Variation (%) = (SD/Mean) × 100; SE = Standard Error = SD/√n (n = 3 replicates)

Table 5b: Tuckey's test, Shapiro-Wilk normality test on yield attributes

Variable	Treatment (F)	effect *P*-value	Error (MS)	variability Coefficient variation (CV)	of Tukey's test (*P*)	Relative efficiency (RCBD)	Shapiro-Wilk (W)
Plant height (H)	1.20	0.3635	2.46304	1.54	0.4374	1.18	0.9734
Spike length (SL)	1.68	0.1926	0.05827	2.43	0.1881	1.18	0.8560
Grains per spike (GPS)	0.89	0.5420	9.45214	5.81	0.0908	0.92	0.9352
1000 grains weight	1.22	0.3548	11.9166	8.73	0.9370	0.95	0.9576
Yield	1.21	0.3573	12.9866	8.73	0.9358	0.95	0.9560

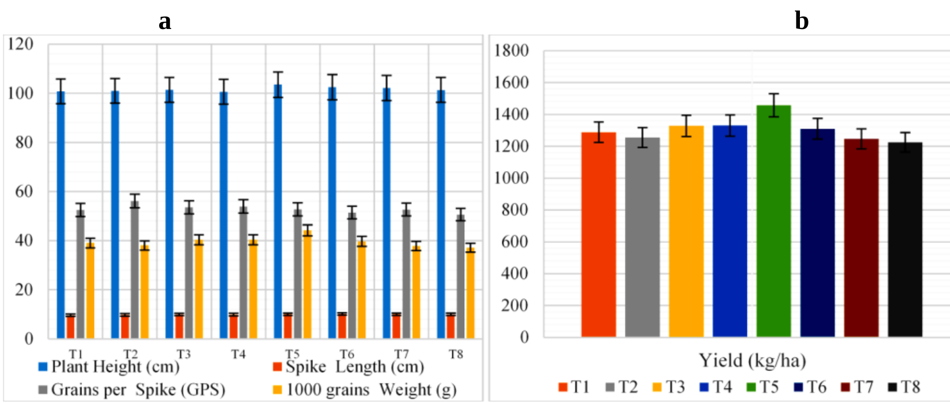

Fig. 3: Effects of standard urea and neem-coated urea with variable rates of water retention polymers on the plant height, spike length, number of grains per spike, 1000 grains (**a**) and yield (**b**)

water demand (CWR) seventh treatment and eighth treatment shown by raised WRPs (seventh treatment and eighth treatment) indicated that by improving soil water retention, increasing WRPs application reduces crop water demand even further. Demand was lower in plot (third treatment –eighth treatment) treated under irrigation water demand (IWR) than in control treatments (first treatment and second treatment). This implied that WRPs effectively reduced the water needed to offset losses, hence lowering the irrigation water demand and enhancing soil water retention and frequency of irrigation events. In essence, the WRPs application may lower the demand for further irrigation by enhancing soil water retention (Fig. 4b).

Interactive effects of WRPs, SU and NCU on yield, WUE, WP and NUE

The effect of WRPs, SU, and NCU on WUE, water productivity and NUE in agricultural operations was examined. It was noted that crop production and NUE under varying application rates of nitrogen fertilizers, especially NCU, SU and others (Table 6). This information offered understanding of how WRP interacts with many urea types and how this affects NUE and eventually crop production. Higher WRP application rates greatly enhanced WUE, showing the importance of WRPs in lowering soil evaporation losses and hence optimizing crop water use. With the highest WUE, eighth treatment showed significantly improved water conservation and crop output per unit of applied water with WRPs. The WP also improved with higher WRP application rates, with eighth treatment achieving a WP of 1.28 kg m^{-3}, significantly higher than control treatments. However, the effect on crop yield was inconclusive, as other factors like nutrient availability, soil health, and environmental conditions may also influence yield. The NUE was a crucial factor in assessing the efficiency of nitrogen fertilizers, and treatments with WRPs, especially those using NCU, showed

Table 6: Treatments effect on yield, IWUE, water productivity and NUE

Treatments	Total water applied (mm)	CWR (mm)	IWR (mm)	Total water applied (m^3 ha^{-1})	Yield (kg ha^{-1})	IWUE (kg ha^{-1} mm^{-1})	WP (kg m^{-3})	NUE
T1	615a	450	350	6150a	3855b	6.26a	0.6268a	20.8c
T2	534b	450	350	5340b	3760c	7.04b	0.7041b	20.3d
T3	479c	450	350	4790c	3984a	8.31c	0.8317c	21.5b
T4	429d	450	350	4290d	3982a	9.28d	0.9282d	21.5b
T5	400e	450	350	4000e	4362a	10.90e	1.0905e	23.6a
T6	377f	450	350	3770f	3923a	10.40e	1.0405e	21.2c
T7	333g	450	350	3330g	3734c	11.21f	1.1213f	20.2d
T8	286h	450	350	2860h	3668d	12.82g	1.2825g	19.8e

Values within each column followed by different superscript letters are significantly different at $P < 0.05$ (Tukey's HSD test after one-way ANOVA). CWR = Crop water requirement; IWR = Irrigation water requirement. IWUE = Irrigation water use efficiency, WP = Water productivity; NUE = Nitrogen use efficiency

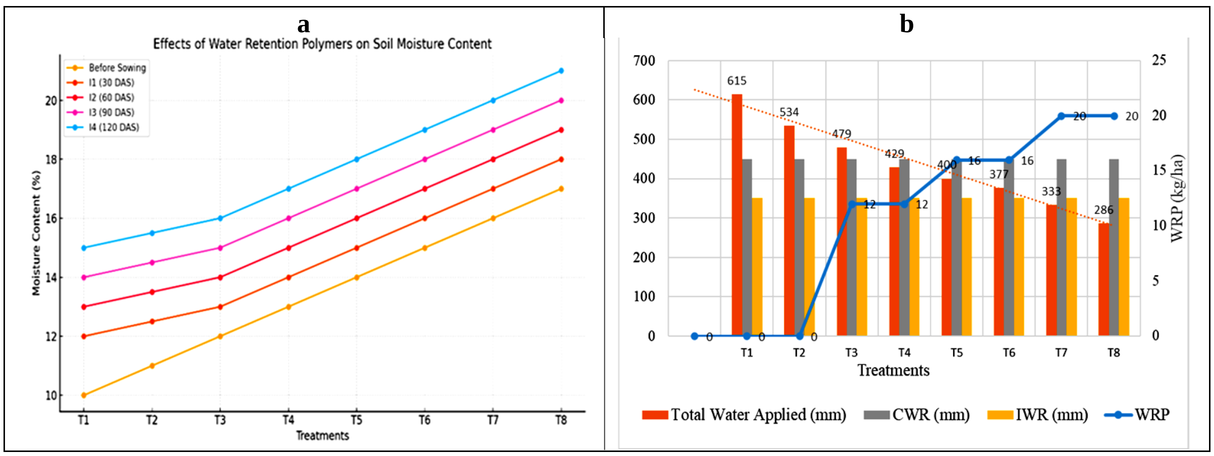

Fig. 4: Effects of water retention polymers on soil moisture content (**a**) and the depth of water applied, crop water requirement, irrigation water requirement (**b**)

better NUE than control and SU treatments. SU showed higher NUE than NCU across all WRP application rates, suggesting that NCU efficiency in providing nitrogen may not match SU.

Fig. 5a showed the impact of WRPs on crop yield across eight treatments. Fifth treatment where with Standard Urea combined with WRP at 16 kg ha^{-1}showed the highest yield, exceeding 4000 kg ha^{-1}. Other treatments showed similar yields, suggesting that fifth treatment may have improved nutrient availability or soil quality. Overall, fifth treatment was the most beneficial treatment (Fig. 5a). With a smaller range and somewhat lower median yield of 3850 kg ha^{-1}, although NCU showed more variability, SU achieved higher maximum yields. Data further illustrated that among eight treatments, the effects of WRPs in crop NUE were positive. With NUE higher than 20 kg ha^{-1}, fifth treatment indicated the most effective NUE. Other treatments showed similar NUE values, suggesting WRP generally enhances NUE (Fig. 5b). SU outperformed NCU at 16.0 kg ha^{-1} WRPs, while NCU maintains consistent yields. Reduced yields resulting from excessive WRP indicated the need for ideal WRP levels and urea type choice for maximum crop yield. The data presented as boxplot revealed that SU boasted a greater range of yield values and a higher median yield approximately 4000 kg ha^{-1} (Fig. 5c). The peak in fifth treatment suggested optimizing WRP application for maximum efficiency. SU achieved the highest NUE at 15.0 kg ha^{-1} WRP, while NCU consistently increased to 15.0 kg ha^{-1} WRP. NUE declined beyond 15.0 kg ha^{-1} WRP, suggesting potential saturation or inhibitory effects of excessive WRP. However, NCU maintained a steadier NUE performance (Fig. 5b). A comparison of NUE with SU and NCU is given in Fig. 5d. SU had a higher range of NUE values, with a median slightly above 21 kg ha^{-1} and a maximum exceeding 23.5 kg ha^{-1}. NCU had a narrower range and more consistent performance, while NUE variability was greater for SU.

Fig. 6a shows the impact of WRPs on WP across eight treatments. Treatment eight achieved the highest productivity (1.2825 kg m^{-3}), outperforming the other treatments. WP increased progressively from first treatment to eighth treatment, indicating a positive impact of WRPs with their increased application. Treatments fifth treatment where with Standard Urea combined with WRP at 16 kg ha^{-1}, sixth treatment where with Neem Coated Urea combined with WRP at 16 kg ha^{-1}, and seventh treatment maintained moderate productivity values. Fig. 6b compares the WP between SU and NCU. Both had a similar median WP (~1.0 kg m^{-3}), but NCU had a wider range with higher maximum

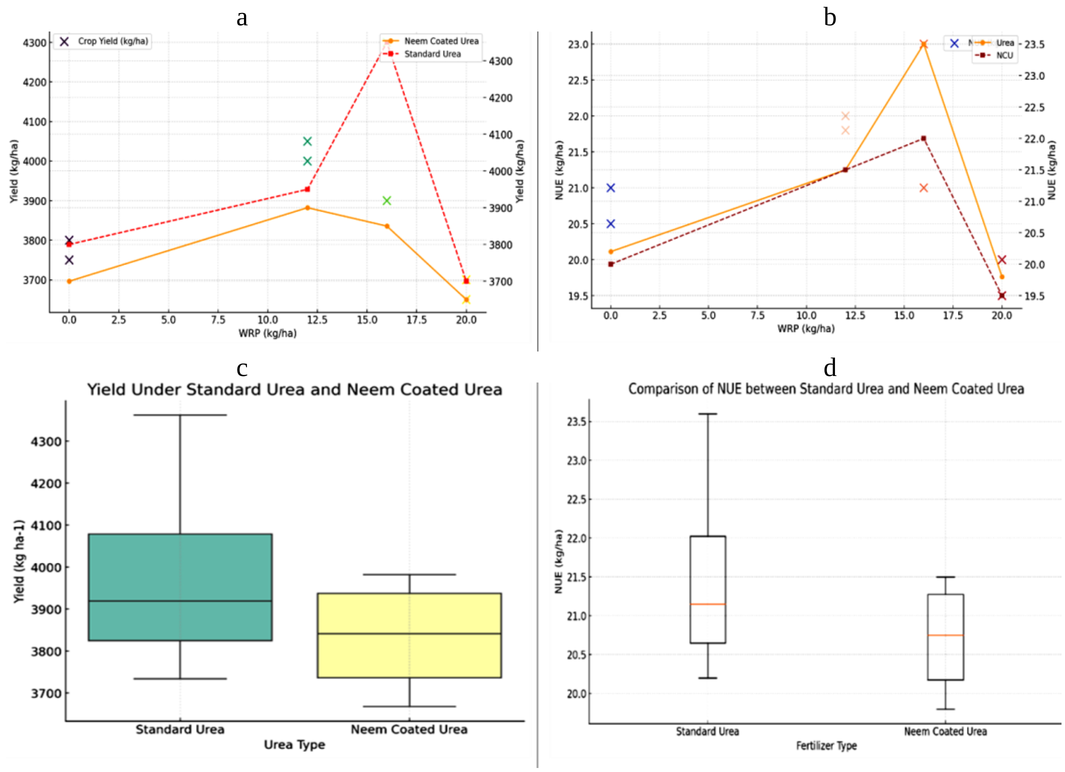

Fig. 5a–d: Effects of water retention polymers, neem coated urea and standard urea on yield and nitrogen use efficiency

values. SU had a narrower WP range, while NCU outperformed SU in potential peak productivity but had greater variability. Fig. 6c the impact of WRPs on WP at different application rates. The control treatment showed minimal WP, while higher WRP application rates increased WP, peaking at 20 kg ha^{-1} with the highest median and narrow variability. Treatment at 16 kg ha^{-1} also improved WP, but with a smaller range. The results suggested a positive relationship between WRP application rates and WP. Fig. 6d showed that eighth treatment achieved the highest (IWUE), with fifth treatment to eighth treatment showing significant improvements compared to first treatment to fourth. first treatment had the lowest IWUE, suggesting that eighth treatment optimizes water used for maximum productivity, with fifth treatment to eighth treatment showing the least improvement. The plot Fig. 6a-d compares IWUE between SU and NCU treatments. Both had similar median values, but NCU had a wider range and higher maximum value. SU showed narrower variability, suggesting its effectiveness may depend on environmental or management factors. The impact of WRPs on IWUE. The control group depicted minimal IWUE, while higher WRP levels consistently increase IWUE, reaching maximum at 20 kg ha^{-1}. Treatments at 16 and 20 kg ha^{-1} showed significantly higher IWUE, indicating enhanced WP. Variability decreased slightly at higher WRP levels, suggesting consistent improvements in water efficiency.

Correlation analysis between WRP, NUE, IWUE & WP

The correlation matrix revealed a strong positive correlation between WRPs and NUE in Fig. 7, indicating that WRP application significantly enhanced NUE. WRP also showed a high correlation with IWUE and WP, indicating its role in improving water management. NUE strongly correlated with WRP and IWUE, highlighting its link to WUE and NUE. IWUE and WP exhibited a tight positive correlation, implying that improvements in IWUE directly enhanced WP. These relationships demonstrated the synergistic effects of WRP in enhancing resource efficiency for sustainable wheat growth. Application of WRP not only preserved soil moisture but also increased nitrogen absorption, hence improving wheat crop performance.

Discussion

This research revealed new aspects of the application of WRPs, and improved nitrogen fertilizers use in significantly enhancing wheat yield attributes with optimizing NUE and WP. However, formulations coated with neem are known to lessen nitrogen volatilization and leaching, which proved its advantages over time. To maximize the effects of NCU on crop performance, future studies should focus on adjusting the rates and timing of application as like previous researchers performed (Kumar *et al.* 2021; Singh *et al.* 2022a, b; Ali and Khan 2022; Choudhary *et al.* 2023; Patel *et al.* 2023).

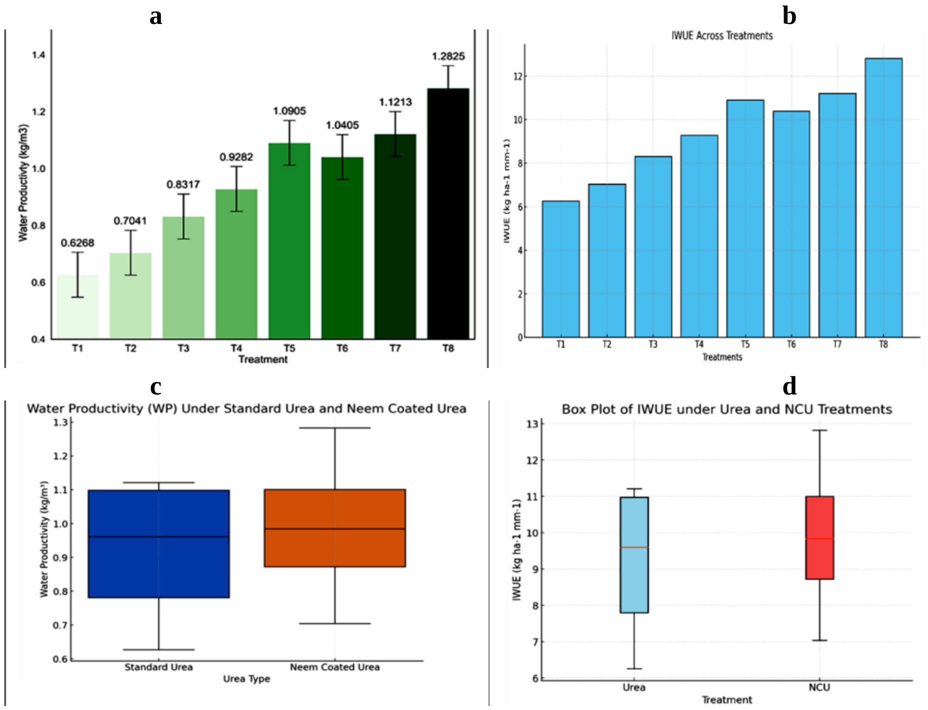

Fig. 6a–d: Effects of water retention polymers, neem coated urea, and standard urea on water productivity and irrigationwater use efficiency

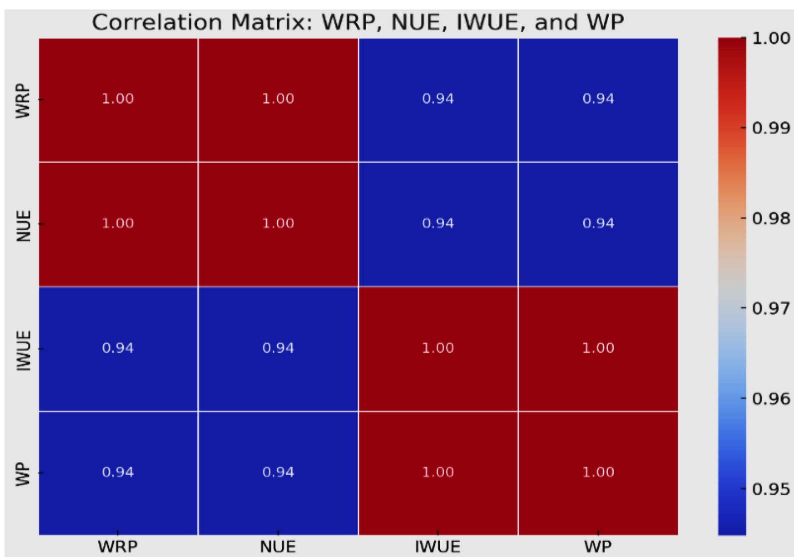

Fig. 7: Correlation matrix between water retention polymers, nitrogen use efficiency, irrigationwater use efficiency, water productivty

This study found no significant differences between the interactive effects of NCU and SU integrated with WRPs. Fifth treatment exhibited maximum yield and proved best combination of treatment. The statistical analysis RCBD, Tuckey's test, mean, SD, CV and SE values indicated that plant height, spike length, grains per spike, 1000 grain weight and yield in Fig. 3a, as has been reported by various studies (Aziz *et al.* 2019; Kumari *et al.* 2019; Altaf *et al.* 2021; Bandak *et al.* 2021; Folina *et al.* 2021; Rehman *et al.* 2021; Choudhary *et al.* 2023; Khan *et al.* 2023). Research on wheat found that NCU, normal urea, and WRPs increased crop yield and NUE but also reduced water stress and improved plant development. This redefined the combination of NCU and WRPs improved nutrient use and yield, making it a sustainable approach for increasing crop productivity and NUE, especially in areas with limited water supplies just like in sandy soils (Andry *et al.* 2009; Thind *et al.* 2010; Abel 2013; Sohail-Ur-Raza *et al.* 2015; Yu *et al.* 2017; Bana *et al.* 2018; Albalasmeh *et al.* 2022; Shi *et al.* 2023).

Ther WRPs and NCU showed potential for sustainable agricultural approaches, improving crop output and NUE, especially during dry periods (Sharma and Kumawat 2019). Although moderate WRP rates (16 kg ha^{-1}) were the most effective, higher WRP rates (20 kg ha^{-1}) in combination with NCU considerably enhanced NUE by minimizing nitrogen volatilization and leaching (Shivay *et al.* 2016). NCU beat regular urea (Basso *et al.* 2017; Raza *et al.* 2021) by enhancing nutrient release and hence lowering nitrogen losses. The need for ideal application rates is underlined by the fact that too high WRP treatments usually resulted in insufficient nitrogen availability. SU yields higher peak yields, while NCU offers stability. WRP in fertilizers significantly influences NUE, with SU showing superior NUE. The optimal NUE required adjusting fertilizer to WRP ratios. Interaction with fertilizers was crucial for increased in NUE, WUE, and WP (Ostrand *et al*. 2020; Lal *et al.* 2021; Patra *et al.* 2022; Bana *et al.* 2023; Xu *et al.* 2023).

This study found promising results by application of rates of WRPs 16–20 kg ha^{-1} produced the best outcomes; WRPs assisted to boost WP and WUE. Though it had a rather lower WUE than seventh treatment, most likely from overwatering, the treatment with 20 kg ha^{-1} WRPs produced significantly higher yield. This emphasizes the requirement of reaching the best efficacy by matching WRPs rates with environmental and irrigation variables. Although WRPs raised NUE, WUE, and WP, yield values stayed quite highly linked with nitrogen supply and soil conditions. This study revealed that WRPs significantly impact crop productivity by interacting with different urea forms. SU yields increased with WRPs, while NCU produced consistent yields. High WRPs application can reduce soil aeration and nutrient absorption, requiring adaptation to site-specific conditions (Liao *et al.* 2016; Tahir *et al.* 2016; Yadav *et al*. 2022b).

The WP was improved more by using NCU with water retention polymers fourth, sixth treatment, eighth treatment when compared to Standard Urea used with water retention polymers third treatment, fifth treatment, seventh treatment, where water production increased at the maximal WRP rate of 20 kg ha^{-1}. In previous studies, the combined impacts of WRPs and NCU were most evident (Liao *et al.* 2016; Zaman *et al.* 2018). Souza *et al.* (2023) found that NCU's gradual nitrogen release promotes crop development in water-limited environments, while WRPs improve soil moisture retention, likely due to its slow-release character that enhances nitrogen absorption (Li *et al.* 2014; Singh *et al.* 2022a, b; Souza *et al.* 2023) and supported higher WP. Nevertheless, small WRP rates (16 kg ha^{-1}) could had negative effects, perhaps resulting from mismatched crop needs or overwatering.

This study found that WRPs' water-holding capacity was significantly enhanced when combined with NCU to fulfill the crop water requirement, due to which CWR decreased as the WRPs rates from second treatment to eighth treatment increased respectively, depicting the need to match fertilizer release rates with nutrient needs. This integrated approach with NCU had achieved maximum WP but had varying performance compared to standard urea (Tahir *et al.* 2016; Ostrand *et al.* 2020; Yadav *et al.* 2022a). Future research should focus on long-term economic and environmental impacts, sustainable agriculture, and integrating WRP and fertilizer techniques with irrigation approaches for best efficacy, while also focusing on ideal application techniques and cost-effectiveness (Lal *et al.* 2021; Patra *et al.* 2022; Xu *et al.* 2023).

The correlation matrix between WRP, WUE, NUE and WP had investigated to break down the interactive effects of WRPs with SU and NCU on WUE, NUE and WP were also investigated in research by Sharma and Kumawat (2019) to be important in improving WP, IWUE and NUE. With their preservation of soil moisture and reduction of leaching, the strong correlation between WRPs and NUE ($r = 1.00$) indicated that WRPs help to absorb nitrogen. The relationship between WRPs, IWUE and WP is strong, indicating its effectiveness in improving water management in arid environments, with an ideal correlation of 1.00 indicating direct productivity increase (Li *et al.* 2014; Kumar *et al.* 2023). The study highlighted the importance of regulated nutrient release in sustainable agriculture and water resources planning and management to improve resource use. It is suggested that improve WUE and NUE by wheat crop may depend on WRPs and nitrogen use optimization.

Conclusion

The use of WRPs significantly enhanced soil moisture retention, with higher rates lowering the demand for irrigation and agricultural water use and improving IWUE and WP (maximum as 1.282 kg m^{-3} in eighth treatment where with Neem Coated Urea combined with WRP at 20 kg ha^{-1}. However, WRPs at 16 kg ha^{-1} in fifth treatment where with Standard Urea combined with WRP at 16 kg ha^{-1}, and sixth treatment where with Neem Coated Urea combined with WRP at 16 kg ha^{-1}, yielded best results due to optimum soil water retention, 20 kg ha^{-1} (seventh treatment with Standard Urea combined with WRP at 20 kg ha^{-1} and eighth treatment where with Neem Coated Urea combined with WRP at 20 kg ha^{-1}, reduced yield, highlighting the risks of over-application and excessive moisture retention. Among fifth treatment and sixth treatment and in other pairs of nitrogen treatments, the study found that normal urea outperformed NCU in terms of agricultural output and NUE maximum value as 23.6 in fifth treatment where with Standard Urea combined with WRP at 16 kg ha^{-1}, despite NCU's gradual nitrogen release aiding water management but not meeting current nitrogen demands, especially in sandy soils. Results suggested that by applying traditional urea along with WRP at a rate of 16 kg ha^{-1} was the best combination in fetching wheat yield whilst economizing on resources. Moreover, coordinating NCU's nitrogen release rate with wheat crop nitrogen needs can reduce nitrate losses and increase WUE. The study suggested that farmers in sandy soils can improve agricultural practices by sowing wheat in mid-November, ensuring adequate irrigation, and using a balanced NPK fertilizer application with WRP to achieve profitable crop production. Further field trials and practical evaluations are required to mitigate future water crisis and food security challenges to find out optimum levels of fertilizers and WRPs applications under variable agro-ecological conditions.

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Author Contributions

All authors contributed to the study conception, design, data collection, analysis, and manuscript writing. All authors read and approved of the final manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Data Availability

All data generated or analyzed during this study are available from the corresponding authors upon reasonable request.

Ethics Approval

This article does not contain any studies involving human participants or animals performed by any of the authors.

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