



RESEARCH ARTICLE

Influence of coated urea on yield response, energetics and economics of wheat under the Shivalik foothills of Jammu

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Abstract

The study evaluated the impact of coated urea fertilisers on the energy efficiency and economic performance of wheat grown under irrigated conditions in the humid eco-region of the Western Himalayas. A field experiment was conducted during the rabi seasons of 2017–18 and 2018–19 at the research farm of Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST), Jammu, Chatha, using a randomized block design (RBD) with 11 treatments and 3 replications. The soil was sandy clay loam with slightly alkaline pH, low organic carbon and nitrogen (N) and medium phosphorus (P) and potassium (K). Treatments included conventional urea, zinc-coated urea (ZnCU), neem-coated urea and their combinations at different N levels, along with recommended PKZn fertilisers. Results showed that application of 100 % recommended N through ZnCU + PKZn recorded the highest total energy input, 21308.02 MJ ha⁻¹ and output (84426.33 MJ ha⁻¹). Conventional urea exhibited the maximum specific energy (10 MJ kg⁻¹), while the combination of ZnCU and neem-coated urea at 85 % N achieved the highest energy productivity (0.113 kg MJ⁻¹). The control recorded the highest energy-use efficiency (4.50). ZnCU-based treatments at both 100 % and 85 % N levels significantly improved grain yield, with comparable results across treatments. Economically, 100 % ZnCU + PKZn recorded the highest net returns and benefit-cost ratio, demonstrating its superiority for enhancing energy efficiency, productivity and profitability of wheat in the region.

Keywords: energy input; neem-coated urea; productivity; specific energy; zinc-coated urea

Introduction

Wheat is one of the most important cereal crops globally and a key pillar of food security in India, where it is the second most important crop after rice, according to the Ministry of Agriculture and Farmers Welfare (1). It covered about 31.36 million hectares with a production of approximately 107.6 million metric tonnes and an average yield of about 3.44 t/ha (3440 kg/ha), while more recent estimates (2023–24) indicate production exceeding 110 million tonnes. India is the world's second-largest wheat producer after China; in the Union Territory of Jammu and Kashmir, wheat is a major rabi crop with production around 1.4 million tonnes in 2020–21 as reported in regional agricultural statistics, though productivity remains below the national average due to limited irrigation, lower mechanisation and climatic variability; to enhance nitrogen use efficiency (NUE) and reduce losses from conventional urea, several slow-release formulations such as neem-coated urea (NCU), sulphur-coated urea (SCU), polymer-coated urea (PCU) and zinc-coated urea (ZnCU) have been developed and evaluated in

agronomic studies (2). The Government of India made 100 % neem-coating of subsidised urea mandatory from 25 May 2015 under the fertiliser control order to curb diversion and improve NUE, documenting improved nitrogen retention, higher uptake and yield benefits in wheat compared with conventional urea (3).

Previous studies showed that ZnCU not only enhances crop yields but also reduces the need for additional zinc (Zn) application (4). With India's growing population and increasing food demand, intensive cropping systems requiring substantial energy inputs have become essential. Energy plays a vital role in agriculture, supporting key activities such as fertiliser production, irrigation, farm mechanisation, pest management and transportation (5). To achieve India's food production goals of over 250 million tonnes, the energy demand is estimated to reach nearly 9 billion joules. However, with rising energy costs and declining resource availability, using energy efficiently in agriculture has become increasingly important. Reliable access to electricity is essential for farmers to enhance productivity and

ensure efficient farm operations. In view of these challenges, the present study was undertaken to examine how different coated urea formulations can improve energy efficiency, crop yield and the economic sustainability of wheat cultivation under irrigated conditions in the western Himalayan region of Jammu. The research assessed the effects of various coated urea types, including neem-coated urea, Zn-coated urea and their combined application to determine which formulation most effectively enhances energy use efficiency and profitability of wheat production in this specific agro-climatic region.

Materials and Methods

Experimental Site

A field experiment was conducted during the rabi seasons of 2017–18 and 2018–19 at the research farm of SKUAST-Jammu, situated in Chatha. The site is positioned at 32°40' N latitude, 74°58' E longitude and lies 320 m above sea level. The area has a subtropical climate, marked by hot, dry summers, a humid monsoon period and cool, dry winters. Meteorological data show that the South-West monsoon (from July to October) accounts for nearly 72 % of the total annual rainfall, while the remaining precipitation occurs as occasional winter showers caused by western disturbances between December and March. During the wheat growth period (October–April), the average maximum temperature ranged from 13.0–34.3 °C and the minimum temperature varied between 2.9–20.7 °C (Fig. 1). The experimental soil was identified as sandy clay loam with a slightly alkaline pH. Laboratory testing indicated that the soil was low in organic carbon and available nitrogen (N), while phosphorus (P) and potassium (K) levels were moderate. Standard analytical techniques were used to measure nutrient content: available N was estimated by the alkaline permanganate method (5), available P by the Olsen method (6) and available K through the neutral normal ammonium acetate extraction method (7). Organic carbon was estimated using the Walkley and Black wet oxidation method (8). Additionally, extractable Zn was measured using the diethylene triamine pentaacetic acid (DTPA) extraction method

Table 1. Physical and chemical characteristics of the soil of the experimental field

Soil characteristics	Values	
	2017	2018
pH (1:2.5)	7.18	7.24
EC (dS/m) at 25 °C	0.16	0.18
Organic carbon (g kg ⁻¹)	3.75	3.78
Available nitrogen (mg kg ⁻¹)	107.26	115.60
Available phosphorus (mg kg ⁻¹)	5.07	6.66
Available potassium (mg kg ⁻¹)	49.42	57.68
Available zinc (mg kg ⁻¹)	0.52	0.54

Table 2. Treatment details

S. No.	Treatments	Symbols used
1.	No nitrogen + Recommended P, K & Zn RDF (Control)	T ₁
2.	100 % Rec. N through Urea + Rec. P, K & Zn	T ₂
3.	70 % Rec. N through NCU + Rec. P, K & Zn	T ₃
4.	85 % of Rec. N through NCU + Rec. P, K & Zn	T ₄
5.	100 % of Rec. N through NCU + Rec. P, K & Zn	T ₅
6.	70 % of Rec. N through ZnCU + Rec. P, K & Zn	T ₆
7.	85 % of Rec. N through ZnCU + Rec. P, K & Zn	T ₇
8.	100 % of Rec. N through ZnCU + Rec. P, K & Zn	T ₈
9.	70 % of Rec. N through NCU + ZnCU + Rec. P, K & Zn	T ₉
10.	85 % of Rec. N through NCU + ZnCU + Rec. P, K & Zn	T ₁₀
11.	100 % of Rec. N through NCU + ZnCU + Rec. P, K & Zn	T ₁₁

N: nitrogen; Rec.: recommended; P: phosphorus; K: potassium; Zn: zinc; RDF: recommended dose of fertilisers; NCU: neem coated urea; ZnCU: zinc coated urea

and values were found to be below the critical threshold, indicating potential Zn deficiency in the soil (Fig. 2, Table 1) (9).

Experimental design and treatment details

The experiment was designed to evaluate the effects of different N fertiliser treatments on wheat growth using prilled urea, NCU, ZnCU and a combination of NCU and ZnCU at varying nitrogen levels. A total of 11 treatment combinations were tested (Table 2). Treatment T₁ served as the control and received no nitrogen but was supplied with the recommended doses of P, K and Zn. Treatment T₂ received 100 % of the recommended N through prilled urea along with the recommended P, K and Zn. Treatments T₃, T₄ and T₅ received 70 %, 85 % and 100 % of the recommended N through NCU respectively, along with uniform doses of P, K and Zn. Similarly, treatments T₆, T₇ and T₈ received 70 %, 85 % and 100 % N through ZnCU, while treatments T₉, T₁₀ and T₁₁ comprised a combination of NCU and ZnCU at 70 %, 85 % and 100 % N levels respectively, along with the full recommended doses of P, K and Zn. The experiment was laid out in a randomized block design (RBD) with 3 replications to ensure statistical reliability and to minimise treatment variability. Detailed treatment specifications are presented in Table 2.

The selection of 70 %, 85 % and 100 % of the recommended N levels was based on the hypothesis that coated urea formulations enhance NUE, thereby allowing a reduction in N application without compromising crop performance. The 100 % level represents the standard recommended dose for optimal yield under conventional practices, while the 85 % and 70 % levels were included to assess whether improved NUE from coated fertilisers could sustain yield and profitability at reduced N inputs, thereby lowering input costs and minimising environmental losses.

Coating methods

To prepare ZnCU, commercial-grade prilled urea (1.65 mm diameter) was first treated with a gum acacia solution at a rate of 2 g kg⁻¹ of urea, following the standard coating protocol. The mixture was thoroughly agitated to ensure uniform distribution of the adhesive, forming a thin film over the granule surface. Subsequently, zinc sulphate heptahydrate (ZnSO₄·7H₂O) was added at a rate equivalent to 21.0 kg per tonne of urea (2.1 % w/w of urea) and the material was mixed uniformly to facilitate even deposition of zinc on the granules. The final theoretical Zn content was calculated based on the Zn concentration in ZnSO₄·7H₂O (approximately 21 % Zn), resulting in an estimated Zn enrichment of about 0.44 % elemental Zn by weight of urea. The freshly prepared ZnCU was air-dried under shade to stabilise the coating and then used for field application.

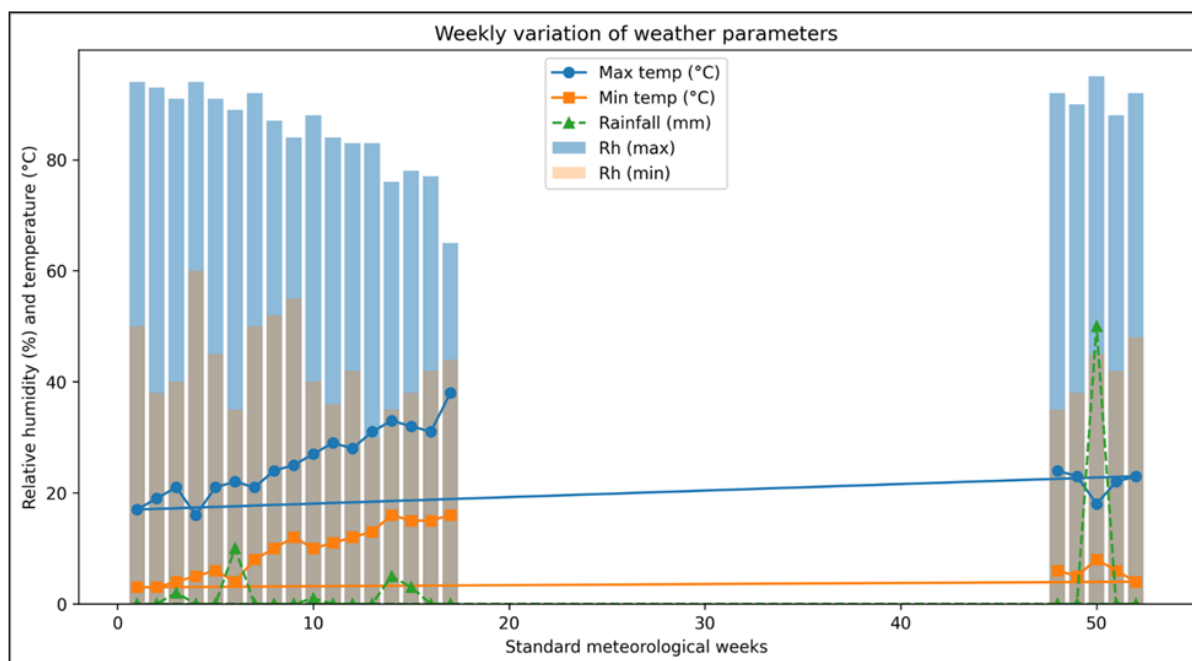


Fig. 1. Weather parameters recorded during crop growing season (mean of two seasons).

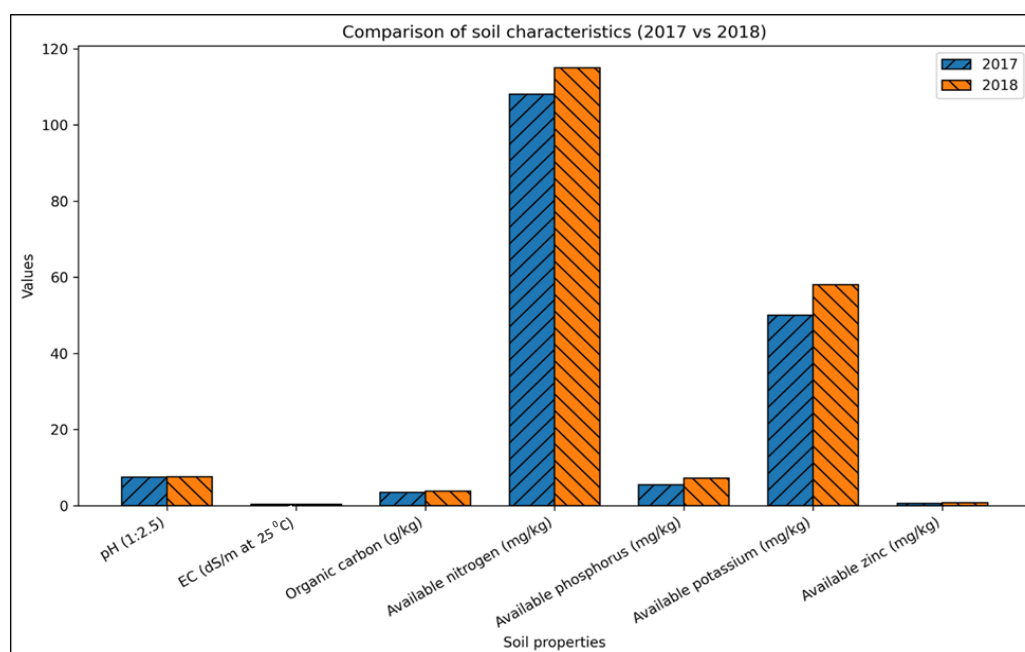


Fig. 2. Graph representing physical and chemical characteristics of soil of experimental site.

Neem-coated urea (NCU), procured commercially, was further subjected to the same Zn-coating procedure to produce NCU + ZnCU for experimental use. To ensure coating efficiency and validate the final Zn concentration, representative samples of coated urea were analysed for total Zn content using standard analytical procedures (e.g., acid digestion followed by atomic absorption spectrophotometry or ICP-OES). Coating uniformity was assessed through random granule sampling and visual inspection, while nutrient content verification confirmed that the achieved Zn concentration closely matched the calculated theoretical value.

To prepare the ZnCU, commercial-grade prilled urea (1.65 mm in diameter) was initially treated with a gum acacia solution, applied at a rate of 2 g kg⁻¹ of urea, following the recommended coating protocol. The mixture was thoroughly agitated to ensure uniform distribution of the gum acacia, forming a thin adhesive film over the surface of the urea granules. Subsequently, 21.0 kg of zinc sulphate heptahydrate (ZnSO₄·7H₂O)

was added to the coated prills, followed by additional mixing to facilitate the even deposition of a Zn layer. This freshly prepared ZnCU was immediately utilised for field application. Neem-coated urea, obtained commercially, was similarly treated using this Zn-coating procedure to produce zinc NCU + ZnCU for experimental use.

Fertiliser application

During both study years, the wheat variety HD-3086 was planted at a seed rate of 100 kg per hectare with 20 cm row spacing, sown on November 27 in the first season and November 24 in the second. The N requirement was met using different fertiliser sources, namely prilled urea, NCU, ZnCU and a combination of NCU and ZnCU. The P and K were supplied through single superphosphate and muriate of potash (MOP) respectively and the recommended doses of P₂O₅ and K₂O were uniformly applied to all treatments. Nitrogen was applied in split doses, with the first at the crown root initiation (CRI) stage and the second prior to booting. For weed management, pendimethalin was applied at 1.5 kg ha⁻¹ two days

after sowing. Crop protection and intercultural operations were conducted following the recommended agronomic practices as outlined in the standard package developed by SKUAST-J (10). Irrigation was applied as needed to sustain optimal soil moisture during the entire growing period. Once the crop reached maturity, the wheat from each plot was harvested manually and threshed individually. Observations were collected on various growth characteristics, yield components, grain yield and straw yield.

Statistical analysis

Statistical analysis was conducted using analysis of variance (ANOVA) under a randomized block design (RBD) and treatment means were compared using the *F*-test, based on the null hypothesis framework (11). Wherever relevant, the standard error of the mean and the critical difference at a 5 % level of significance were computed to determine statistically meaningful differences among treatments.

Results

Energy input analysis

The energy input analysis indicated that the total energy consumption was 13189.25 MJ ha⁻¹. Among the various inputs, single super phosphate (SSP) contributed the highest energy equivalent (3893.72 MJ ha⁻¹), followed by irrigation (2832.5 MJ ha⁻¹). Energy used for land preparation through tractor operation accounted for 1992 MJ ha⁻¹, while diesel fuel consumption contributed 1970.85 MJ ha⁻¹ to the total energy input. The energy equivalent of a seed was 1510 MJ ha⁻¹. Among the other inputs, MOP contributed 468.3 MJ ha⁻¹ and zinc sulphate (ZnSO₄) accounted for 418 MJ ha⁻¹, whereas human labour contributed the least energy input with 103.88 MJ ha⁻¹. Overall, fertiliser inputs, irrigation and land preparation constituted the major share of the total energy consumption in the production system (Table 3).

The total energy input varied among different N management treatments. The control treatment (T₁) with recommended P, K and Zn recorded a total energy input of 13189.25 MJ ha⁻¹. Application of 100 % recommended N through urea along with recommended PKZn (T₂) resulted in the highest total energy input of 29627 MJ ha⁻¹, where N alone contributed 16437.75 MJ ha⁻¹. Treatments receiving N through NCU recorded total energy inputs of 24703.25 MJ ha⁻¹ (T₃: 70 % N), 27195.43 MJ ha⁻¹ (T₄: 85 % N) and 29627 MJ ha⁻¹ (T₅: 100 % N). Similarly, N supplied through ZnCU showed total energy inputs of 24552.39 MJ ha⁻¹ (T₆: 70 % N), 26987.03 MJ ha⁻¹ (T₇: 85 % N) and 29426.78 MJ ha⁻¹ (T₈: 100 % N), including a small contribution from ZnSO₄. In treatments where N was applied through a combination of NCU and ZnCU, the total energy input was 24595.66 MJ ha⁻¹

(T₉: 70 % N), 25844.84 MJ ha⁻¹ (T₁₀: 85 % N) and 27057.29 MJ ha⁻¹ (T₁₁: 100 % N). Overall, the results indicated that total energy input increased with higher N application levels, irrespective of the N source (Table 4).

The pooled analysis of 2 years revealed that the fixed energy input remained constant at 13189.25 MJ ha⁻¹ across all treatments, whereas variable and total energy inputs varied depending on the N source and level applied. The control treatment (T₁) recorded 13189.25 MJ ha⁻¹ as both variable and total energy input. Among the fertilised treatments, the highest variable energy input (29627.00 MJ ha⁻¹) was observed with 100 % recommended N through urea (T₂) and 100 % recommended N through NCU (T₅), resulting in a total energy input of 21408.13 MJ ha⁻¹. Treatments receiving 70 % and 85 % recommended N through NCU recorded total energy inputs of 18946.25 MJ ha⁻¹ (T₃) and 20192.34 MJ ha⁻¹ (T₄) respectively. Similarly, ZnCU treatments showed total energy inputs of 18870.82 MJ ha⁻¹ (T₆) at 70 % N, 20088.14 MJ ha⁻¹ (T₇) at 85 % N and 21308.02 MJ ha⁻¹ (T₈) at 100 % N. In treatments where N was applied through a combination of NCU and ZnCU, the total energy input was 18892.46 MJ ha⁻¹ (T₉) at 70 % N, 19517.05 MJ ha⁻¹ (T₁₀) at 85 % N and 20123.27 MJ ha⁻¹ (T₁₁) at 100 % N. Overall, the results indicated that variable and total energy inputs increased with higher N application levels irrespective of the N source, while the fixed energy input remained unchanged across treatments (Table 5 & Fig. 3). The effect of urea and coated urea on yield is shown in Fig. 4.

Effect of different nitrogen sources on grain and straw yield, energy output and total energy production of rice

As shown in Fig. 5, application of slow-release coated urea, particularly Zn-coated urea alone or in combination with NCU, significantly improved energy output. The quantities of energy output produced by wheat were significantly influenced by different sources and levels of slow-release coated urea (Table 6 & Fig. 6). The results indicated that all N treatments recorded higher grain yield, straw yield and total energy output compared with the control (recommended PKZn). The maximum grain yield (4614 kg ha⁻¹), grain energy output (69671.4 MJ ha⁻¹), straw yield (7934.5 kg ha⁻¹) and straw energy output (99181.25 MJ ha⁻¹) were recorded under 100 % recommended N through ZnCU + recommended PKZn (T₈), which also produced the highest total energy output (84426.33 MJ ha⁻¹) with a 29.73 % increase over control. This was closely followed by 100 % recommended N through NCU + ZnCU + recommended PKZn (T₁₁) and 85 % recommended N through ZnCU + recommended PKZn (T₇), which recorded total energy outputs of 82956.03 and 82380.33 MJ ha⁻¹ with 28.48 and 27.98 % increase over control respectively. The

Table 3. Fixed energy equivalent of inputs in agricultural operations used in the present study (pooled data of 2 years)

Sl. No.	Particulars	Unit	Quantity/ha	Total energy equivalent (MJ/ha)
1	Land preparation: tractor	hr	6	1992
2	Diesel fuel	L	35	1970.85
3	Human labour	Man-days	53	103.88
4	Irrigation	m ³	2750	2832.5
5	Seed	kg	100	1510
6	SSP	kg	313	3893.72
7	MOP	kg	42	468.3
8	ZnSO ₄	kg	20	418
	Total			13189.25

SSP: single super phosphate; MOP: muriate of potash; ZnSO₄: zinc sulphate.

Table 4. Variable energy equivalent for slow release coated urea (pooled data of 2 years)

Sl. No.	Treatment details	Particular	Unit	Quantity	Total equivalent energy (MJ/ha)
T ₁	Control (Recommended PKZn)				13189.25
T ₂	100 % Recommended N through urea + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	271.25	16437.75
		Total			29627
T ₃	70 % Recommended N through NCU + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	190	11514
		Total			24703.25
T ₄	85 % Recommended N through NCU + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	231.125	14006.1775
		Total			27195.4275
T ₅	100 % Recommended N through NCU + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	271.25	16437.75
		Total			29627
T ₆	70 % Recommended N through ZnCU + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	186.2	11283.72
		ZnSO ₄ 7 H ₂ O	kg	3.8	79.42
		Total			24552.39
T ₇	85 % Recommended N+ through ZnCU + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	225.81	13684.088
		ZnSO ₄ 7 H ₂ O	kg	5.44	113.696
		Total			26987.031
T ₈	100 % Recommended N through ZnCU + Recommended PKZn	Fixed price			13189.25
		Nitrogen	kg	266.075	16124.1475
		ZnSO ₄ 7 H ₂ O	kg	5.42	113.3825
		Total			29426.77875
T ₉	70 % Recommended N through NCU +ZnCU + Recommended PKZn	Fixed price			13189.25
		NCU	kg	95	5757
		ZnCU			
		Nitrogen	kg	92.29	5592.774
		Zn		2.714	56.639
		Total			24595.6615
T ₁₀	85 % Recommended N through NCU +ZnCU+ Recommended PKZn	Fixed price			13189.25
		NCU	kg	115.62	5757
		ZnCU			
		Nitrogen	kg	112.9	6841.74
		Zn		2.72	56.848
		Total			25844.839
T ₁₁	100 % Recommended N through NCU +ZnCU+ Recommended PKZn	Fixed price			13189.25
		NCU	kg	135.62	5757
		ZnCU			
		Nitrogen	kg	132.91	8054.346
		Zn		2.7124	56.689
		Total			27057.2875

N: nitrogen; Rec.: recommended; P: phosphorus; K: potassium; Zn: zinc; RDF: recommended dose of fertilisers; NCU: neem coated urea; ZnCU: zinc coated urea.

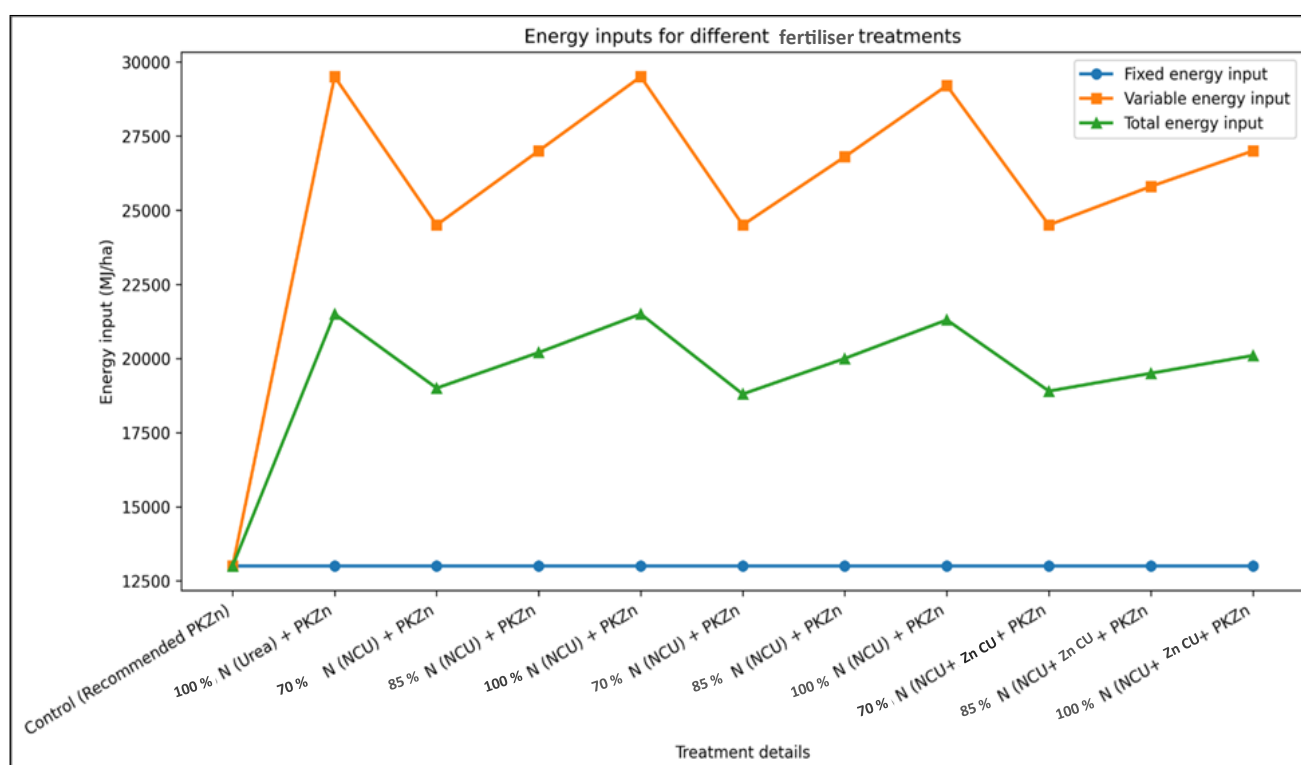
Table 5. Fixed, variable and total energy input for slow-release coated urea (pooled data of 2 years)

Sl. no.	Treatment details	Fixed energy input (MJ/ha)	Variable energy input (MJ/ha)	Total energy input (MJ/ha)
1	Control (Recommended PKZn)	13189.25	13189.25	13189.25
2	100 % Recommended N through urea + Recommended PKZn	13189.25	29627.00	21408.13
3	70 % Recommended N through NCU + Recommended PKZn	13189.25	24703.25	18946.25
4	85 % Recommended N through NCU + Recommended PKZn	13189.25	27195.43	20192.34
5	100 % Recommended N through NCU + Recommended PKZn	13189.25	29627.00	21408.13
6	70 % Recommended N through ZnCU + Recommended PKZn	13189.25	24552.39	18870.82
7	85 % Recommended N through ZnCU + Recommended PKZn	13189.25	26987.03	20088.14
8	100 % Recommended N through ZnCU + Recommended PKZn	13189.25	29426.78	21308.02
9	70 % Recommended N through NCU +ZnCU + Recommended PKZn	13189.25	24595.66	18892.46
10	85 % Recommended N through NCU +ZnCU + Recommended PKZn	13189.25	25844.84	19517.05
11	100 % Recommended N through NCU +ZnCU+ Recommended PKZn	13189.25	27057.29	20123.27

Table 6. Quantities of energy output produced by wheat under different sources of slow-release coated urea (pooled data of 2 years)

Sl. No.	Treatment details	Grain yield (kg/ha)	Grain yield energy output (MJ/ha)	Straw yield (kg/ha)	Straw yield energy output (MJ/ha)	Total energy output (MJ/ha)	Percentage total output increase over control
1	Control (Recommended PKZn)	2861.5	43208.65	6035.5	75443.75	59326.2	-
2	100 % Recommended N through urea + Recommended PKZn	4283	64673.3	7528	94100	79386.65	25.27
3	70 % Recommended N through NCU + Recommended PKZn	3937	59448.7	6991	87387.5	73418.1	19.19
4	85 % Recommended N through NCU + Recommended PKZn	4329.5	65375.45	7526.5	94081.25	79728.35	25.59
5	100 % Recommended N through NCU + Recommended PKZn	4436	66983.6	7646.5	95581.25	81282.43	27.01
6	70 % Recommended N through ZnCU + Recommended PKZn	3998	60369.8	7097.5	88718.75	74544.28	20.41
7	85 % Recommended N through ZnCU + Recommended PKZn	4506.5	68048.15	7737	96712.5	82380.33	27.98
8	100 % Recommended N through ZnCU + Recommended PKZn	4614	69671.4	7934.5	99181.25	84426.33	29.73
9	70 % Recommended N through NCU + ZnCU + Recommended PKZn	3983.5	60150.85	7069	88362.5	74256.68	20.11
10	85 % Recommended N through NCU + ZnCU + Recommended PKZn	4409.5	66583.45	7586	94825	80704.23	26.49
11	100 % Recommended N through NCU + ZnCU + Recommended PKZn	4545.5	68637.05	7782	97275	82956.03	28.48
SEm±		1.01		1.34			
CD (5 %)		3.03		4.0			

N: nitrogen; Rec.: recommended; P: phosphorus; K: potassium; Zn: zinc; RDF: recommended dose of fertilisers; NCU: neem coated urea; ZnCU: zinc coated urea.

**Fig. 3.** Fixed, variable and total energy input for slow release coated urea.

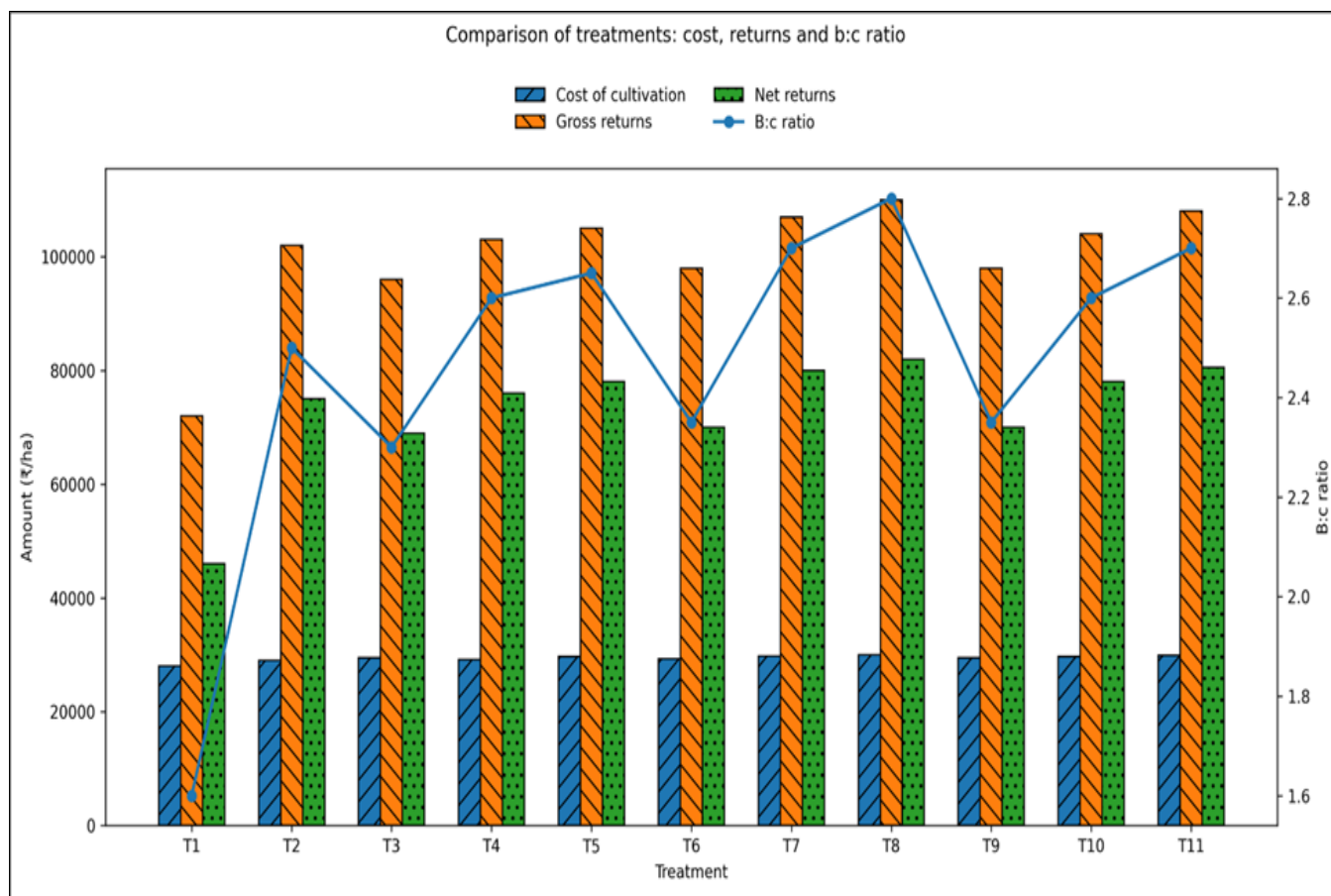


Fig. 4. Effect of coated urea on yield and economics of wheat.

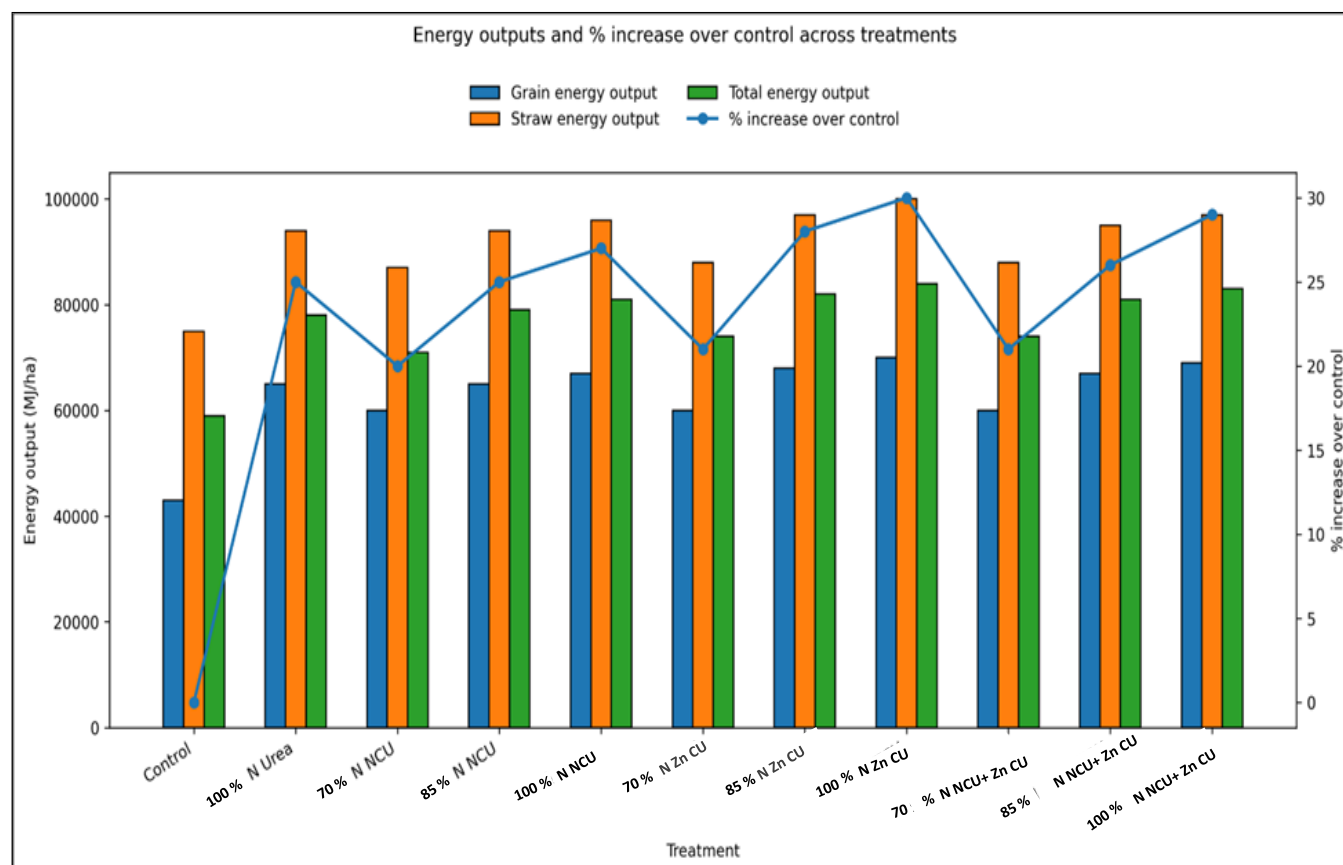


Fig. 5. Energy indices of wheat under different sources of slow-release coated urea.

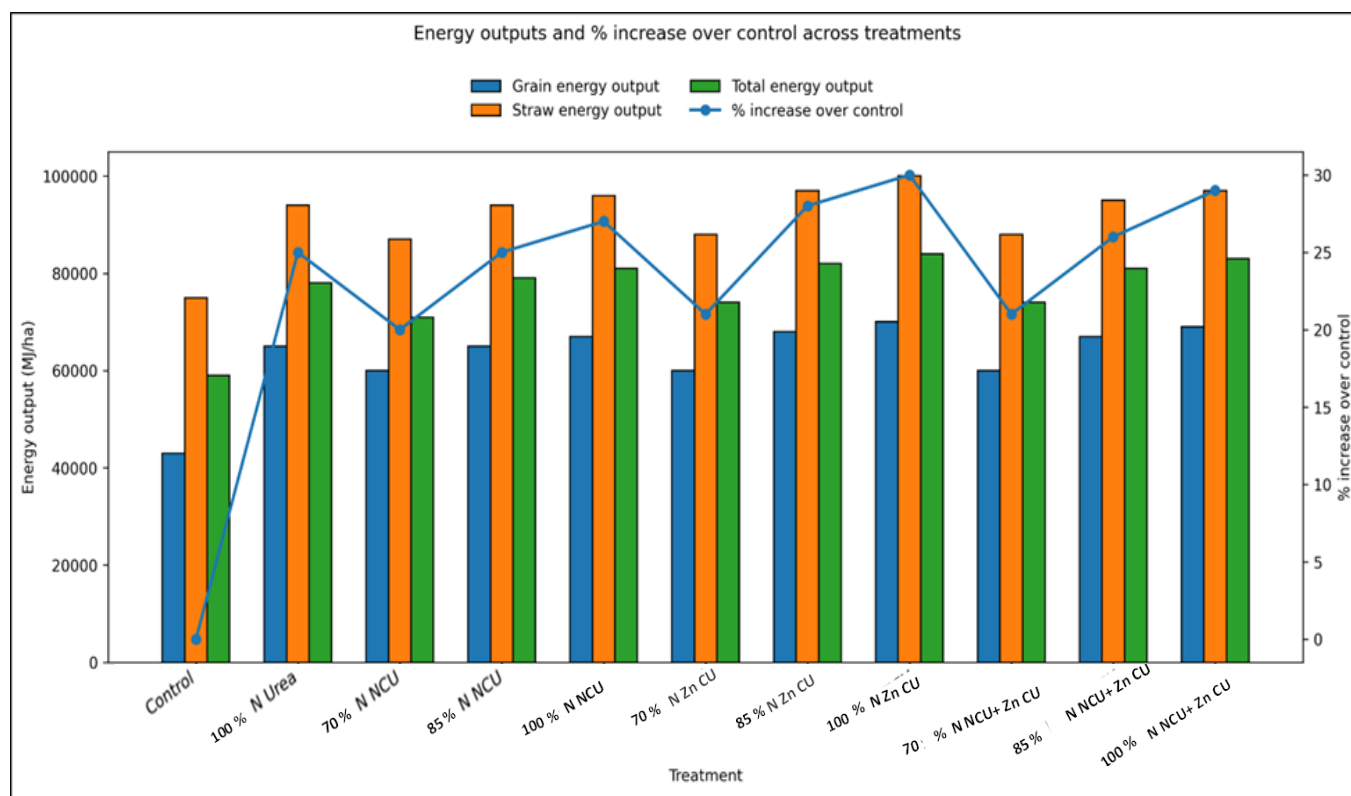


Fig. 6. Quantities of energy output produced by wheat under different sources of slow-release coated urea.

treatments involving NCU alone also showed considerable improvement in energy output, where 100 % recommended N through NCU (T_5) recorded 81282.43 MJ ha⁻¹ with 27.01 % increase over control. In contrast, the lowest energy output (59326.2 MJ ha⁻¹) was observed under the control treatment. Overall, the application of slow-release coated urea, particularly ZnCU at 100 % recommended N level, proved most effective in enhancing grain and straw energy output and total energy production in wheat.

Energy indices of wheat as influenced by different sources of slow-release coated urea (pooled data of two years)

The energy indices of wheat were markedly influenced by different sources and levels of slow-release coated urea (pooled data of two years). Energy input (EI) varied from 26378.5 MJ ha⁻¹ in the control (recommended PKZn) to 42816.25 MJ ha⁻¹ under 100 % recommended N through urea or NCU with recommended PKZn. The highest energy output (EO) of 168852.7 MJ ha⁻¹ was recorded under 100 % recommended N through ZnCU + recommended PKZn (T_8), followed by 100 % recommended N through NCU + ZnCU + recommended PKZn (T_{11}) with 165912.1 MJ ha⁻¹ and 85 % recommended N through ZnCU (T_7) with 164760.7 MJ ha⁻¹. Consequently, the maximum net energy (NE) of 126237 MJ ha⁻¹ was also observed in T_8 , followed by T_{11} (125666 MJ ha⁻¹) and T_7 (124584 MJ ha⁻¹). The highest energy use efficiency (4.14) and energy productivity (0.113 kg MJ⁻¹) were recorded under 85 % recommended N through NCU + ZnCU + recommended PKZn (T_{10}), which was closely followed by T_{11} with similar energy productivity (0.113 kg MJ⁻¹). The lowest specific energy (8.85 MJ kg⁻¹) was also recorded under T_{10} and T_{11} , indicating more efficient energy utilisation for grain production. In contrast, the control treatment recorded the lowest energy output and net energy, although it showed relatively higher specific energy requirement. Overall, the results indicated that application of

slow-release coated urea, particularly ZnCU alone or in combination with NCU, significantly improved energy output and energy efficiency of wheat compared with the conventional fertilisation practice (Fig. 5, Table 7).

Economics of wheat production as influenced by different sources of slow-release coated urea

The economics of wheat production varied considerably with different sources and levels of slow-release coated urea. The cost of cultivation ranged from ₹28168.0 in the control (T_1 : no N + recommended P, K and Zn) to ₹29986.5 under 100 % recommended N through ZnCU + recommended P, K and Zn (T_8). The highest gross returns (₹109004.7), net returns (₹82520.10) and benefit-cost ratio (2.76) were recorded with T_8 , indicating superior economic performance of Zn-coated urea at 100 % recommended nitrogen level. This was closely followed by T_7 (85 % recommended N through ZnCU) and T_{11} (100 % recommended N through NCU + ZnCU), which recorded net returns of ₹80080.10 and ₹80725.80 with B: C ratios of 2.69. The treatments involving NCU alone also showed higher profitability compared with conventional urea, where T_5 (100 % recommended N through NCU) recorded net returns of ₹78464.20 and a B: C ratio of 2.64. In contrast, the control treatment (T_1) recorded the lowest gross returns (₹71825.67), net returns (₹46078.15) and B:C ratio (1.64). Overall, the results revealed that application of Zn-coated urea, particularly at 100 % recommended N level, proved most profitable for wheat cultivation compared with conventional urea and other N treatments (Table 8 & Fig. 4). Since the results are presented as pooled over 2 years, appropriate statistical procedures were undertaken before pooling. Homogeneity of variance was tested (e.g., using Bartlett's or Levene's test) and the year × treatment interaction was evaluated through two-way ANOVA. As the interaction effect was found to be non-significant and the variance across years was homogeneous, the data were pooled to obtain a more reliable estimate of

treatment effects across years.

Discussion

Among the various coated urea formulations, ZnCU demonstrated the highest efficacy in improving grain and straw yields, though the difference compared to neem-coated and neem-zinc composite-coated urea was marginal. The key role of neem and ZnCU in promoting shoot and root elongation in wheat crops is attributed to the stimulation of auxin hormone activity. Additionally, Zn enhances internodal elongation and mitigates leaf senescence, contributing to improved yield-related traits as well as increased grain and straw production. The findings are consistent with the previous observations, reinforcing the positive impact of coated fertilisers on wheat productivity (12, 13). These enhanced returns were primarily attributed to improved wheat productivity and more efficient fertiliser utilisation, which is consistent with earlier findings (14, 15). This improvement can be attributed to the capacity of coated N fertilisers to facilitate the mineralisation of both native and immobilised N, allowing for a steady and prolonged N release (16, 17). The treatment that combined *Rhizobium* (Rec) at full concentration with N supplied through ZnCU along with Rec, P, K and Zn (T₈), performed better than other treatments in enhancing key yield attributes such as the number of effective tillers per meter row, grains per spike and 1000-grain weight (18, 19). Furthermore, the use of coated fertilisers significantly increased tiller formation by enhancing Zn-related membrane stability, stimulating auxin and chlorophyll production

and optimising N metabolism. These physiological benefits contributed to greater photosynthetic efficiency and more effective translocation of assimilates to the grains, ultimately resulting in higher yields. From an economic standpoint, analysis based on net returns and benefit-cost (B: C) ratios indicated that NCU, with a coating cost of INR 33529.19–34140.43 per hectare, was more cost-effective compared to ZnCU (19, 20). The most effective treatment (T₈: 100 % N through zinc coated urea with Rec, P, K and Zn) generated superior net returns (INR 88202.38 and 95797.62/ha in consecutive years) with B: C ratio of 2.64 and 2.85, outperforming other treatments (T₁₁: 2.57; T₁₂: 2.81) (21, 22). Analysis of energy utilisation patterns revealed that commercial energy sources including fossil fuels, electricity and agrochemicals, accounted for about 90.2 % of total energy input, whereas non-commercial sources contributed only 9.9 %. Punjab exhibited the highest dependence on commercial energy (91.7 %), highlighting the strong influence of intensive mechanisation on agricultural sustainability and production economics (23, 24). For greater transparency and reproducibility, the basis for calculating gross returns has been clearly specified. Gross returns were computed using the prevailing minimum support price (MSP) for wheat announced by the Government of India for the respective study years. The MSP values considered were ₹1975 per quintal in the first year (2020–21) and ₹2015 per quintal in the second year (2021–22) and both grain and straw yields were valued accordingly using either MSP or the average local market price where applicable. Explicit reporting of these price assumptions ensures

Table 7. Energy indices of wheat under different source of slow-release coated urea (pooled data of 2 years)

Sl. No.	Treatment details	EI (MJ ha ⁻¹)	EO (MJ ha ⁻¹)	NE (MJ ha ⁻¹)	EUE	EP (kg MJ ⁻¹)	Specific energy (MJ/kg)
1	Control (Recommended PKZn)	26378.5	118652.4	92274	4.50	0.108	9.22
2	100 % Recommended N through urea + Recommended PKZn	42816.25	158773.3	115957	3.71	0.100	10.00
3	70 % Recommended N through NCU + Recommended PKZn	37892.5	146836.2	108944	3.88	0.104	9.62
4	85 % Recommended N through NCU + Recommended PKZn	40384.68	159456.7	119072	3.95	0.107	9.33
5	100 % Recommended N through NCU + Recommended PKZn	42816.25	162564.9	119749	3.80	0.104	9.65
6	70 % Recommended N through ZnCU + Recommended PKZn	37741.64	149088.6	111347	3.95	0.106	9.44
7	85 % Recommended N through ZnCU + Recommended PKZn	40176.28	164760.7	124584	4.10	0.112	8.92
8	100 % Recommended N through ZnCU + Recommended PKZn	42616.03	168852.7	126237	3.96	0.108	9.24
9	70 % Recommended N through NCU + ZnCU + Recommended PKZn	37784.91	148513.4	110728	3.93	0.105	9.49
10	85 % Recommended N through NCU + ZnCU + Recommended PKZn	39034.09	161408.5	122374	4.14	0.113	8.85
11	100 % Recommended N through NCU + ZnCU + Recommended PKZn	40246.54	165912.1	125666	4.12	0.113	8.85

E1: energy input; EO: energy output; NE: net energy; EUE: energy use efficiency; EP: energy productivity; SE: specific energy.

Table 8. Effect of coated urea on yield and economics of wheat (pooled data of 2 years)

Treatments	Cost of cultivation	Gross returns	Net returns (₹10000m ⁻²)	B:C ratio
T ₁ No N + Rec. P, K & Zn	28168.0	71825.67	46078.15	1.64
T ₂ 100 % Rec. N through Urea + Rec. P, K & Zn	29700.5	101931.67	75377.90	2.54
T ₃ 70 % Rec. N through NCU + Rec. P, K & Zn	29297.8	96395.67	68697.30	2.35
T ₄ 85 % of Rec. N through NCU + Rec. P, K & Zn	29537.0	102890.0	76349.30	2.59
T ₅ 100 % of Rec. N through NCU + Rec. P, K & Zn	29773.8	104894.0	78464.20	2.64
T ₆ 70 % of Rec. N through ZnCU + Rec. P, K & Zn	29527.5	98411.67	70131.65	2.38
T ₇ 85 % of Rec. N through ZnCU + Rec. P, K & Zn	29760.5	106340.7	80080.10	2.69
T ₈ 100 % of Rec. N through ZnCU + Rec. P, K & Zn	29986.5	109004.7	82520.10	2.76
T ₉ 70 % of Rec. N through NCU + ZnCU + Rec. P, K & Zn	29503.2	98053.0	69831.55	2.37
T ₁₀ 85 % of Rec. N through NCU + ZnCU + Rec. P, K & Zn	29745.2	103495.0	77786.30	2.62
T ₁₁ 100 % of Rec. N through NCU + ZnCU + Rec. P, K & Zn	29977.2	107266.0	80725.80	2.69

N: nitrogen; Rec.: recommended; P: phosphorus; K: potassium; Zn: zinc; RDF: recommended dose of fertilisers; NCU: neem coated urea; ZnCU: zinc coated urea.

clarity in economic analysis and facilitates replication of the results.

This study demonstrated that applying the full recommended N dose through ZnCU, along with P, K and Zn (treatment T₈), resulted in the highest grain and straw yields. Comparable results were obtained with 85 % of the recommended N, indicating that slightly reduced N levels can still achieve near-optimal performance. Fertilisers were identified as the largest contributor to energy input (40–45 %), followed by diesel (25–30 %) and electricity (15–20 %), emphasising the importance of efficient nutrient management. The findings indicate that using improved fertilisers such as ZnCU, combined with the recommended P, K and Zn, can enhance NUE by 25–30 % and improve energy utilisation in wheat cultivation. Overall, the results support the conclusion that coated urea formulations and optimised nutrient application can increase crop productivity and resource efficiency under the experimental conditions.

This study found that using the full recommended amount of N through ZnCU, along with P, K and Zn (treatment T₈), produced the highest grain and straw yields. These results were almost the same as those achieved with 85 % of the recommended N, showing that slightly lower N levels can still perform well. The study also showed that larger farms used energy more efficiently than smaller ones, suggesting that small farmers could improve productivity by using more farm machinery. Among all energy inputs, fertilisers contributed the most (40–45 %), followed by diesel (25–30 %) and electricity (15–20 %), which points to the need for better nutrient management. The findings highlight that using improved fertilisers like ZnCU on small farms and precision nutrient management on larger farms can increase N efficiency by 25–30 % and lower the energy use in wheat cultivation. Overall, the results show that adopting farm-size-specific practices can boost both crop yields and resource efficiency in cereal production.

Conclusion

This study clearly demonstrates that coated urea formulations, particularly zinc-coated urea (ZnCU), play a pivotal role in enhancing wheat productivity, nutrient use efficiency (NUE) and energy utilisation. The integration of ZnCU with balanced applications of phosphorus (P), potassium (K) and zinc (Zn), especially under treatment T₈, resulted in superior grain and straw yields, improved physiological traits and greater economic returns. Importantly, the findings highlight that near-optimal yields can be achieved even with slightly reduced nitrogen (N) levels, underscoring the potential for resource-efficient nutrient management. From an economic perspective, neem-coated urea (NCU) proved more cost-effective due to lower coating costs, while ZnCU delivered higher physiological and yield benefits. The balance between cost-effectiveness and productivity gains suggests that farm-size-specific strategies, precision nutrient management for larger farms and improved fertiliser use for smaller farms can maximise both profitability and sustainability. Energy analysis further revealed that fertilisers remain the largest contributor to input energy, followed by diesel and electricity, emphasising the need for efficient nutrient management to reduce energy intensity. The study also underscores the importance of mechanisation in improving energy efficiency, particularly for smallholder farmers. Overall, the results confirm that

adopting coated urea formulations, coupled with optimised nutrient application, can significantly enhance wheat yields, improve NUE by 25–30 % and strengthen energy sustainability. These findings provide a strong basis for promoting coated fertilisers as a practical and scalable strategy to achieve higher productivity, profitability and resource efficiency in cereal-based farming systems.

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Authors' contributions

MA and MG performed the experiments, RS and S designed the research. N and MK wrote the manuscript. MA, ST, VK, VB revised and RK corrected the manuscript. All authors have contributed to different sections of writing, reviewing, correcting and statistical analysis. All authors read and approved the final manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (OpenAI, GPT-5 model) in order to assist in improving the language, grammar and clarity of the manuscript. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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