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Research Article

Efficacy of Microbially Impregnated Polymer-Coated Nitrogen Fertilizers for Improving Growth, Yield and Nitrogen-Use Efficiency of Wheat (*Triticum aestivum* L.)

^aAiman Amjad, ^bNasir Ahmed Rajput, ^bMuhammad Atiq, ^bHadeeqa Riasat, ^cJamil Shafi, ^bMuhammad Jahanzaib Matloob, ^dAbdul Hannan, ^eAsia Kainat, ^bAsifa Nazar, ^bAyesha Sadiqa, ^bMeesam Raza, ^bMuhammad Tehseen Shafqat

^a Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan.

^b Department of Plant Pathology, Faculty of Agriculture, University of Agriculture, Faisalabad, Pakistan.

^c Department of Plant Pathology, Sub-Campus Constituent College, Depalpur, Okara, University of Agriculture, Faisalabad, Pakistan.

^d Department of Plant Pathology, Ghazi University, Dera Ghazi Khan, Pakistan.

^e Department of Botany, Faculty of Basic Sciences, University of Agriculture, Faisalabad, Pakistan.

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ABSTRACT

Efficient nitrogen management is essential for improving wheat productivity and nutrient-use efficiency while reducing nutrient losses. This study evaluated polymer-coated and microbially impregnated polymer-coated (MEP-coated) urea and calcium ammonium nitrate (CAN) for their effects on wheat growth, yield, nutrient accumulation, and nitrogen-use efficiency. MEP-coated fertilizers, particularly MEP-coated CAN (T7), consistently improved crop performance compared with corresponding uncoated and polymer-coated fertilizers. T7 produced the greatest plant height (108.33 cm), fertile tiller density (327 m⁻²), chlorophyll index (54.04 SPAD), spikelet number (20 spikelets spike⁻¹), root weight (1.94 g), root length (23.09 cm), and 1000-grain weight (47.50 g). It also resulted in the highest straw (8750 kg ha⁻¹) and biological yields (12,357 kg ha⁻¹), representing a 19.22% increase in biological yield over uncoated CAN. T7 increased grain and straw N concentrations by 13.46% and 31.78%, respectively, relative to uncoated CAN, and also showed greater P and K concentrations and nutrient uptake. The highest NUE (17.79%) and agronomic N-use efficiency were recorded with MEP-coated CAN. Principal component analysis indicated strong associations among growth, yield, and nutrient-related variables, with PC1 and PC2 explaining 91.27% and 2.87% of the total variation, respectively. Overall, MEP-coated fertilizers, particularly MEP-coated CAN, improved wheat growth, productivity, nutrient acquisition, and N-use efficiency under the conditions of this study, indicating their potential for more efficient fertilizer-N management.

Corresponding Author: Muhammad Atiq

Email: muhammad.atiq@uaf.edu.pk

Introduction

Agriculture is a major contributor to Pakistan's economy and depends on efficient management of water and nutrients to sustain crop productivity. Wheat production, in particular, requires substantial nitrogen (N) inputs to achieve high yields; however, a considerable proportion

of applied N can be lost through ammonia volatilization, leaching, runoff, and denitrification, thereby reducing nitrogen-use efficiency (NUE) and increasing the environmental costs of fertilization (Achat et al., 2016; Ahmad et al., 2025; Atiq et al., 2026). Improving NUE is therefore essential for sustaining crop productivity while

minimizing avoidable fertilizer losses and associated environmental impacts. Urea and calcium ammonium nitrate (CAN) are among the widely used N fertilizers in wheat production. However, their relatively rapid dissolution and N release can result in temporal mismatches between N availability and crop demand, particularly when fertilizer application is not synchronized with periods of active crop uptake. Polymer-coated fertilizers have consequently been investigated as controlled-release alternatives, as coating composition, thickness, permeability, and degradation characteristics regulate water penetration and nutrient-release kinetics (Yang et al., 2011; Grant et al., 2012; Naz and Sulaiman, 2016; Huett and Gogel, 2000).

Recent research has increasingly explored the integration of coated fertilizers with microbial inoculants and nutrient-solubilizing bacteria, reflecting broader advances in the use of plant growth-promoting rhizobacteria (PGPR) and integrated nutrient management (Adesemoye et al., 2009; Bhattacharyya and Jha, 2012; Souza et al., 2015; Vejan et al., 2016; Khalid et al., 2026). For example, delivery of PGPR through an enriched soil-based carrier has been shown to improve wheat growth and yield under field conditions (Khaliq et al., 2024), while bacterial inoculation has also been associated with improvements in wheat productivity and nutrient-use responses (Ayala Zepeda et al., 2024). More recently, the combination of coated urea with nutrient-solubilizing bacteria has been reported to improve NUE-related parameters in wheat (Mahmood et al., 2025). These findings suggest that integrating controlled nutrient release with microbial delivery may provide a complementary strategy for improving nutrient availability and crop performance.

The key scientific question addressed in the present study is not whether polymer coatings or *Bacillus*-based biofertilizers are individually beneficial, as both approaches have been extensively investigated in the controlled-release fertilizer and PGPR literature (Bhattacharyya and Jha, 2012; Souza et al., 2015; Naz and Sulaiman, 2016). Rather, the study examines whether incorporation of a viable *Bacillus* inoculum into the polymer coating of two commonly used N fertilizers can integrate controlled N delivery and microbial delivery within a single fertilizer granule. The distinctive feature of this formulation is the co-localization of the microbial inoculum and polymer coating on urea and CAN, potentially enabling each fertilizer granule to function simultaneously as an N source and a carrier for microbial

inoculation. This formulation-based approach may improve the temporal coordination between nutrient release and microbial delivery, although such effects require empirical validation under field conditions.

Accordingly, this field study was designed to compare uncoated, polymer-coated, and MEP-coated forms of urea and CAN under uniform wheat production conditions. The specific objectives were to: (i) compare the effects of uncoated, polymer-coated, and MEP-coated urea and CAN on wheat growth and yield; (ii) quantify treatment-associated differences in plant and soil N, phosphorus (P), and potassium (K) concentrations; and (iii) evaluate NUE under field conditions. Because the study did not include pathogen, insect, disease-incidence, or other plant-protection assays, it does not provide direct evidence of a plant-protection effect. Any potential relevance to plant protection is therefore restricted to possible implications for rhizosphere health and should be regarded as a hypothesis requiring dedicated investigation in future studies.

Materials and Methods

Experimental site and design

A field experiment was conducted at the research area of the Institute of Soil and Environmental Sciences (ISES), University of Agriculture, Faisalabad, Pakistan, to evaluate the effects of uncoated, polymer-coated, and microbially impregnated polymer-coated (MEP-coated) urea and calcium ammonium nitrate (CAN) on the growth, yield, and nutrient uptake of wheat (*Triticum aestivum* L.). The experiment was laid out in a randomized complete block design (RCBD) comprising seven treatments with three replications.

Preparation of MEP-coated urea and CAN

Commercial urea and CAN fertilizers were coated under controlled laboratory conditions using a polymer formulation and an endophytic *Bacillus* inoculum, designated AS53, to produce microbial-enhanced polymer-coated fertilizers. The bacterial inoculum was obtained from the Soil Microbiology and Biochemistry Laboratory, ISES, University of Agriculture, Faisalabad. For preparation of the polymer-coated fertilizers, a 10% (w/v) polymer solution was prepared in distilled water, and two successive coating layers were applied to the fertilizer granules. For preparation of MEP-coated fertilizers, the coating suspension consisted of 33% bacterial inoculum, 57% distilled water, and 10% (w/v) polymer. Fertilizer granules were thoroughly mixed with

the respective coating suspension and subsequently spread on polyethylene sheets for drying.

For reproducibility and methodological completeness, the following information was verified against the original laboratory records and incorporated before submission: species-level identification and accession or deposition information for *Bacillus* AS53; culture medium and incubation conditions; inoculum age; initial viable-cell density (CFU mL⁻¹); volume of coating suspension applied per unit mass of fertilizer; drying temperature and duration; viable bacterial population after coating (CFU g⁻¹ fertilizer); precise chemical composition and supplier of the polymer; polymer solids content; and the use and concentrations of any cross-linker, plasticizer, or adhesive. The coating mass or thickness per granule should also be reported. In addition, the method used to characterize fertilizer nitrogen-release kinetics and polymer biodegradability was described where these characteristics were relevant to the interpretation of the treatment effects. These parameters were not reported in the submitted version and were not be inferred without verification from the original experimental records.

Treatments and crop management

The seven experimental treatments were as follows: T1, control (no N fertilizer); T2, uncoated urea; T3, polymer-coated urea; T4, MEP-coated urea; T5, uncoated CAN; T6, polymer-coated CAN; and T7, MEP-coated CAN. Nitrogen, phosphorus, and potassium were applied at rates of 120, 90, and 60 kg ha⁻¹, respectively. Urea or CAN was used as the nitrogen source, whereas diammonium phosphate and muriate of potash were used as the sources of phosphorus and potassium, respectively. Phosphorus and potassium fertilizers were incorporated into the soil at sowing, whereas the respective uncoated, polymer-coated, and MEP-coated N fertilizers were applied at sowing according to the treatment structure.

Wheat cultivar 'Galaxy 2013' was sown using a seed drill on 30 November 2019 at a seed rate of 100 kg ha⁻¹. The herbicides Axal and Alimax were applied at 330 mL acre⁻¹ and 14 g acre⁻¹, respectively. The crop was irrigated five times with canal water during the growing season and harvested on 23 April 2020. Soil samples were collected before sowing and after harvest, and their physicochemical properties were determined using standard analytical procedures described by the U.S. Salinity Laboratory Staff (1954).

Growth, yield, and nutrient measurements

Plant height, spike length, number of spikelets per spike, chlorophyll index (SPAD), number of fertile tillers m⁻², root weight, root length, 1000-grain weight, grain yield, straw yield, and biological yield were recorded. Soil saturation percentage, texture, organic matter content, electrical conductivity (EC), pH, and total N and available P and K concentrations were determined using appropriate standard analytical procedures.

Grain, root, and shoot samples were oven-dried, ground to a uniform particle size, and digested using the method described by Wolf (1982). Nitrogen, phosphorus, and potassium concentrations in the digests were subsequently determined using appropriate analytical procedures. The specific analytical methods, including the detection/quantification procedures and instrumentation used for N, P, and K determination, should be reported to ensure methodological reproducibility.

Nitrogen-use efficiency

Nitrogen-use efficiency (NUE) was calculated from the treatment data. The precise definition and equation used for NUE should be clearly stated and applied consistently throughout the manuscript. The agronomic nitrogen-use efficiency (ANUE) was calculated and was expressed as:

$$ANUE = \frac{Y_N - Y_0}{N_a}$$

Where Y_n is the grain yield obtained with N fertilization, Y_0 is the grain yield of the unfertilized control, and N_a is the amount of N applied (kg N ha⁻¹). The resulting units were reported as kg grain increase per kg N applied. However, the NUE definition and equation used in the submitted analysis were not provided; therefore, the original calculations were checked before assigning the specific NUE metric and equation.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using a randomized complete block design (RCBD) with three independent replications. When the ANOVA indicated significant treatment effects, treatment means were separated using Fisher's least significant difference (LSD) test at $P \leq 0.05$. All statistical analyses were performed using SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

Growth, yield, and nutrient-related variables were recorded at the booting and maturity stages.

Growth and yield parameters of wheat

Treatment T7 (MEP-coated CAN) produced the greatest plant height (108.33 cm), representing an 8.93% increase over T6 (polymer-coated CAN). According to the significance groupings in Figure 1A, T7 and T4 (MEP-coated urea) differed significantly from T6 and T3 (polymer-coated urea). Treatment T7 also produced the longest spikes and the highest number of spikelets per spike (20), followed by T4 (19 spikelets spike⁻¹) Figure 1B. T7 and T4 did not differ significantly in spikelet number Figure 1C. Treatments T6 and T3 produced 17 spikelets spike⁻¹ each, whereas T5 and T2 produced 16 and 15 spikelets spike⁻¹, respectively Figure 1D.

Treatment T7 produced the highest fertile tiller density (327 m⁻²), followed by T4 (305 m⁻²). It also recorded the highest chlorophyll index (54.04 SPAD), approximately 40% greater than that of T5 (uncoated CAN) Figure 2A. T7 produced the greatest root weight (1.94 g) and root length (23.09 cm), followed by T4, which recorded 1.75 g and 19.81 cm, respectively Figure 2B. Root lengths under T6 and T3 were 20.71 and 17.94 cm, respectively (Figure 2C). The previously reported value of 117.94 cm for T3 was corrected to 17.94 cm because the latter is consistent with the value plotted in Figure 2C and with the range observed across treatments. Treatment T7 also produced

the highest 1000-grain weight (47.50 g), followed by T4 (39.61 g), T6 (37.56 g), and T3 (33.32 g) (Figure 2D).

Overall, MEP-coated and polymer-coated fertilizers generally resulted in greater grain and straw yields than their corresponding uncoated fertilizers. Treatment T7 produced the highest straw yield (8750 kg ha⁻¹) and biological yield (12,357 kg ha⁻¹). Compared with T5 (uncoated CAN), T7 increased biological yield by 19.22%, whereas T4 increased biological yield by 14.78% compared with T2 (uncoated urea) Figure 3A-C. The enhanced root development observed under MEP-coated fertilizers was particularly evident in T7, which produced the greatest root weight (1.94 g) and root length (23.09 cm), followed by T4, with values of 1.75 g and 19.81 cm, respectively (Figure 2B-C). Treatment T6 (polymer-coated CAN) recorded a root length of 20.71 cm, whereas T3 (polymer-coated urea) recorded 17.94 cm. These results indicate improved root biomass and elongation under MEP-coated fertilizer treatments relative to the corresponding coated and uncoated fertilizer treatments.

Treatment T7 also produced the highest 1000-grain weight (47.50 g), representing a 54% increase compared with T5 (uncoated CAN). This was followed by T4 (39.61 g), T6 (37.56 g), and T3 (33.32 g) (Figure 2D).

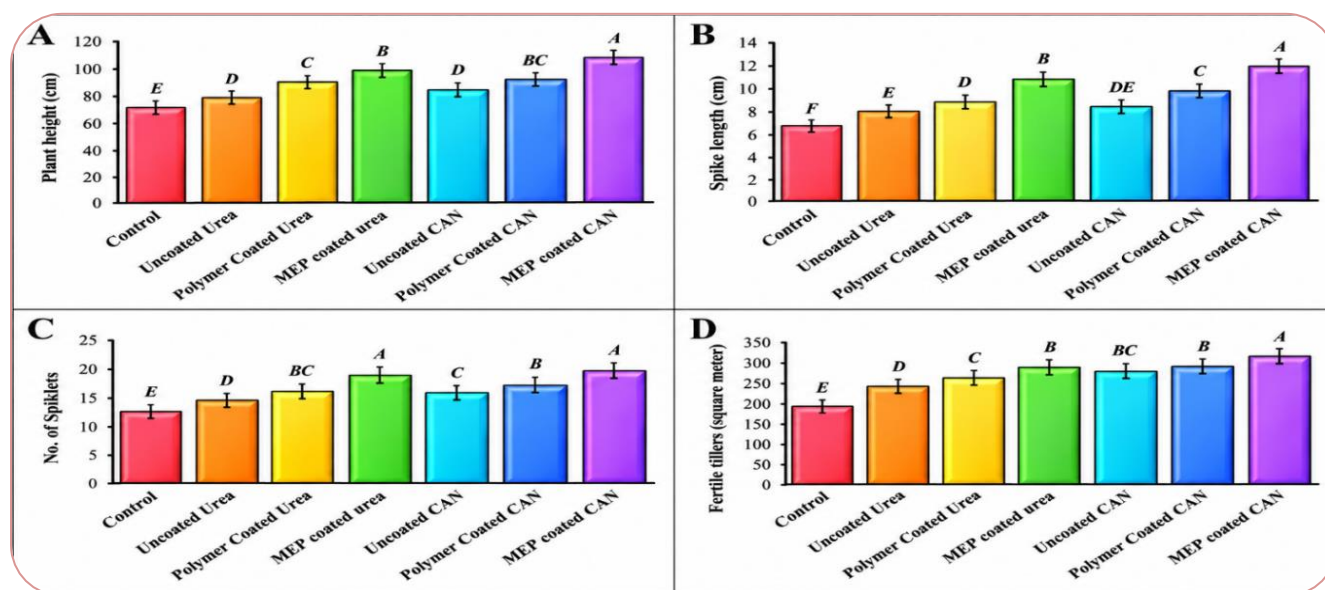


Figure 1. Effects of microbially impregnated polymer-coated urea and calcium ammonium nitrate (CAN) on wheat growth and yield components. (A) Plant height (cm), (B) spike length (cm), (C) spikelets spike⁻¹, and (D) productive tillers m⁻² under different fertilizer treatments. Data are presented as means $\pm$ SE (vertical error bars). Means followed by different capital letters (A–F) differ significantly according to the post hoc multiple-comparison test. Treatments were control (no fertilizer), uncoated urea, polymer-coated urea, MEP-coated urea, uncoated CAN, polymer-coated CAN, and MEP-coated CAN.

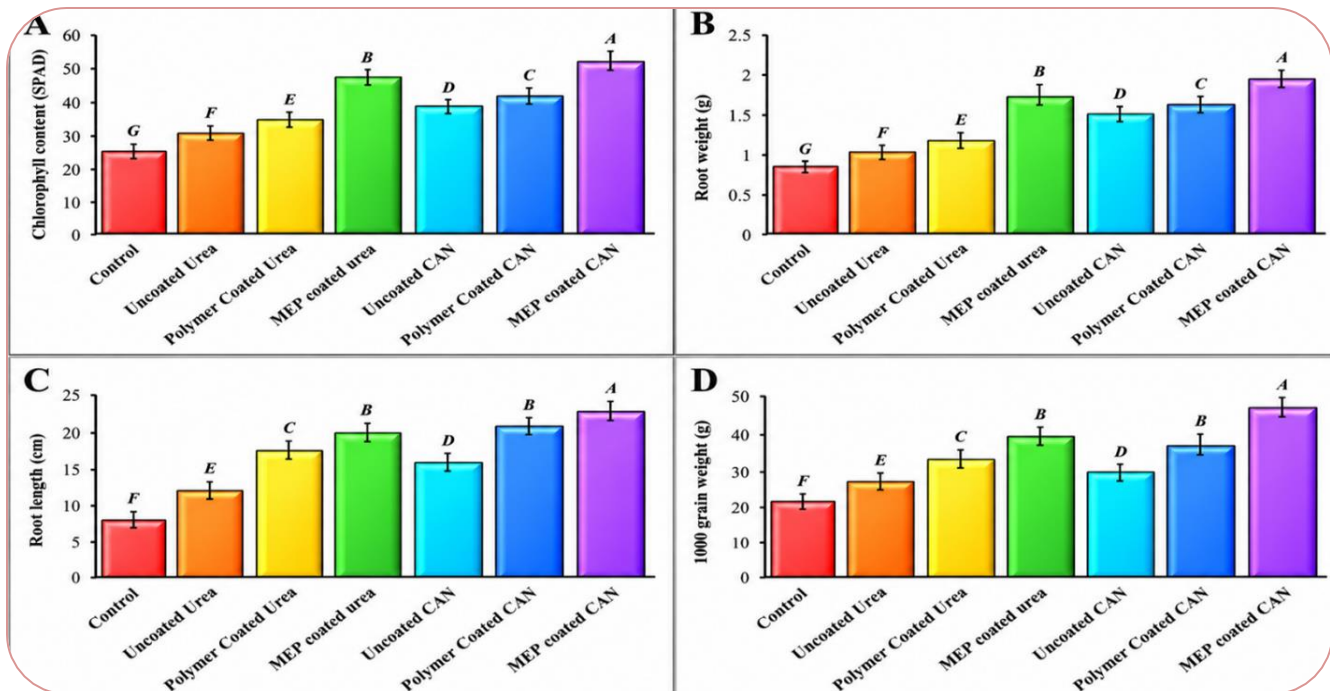


Figure 2. Effects of uncoated, polymer-coated, and microbially impregnated polymer-coated (MEP-coated) urea and calcium ammonium nitrate (CAN) on wheat growth and physiological traits. (A) Chlorophyll content (SPAD), (B) root mass (g), (C) root length (cm), and (D) 1000-grain mass (g) under different fertilizer treatments: Control, uncoated urea, polymer-coated urea, MEP-coated urea, uncoated CAN, polymer-coated CAN, and MEP-coated CAN. Bars represent treatment means, with vertical error bars indicating variation among replicates. Different uppercase letters above bars indicate significant differences among treatments ($P \leq 0.05$).

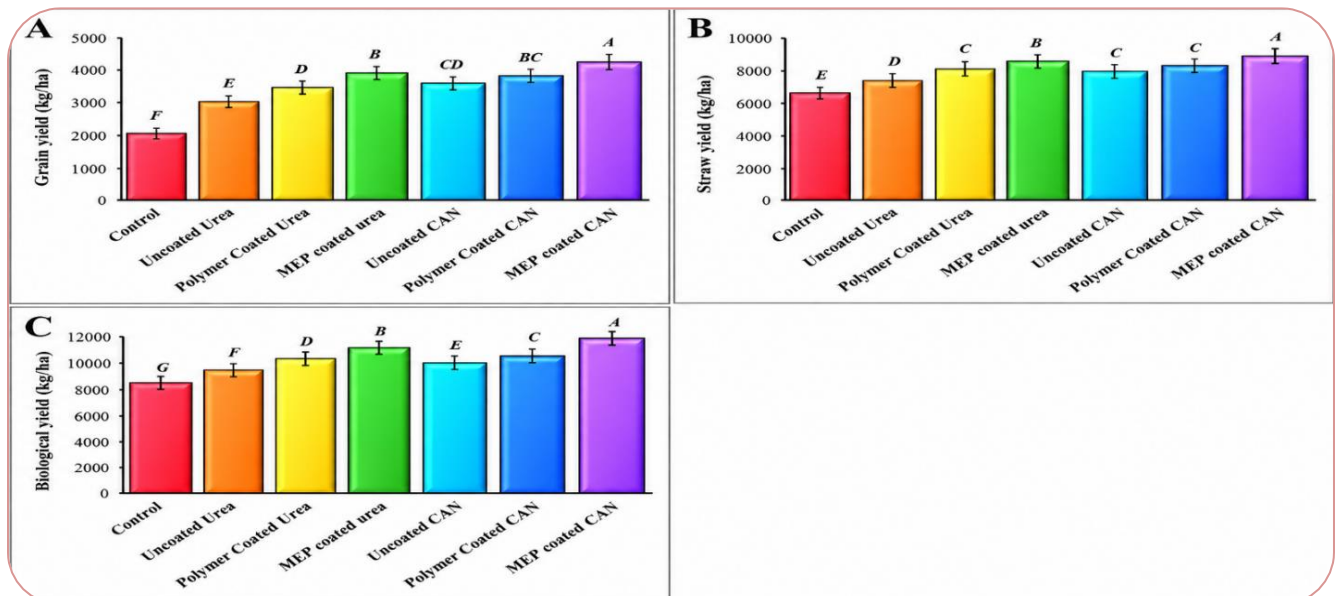


Figure 3. Effects of bare, polymer-coated, and microbially impregnated polymer-coated (MEP-coated) urea and calcium ammonium nitrate (CAN) on wheat yield characteristics: (A) grain yield, (B) straw yield, and (C) biological yield (kg ha^{-1}). Treatments comprised control, bare urea, polymer-coated urea, MEP-coated urea, bare CAN, polymer-coated CAN, and MEP-coated CAN. Bars represent treatment means, with vertical lines indicating variation among replications. Different uppercase letters indicate significant differences among treatments at $P \leq 0.05$.

Wheat crop nutrient concentrations

T7 (MEP-coated CAN) recorded higher soil moisture than the corresponding uncoated and polymer-coated CAN treatments at both sampled depths. In the 0–15 cm soil layer, soil moisture was 45.43% in T7 compared with 39.59% in T6, whereas in the 15–30 cm layer, T7 recorded 43.78%. T7 also increased grain N concentration by 13.46% relative to T5. The previously stated claim that polymer-coated fertilizers “save up to 50% on fertilizer costs” has been omitted because no fertilizer-cost analysis was presented; such a claim requires supporting economic data Figure 4A-D.

Straw N concentration was 0.47% in T7 compared with 0.36% in T5, representing a 31.78% increase. Root N concentration was 2.89% in T7, compared with 2.53% in T4, 2.40% in T6, and 2.27% in T3. Thus, T7 increased root N concentration by approximately 53% relative to T5. T7 also recorded higher soil N concentrations in both the 0–15 and 15–30 cm layers than the corresponding comparison treatments Figure 5A-D.

T7 produced the highest grain P concentration (1.24%) and straw P concentration (0.29%), while root P concentration was also higher under the MEP-coated treatments. In the 0–15 cm soil layer, P concentration was 17.24 ppm in T7 compared with 12.51 ppm in T6, whereas T7 recorded 15.81 ppm P in the 15–30 cm layer. T7 also showed higher K concentrations in grain, straw, roots, and soil than the corresponding uncoated and polymer-coated treatments Figure 6A-D.

The NUE values were corrected for treatment-labeling errors identified in the original manuscript. Figure 7B showed the highest NUE for T7 (MEP-coated CAN; 17.79%), followed by T4 (MEP-coated urea; 15.67%), T6 (polymer-coated CAN; 14.61%), T5 (uncoated CAN; 13.38%), and T3 (polymer-coated urea; 12.39%). The previously reported NUE value of 40% in the abstract was removed because it was not consistent with the values presented in Figure 7 or the corresponding Results.

PCA and correlation

Principal component analysis (PCA) showed that PC1 and PC2 explained 91.27% and 2.87% of the total variation, respectively. The ordination differentiated the fertilizer treatments and revealed positive associations among several growth, yield, and plant nutrient variables. These associations were descriptive and were not interpreted as evidence of causal physiological or microbial mechanisms. In particular, the PCA did not independently establish that MEP coating directly caused the observed relationships

among the measured variables.

Nutrient uptake and agronomic nitrogen-use efficiency

The MEP-coated CAN treatment showed the highest values in the reported nutrient-uptake and agronomic nitrogen-use efficiency analyses. However, the manuscript should clearly distinguish between the NUE metric presented in Figure 7A-B and agronomic N-use efficiency (ANUE) presented in Figure 8A.

Nutrient uptake and ANUE

Nitrogen source and coating treatment significantly affected nutrient uptake and ANUE in wheat. Compared with conventional urea and DAP-based fertilization, MEP-coated CAN showed greater agronomic N-use efficiency. Similarly, MEP-coated urea exhibited higher agronomic N-use efficiency than uncoated and polymer-coated urea, although the response was more pronounced with MEP-coated CAN. The highest agronomic N-use efficiency was recorded for MEP-coated CAN applied in combination with DAP and MOP (Figure 8B). This treatment also resulted in the highest N, P, and K uptake by wheat grain. MEP-coated urea applied with DAP and MOP produced the second-highest NPK uptake. In contrast, the treatment receiving DAP and MOP without an N source recorded the lowest NPK uptake. Overall, the results indicate that the MEP-coated N fertilizers, particularly MEP-coated CAN, were associated with greater nutrient uptake and agronomic N-use efficiency under the conditions of the present experiment.

Discussion

The primary contribution of this study is the field evaluation of the same polymer-coating strategy applied to two nitrogen fertilizers, urea and CAN, with and without incorporation of a *Bacillus* inoculum. Polymer-coated fertilizers and microbial biofertilizers are individually well established; therefore, neither component alone represents a novel concept. The distinctive feature of the present formulation is the co-delivery of fertilizer N and the bacterial inoculum through the same coated granule. Accordingly, the novelty was framed as a formulation and delivery innovation rather than as a claim that either component is individually new. Recent wheat studies similarly indicate that the delivery matrix and inoculation method can substantially influence the performance of PGPR (Khaliq et al., 2024; Mahmood et al., 2025). Thus, the principal contribution of the present study lies in the specific microbially impregnated polymer (MEP)-coated urea/CAN formulations and their field evaluation, rather than in the general concepts of polymer coating or *Bacillus* biofertilization.

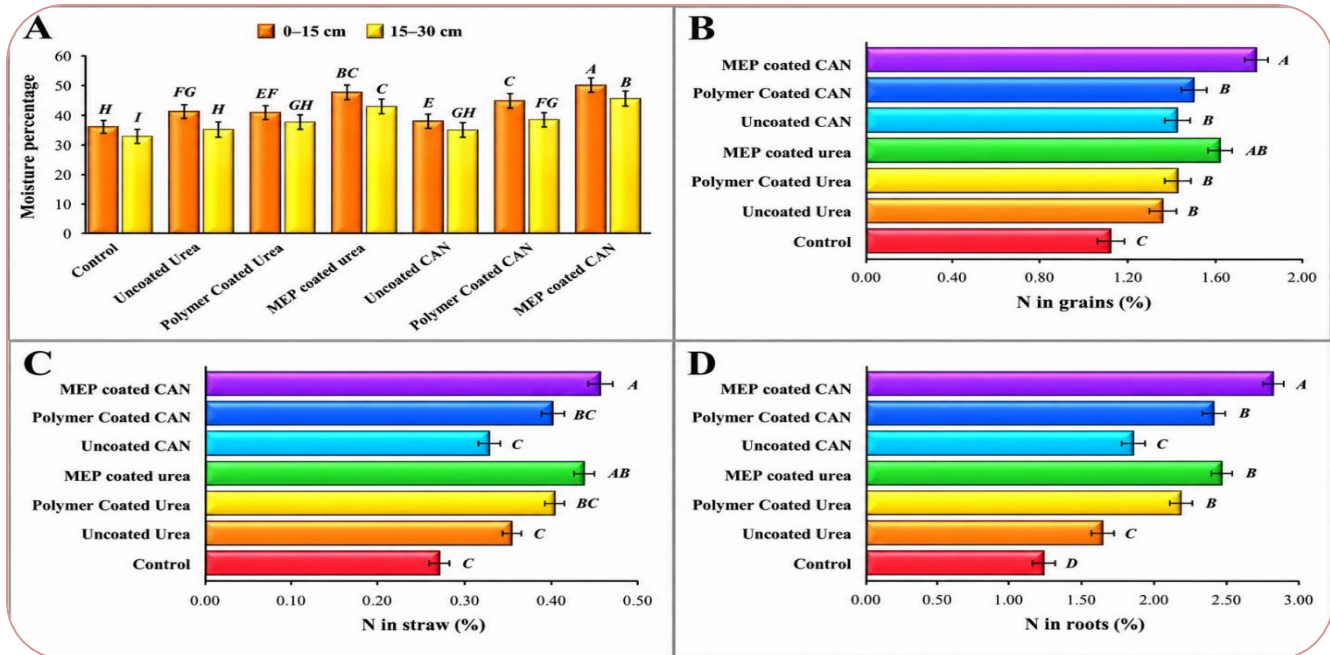


Figure 4. Effects of microbially impregnated polymer-coated urea and calcium ammonium nitrate (CAN) on soil moisture and nitrogen accumulation in wheat. (A) Soil moisture content (%) at 0-15 and 15-30 cm soil depths; (B) N concentration in grain (%); (C) N concentration in straw (%); and (D) N concentration in roots (%). Bars represent means $\pm$ SE of three replicates. Different uppercase letters indicate significant differences among treatments at $p \leq 0.05$. MEP, microbially impregnated polymer-coated.

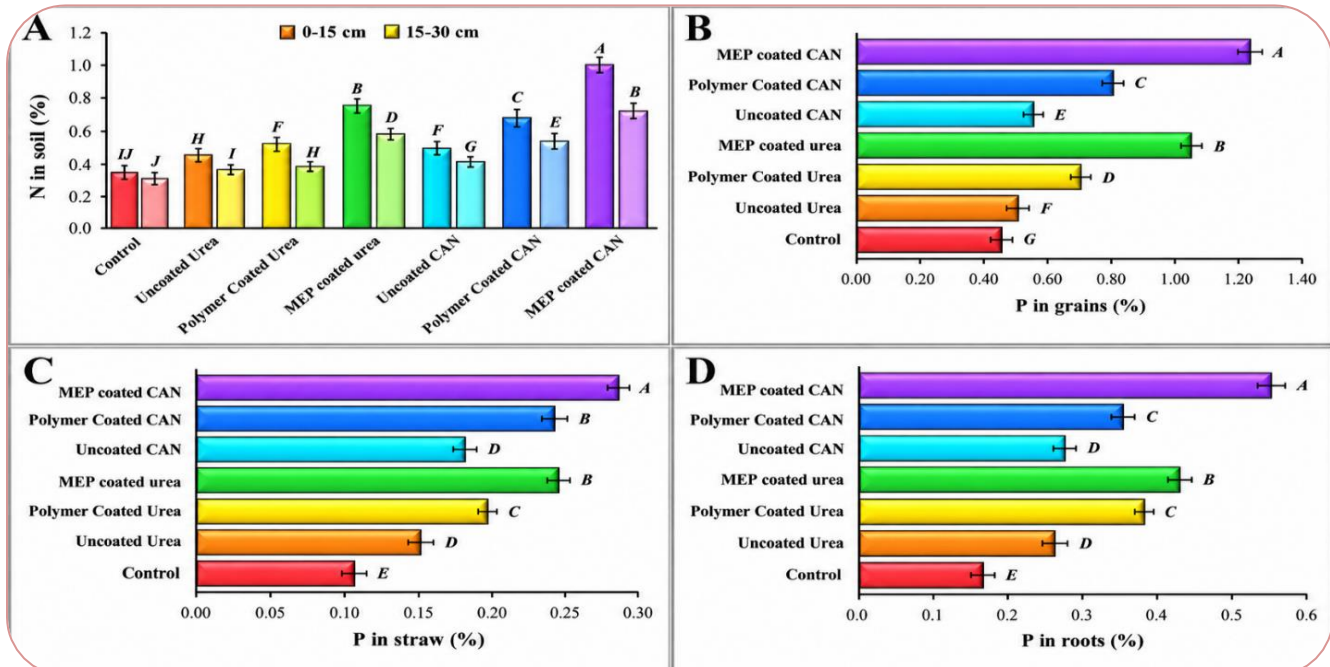


Figure 5. Effects of microbially impregnated polymer-coated (MEP-coated) urea and calcium ammonium nitrate (CAN) on nutrient concentrations in wheat and soil. (A) Soil N concentration (%) at 0-15 and 15-30 cm depths; (B) P concentration in grain (%); (C) P concentration in straw (%); and (D) P concentration in roots (%). Bars represent mean $\pm$ standard error (SE). Different uppercase letters indicate significant differences among treatments at $p \leq 0.05$. MEP = microbially impregnated polymer-coated.

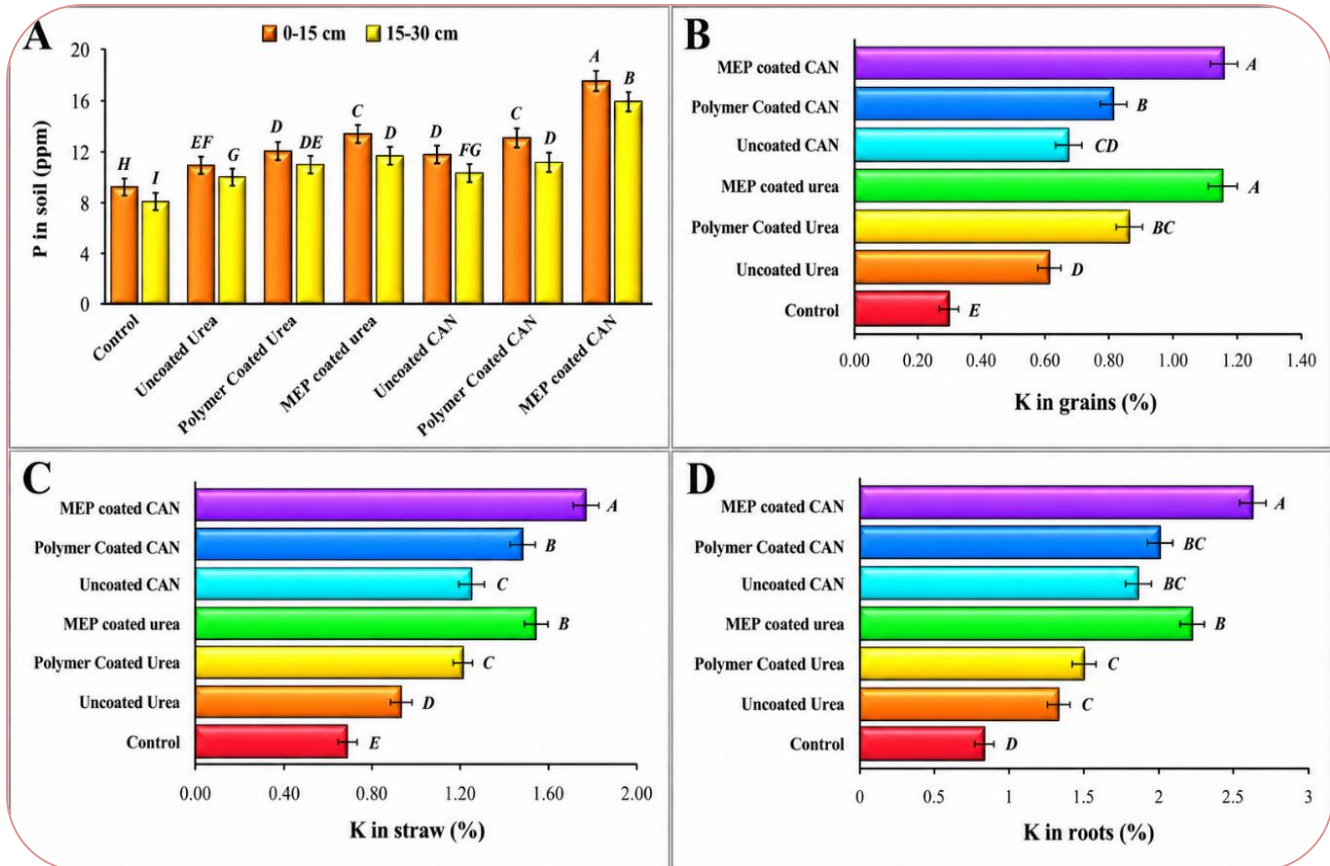


Figure 6. Effects of polymer-coated urea and calcium ammonium nitrate (CAN) impregnated with microorganisms on nutrient concentrations in wheat. (A) Soil phosphorus concentration (ppm) at 0–15 and 15–30 cm depths; (B) grain potassium concentration (%); (C) straw potassium concentration (%); and (D) root potassium concentration (%). Data are presented as means $\pm$ SE. Different uppercase letters indicate significant differences among treatments at $p \leq 0.05$, based on the appropriate statistical test.

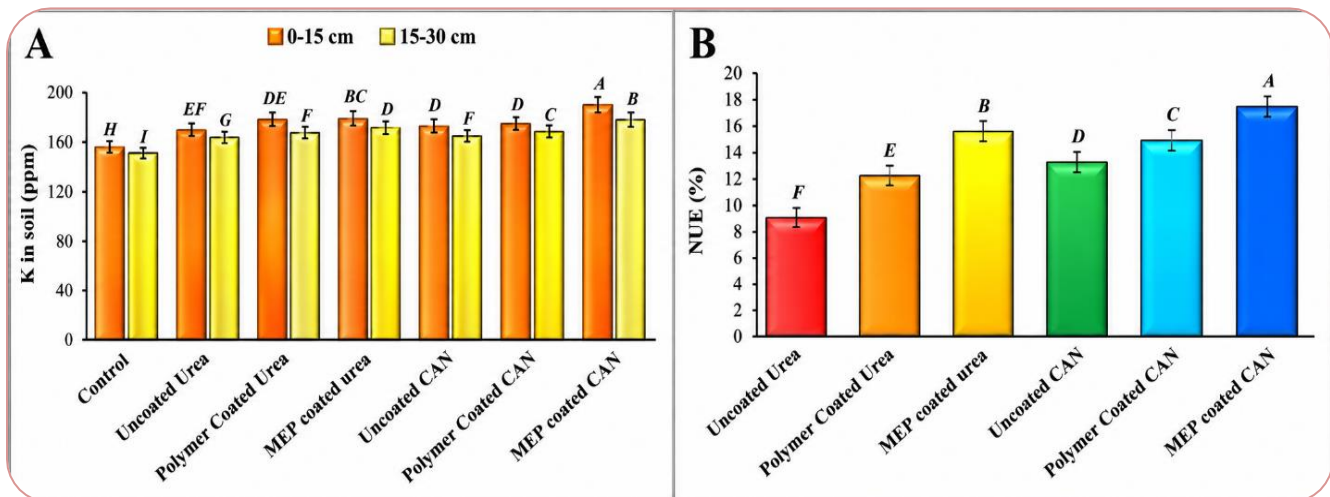


Figure 7. Effects of microbially impregnated polymer-coated urea and CAN on potassium dynamics and NUE in wheat. (A) Soil K concentration (ppm) at 0–15 and 15–30 cm depths; and (B) nitrogen-use efficiency (NUE, %). Error bars represent means $\pm$ SE. Bars with different capital letters indicate significant differences among treatments at $p \leq 0.05$. MEP = microbially impregnated polymer-coated.

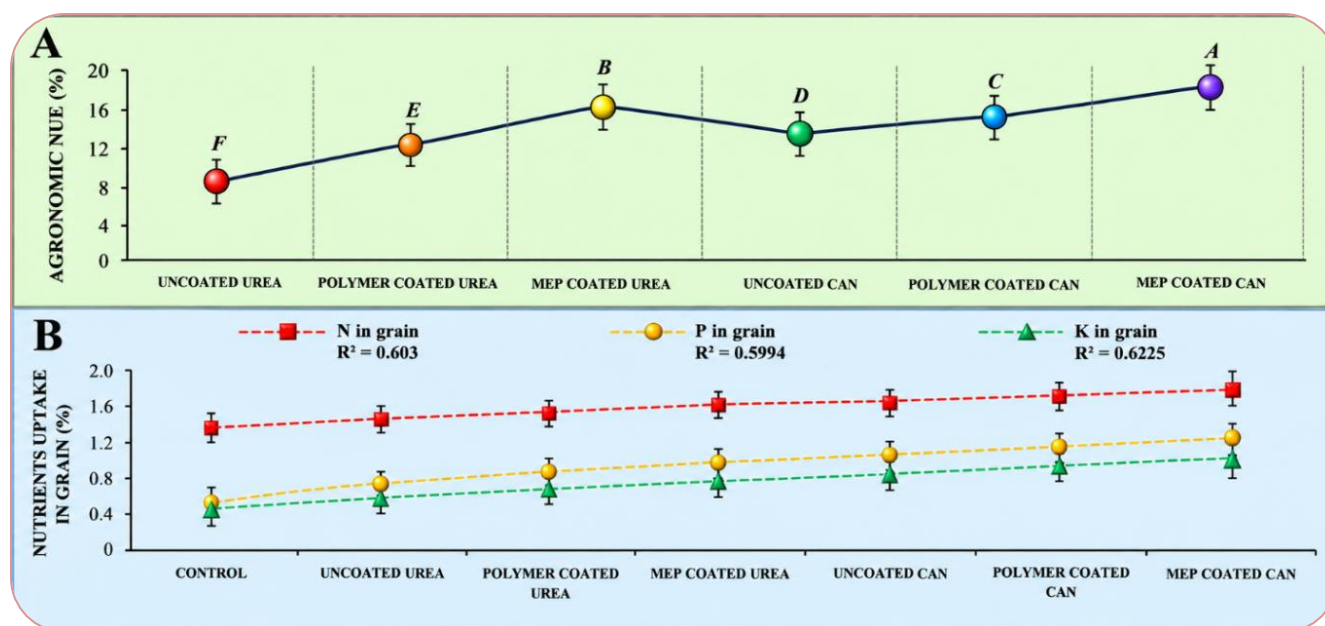


Figure 8. Principal component analysis and correlation analysis of wheat growth, yield, and nutrient-related traits under different fertilizer treatments. (A) (ANUE, %) of wheat under different fertilizer treatments. Means with different capital letters differ significantly according to Tukey's test ($P \leq 0.05$). (B) Relationships between fertilizer treatments and N, P, and K uptake by wheat grains, showing nutrient uptake (%) and coefficients of determination (R^2). Dashed lines indicate linear trends, and error bars represent standard errors (SE). MEP = microbially impregnated polymer-coated.

Across the measured growth variables, T7 (MEP-coated CAN) generally exhibited the strongest performance, including greater plant height, fertile tiller density, chlorophyll index, root biomass, root length and 1000-grain weight. These responses are consistent with the established role of controlled-release N fertilizers in improving the temporal synchronization between N availability and crop demand (Yang et al., 2011; Grant et al., 2012; Naz and Sulaiman, 2016). The stronger response to MEP-coated CAN than to the corresponding urea treatment may also reflect differences in N form, fertilizer composition and N transformation or availability in the soil. However, because fertilizer-release kinetics were not directly measured, the present field data demonstrate improved crop performance under the treatment but do not independently establish the release characteristics of the polymer coating (Wei et al., 2017). Similarly, polymer biodegradability cannot be inferred from crop responses alone and requires direct physicochemical characterization (Majeed et al., 2015). The greater yield and nutrient concentrations observed under the MEP-coated treatments are consistent with previous evidence that microbial inoculants can enhance nutrient acquisition when delivered through suitable

formulations or carriers. Recent field research in wheat has demonstrated that PGPR performance can vary according to the mode of application, including liquid inoculation, seed coating and carrier-based delivery (Khaliq et al., 2024). This finding highlights the potential importance of the delivery system used in the present study and is consistent with broader evidence that inoculant efficacy depends on formulation, carrier characteristics, microbial viability and rhizosphere colonization (Bhattacharyya and Jha, 2012; Souza et al., 2015). Nevertheless, bacterial population dynamics and colonization were not assessed in the present experiment. Consequently, the relative contributions of bacterial establishment and polymer-mediated nutrient availability to the observed crop responses cannot be distinguished. Several responses in the original interpretation were attributed directly to nitrogen fixation, phosphorus solubilization and 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity. These mechanisms were not measured in the present experiment and were therefore not presented as demonstrated explanations. Although these are well-established PGPR traits (Bhattacharyya and Jha, 2012; Souza et al., 2015), the present results provide no direct evidence that they were responsible for the

observed responses. The higher plant N concentration might have resulted from improved synchronization between fertilizer-N availability and crop demand, enhanced root development, altered nutrient uptake efficiency, microbial activity, or a combination of these processes. Similarly, increased P and K concentrations indicate improved plant nutrient status but do not demonstrate that the inoculated *Bacillus* directly solubilized P or K. Demonstrating biological N fixation would require appropriate molecular or isotopic evidence, such as *nifH*-based analyses and/or isotopic approaches. Claims of P solubilization would require validated biochemical or functional assays, whereas attribution to ACC deaminase would require direct measurements of enzyme activity, associated genes or their expression. These mechanisms should therefore be regarded as testable hypotheses for future mechanistic studies rather than established explanations of the present findings.

The corrected root-length value for T3 is 17.94 cm rather than 117.94 cm, which is consistent with the plotted data in Figure 2C. Similarly, the corrected NUE ranking identifies T7 as having the highest reported NUE (17.79%), followed by T4 (15.67%), rather than the 40% value previously reported. These corrections are important because they influence the interpretation of treatment performance and should be verified against the original raw dataset and all corresponding tables, figures and text before resubmission.

The PCA provides a useful multivariate representation of the relationships among treatments and measured variables but should not be interpreted as an independent test of treatment efficacy. The separation of MEP-coated CAN from the control is broadly consistent with the univariate responses, while the associations among N, P, K, SPAD and yield-related variables indicate coordinated variation in plant nutritional and productivity traits. Nevertheless, PCA is descriptive and does not establish causal relationships among these variables. Future experiments should integrate field performance measurements with bacterial abundance and viability, rhizosphere colonization, functional assays and fertilizer-release characterization to determine whether incorporation of the microbial component provides benefits beyond those attributable to the polymer coating and altered N availability.

From a plant-protection perspective, *Bacillus*-based formulations have the potential to influence rhizosphere health and plant resilience, and microbial inoculants are

increasingly being investigated as multifunctional agricultural inputs (Khosro et al., 2026). However, the present experiment did not quantify disease incidence or severity, pathogen populations, induced resistance, insect infestation, nematode damage or direct biocontrol activity. The results therefore should not be interpreted as evidence of direct protection of wheat against plant pathogens. Future studies should further substantiate the plant-protection potential of this approach by incorporating well-defined soil- or foliar-borne pathogen challenges, systematic disease surveillance, and assessments of microbial colonization, persistence, and functional activity, alongside relevant antagonistic and plant-defense responses. The present study provides a promising conceptual link between agronomic nutrient management and plant protection through the integration of beneficial microorganisms into polymer-coated fertilizers, highlighting their potential as a multifunctional strategy for improving crop performance while supporting disease resilience.

Overall, the results support further field evaluation of MEP-coated fertilizers under diverse soil, climatic and management conditions. The most defensible interpretation is that MEP-coated CAN and urea were associated with improved wheat growth, yield, nutrient concentrations and reported NUE relative to the corresponding control treatments under the conditions evaluated. However, the study does not establish the underlying microbial mechanisms, long-term bacterial survival, polymer biodegradation, fertilizer-release kinetics, economic benefits or plant-protection efficacy. These aspects require targeted experimentation before broader agronomic or mechanistic conclusions can be drawn.

Conclusion

Under the field conditions evaluated, MEP-coated urea and CAN generally produced greater wheat growth, yield and nutrient concentrations than the corresponding uncoated and polymer-coated fertilizers, with MEP-coated CAN (T7) exhibiting the strongest overall response across the measured traits. The highest reported NUE was 17.79% for T7. The principal contribution of the study is the field evaluation of a combined fertilizer-microbial delivery formulation in which a *Bacillus* inoculum was incorporated into the polymer coating of N fertilizer. However, the present study does not directly demonstrate biological N fixation, P or K solubilization, ACC deaminase activity, microbial survival and viability following coating,

nutrient-release kinetics, polymer biodegradation, or direct suppression of plant pathogens. Accordingly, the mechanistic basis of these potential functions, as well as their associated agronomic and plant-protection benefits remain to be established. Targeted mechanistic investigations, complemented by multi-season and multi-site field trials, are therefore warranted to validate these processes and determine the consistency and practical relevance of microbial-impregnated polymer-coated fertilizers under diverse agroecological conditions.

Study limitations and reproducibility

The present field experiment demonstrates treatment-associated differences in wheat growth, yield, nutrient concentrations and reported NUE. However, the study does not directly establish bacterial survival during or after the coating process, rhizosphere colonization, polymer biodegradation, fertilizer-release kinetics, biological N fixation, P and K solubilization, ACC deaminase activity, or direct plant-protection efficacy. In addition, the absence of direct measurements of microbial population dynamics limits mechanistic attribution of the observed responses. Future studies should therefore incorporate these endpoints, together with detailed characterization of the coating and fertilizer-release behavior, to improve mechanistic interpretation, reproducibility and validation across contrasting environmental conditions.

Author Contributions

AA and NAR conceptualized the study and designed the experiments. MA conducted the field investigations and performed the experimental work. MA also provided overall supervision and ensured methodological rigor and consistency throughout the study. HR and JS served as co-supervisors, providing critical guidance on experimental design, data interpretation, and scientific refinement at various stages of the research. MJM, AK, AN, AS, MR, and MTS contributed to the preparation of the initial manuscript, including content organization, compilation of results, and integration of preliminary interpretations. All authors subsequently critically reviewed and revised the manuscript, contributed to its intellectual refinement, verified the data and analyses, and approved the final version for submission.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

Policy Addressed

The findings support the inclusion of microbially impregnated polymer-coated fertilizers in integrated nutrient-management strategies to improve wheat productivity and NUE. Policies should encourage their field validation, quality standards, and responsible commercialization. However, multi-location trials, economic analyses, environmental assessments, and evaluation of microbial stability are needed before large-scale adoption.

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