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Slow-released fertilizers optimization and experimental impacts on soil fertility and wheat- maize cropping system

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ABSTRACT: Using of traditional fertilizers to enhance plant productivity extensively causes nutrient loss and environmental hazards. Urea-coated fertilizers are expected to balance the riddle between soil fertility and plant productivity. This study aimed to optimize grain yield prediction based on plant type, soil type, and coated urea levels through the Design Expert Model. Experimental investigations were carried out using sulfur-coated urea (SCU) and urea-formaldehyde (UF) on wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) plants across multiple winter/summer seasons (2019/2020-2020/2021) in a split-plot design. The main plots represented sandy, loamy, and clayey soils, and subgroups (T1, T2, T3) denoted urea, SCU, and UF, respectively, at recommended nitrogen doses. The central composite face-centered (CCFC) model explained 89 % of the total variability, highlighting the optimal 100 % coated urea dose for maximum grain yield. The application of sulfur-coated urea (SCU) enhanced soil pH, electrical conductivity (EC), nitrogen (N), phosphorus (P), potassium (K) availability, dehydrogenase (DHA), and urease activities. The N-coated fertilizers positively correlated with soil fertility and soil microbial biomass (SMB), organic matter (OM), grain yield, and microbial population. The highest wheat and maize yields were observed with SCU application in clayey soil. The principal component analysis (PCA) reinforced the positive correlations between SMB, OM, DHA, and urease, emphasizing their significance in grain and straw yield. Consequently, the application of SCU as a slow-release fertilizer for sulfur and nitrogen nutrients proved beneficial in improving soil characteristics and enhancing plant productivity.
Keywords: coated fertilizers, optimal approach, plant productivity, soil properties

Introduction

The global population growth and the reduction in agricultural land pose challenges to agricultural development worldwide, with ensuring an adequate food supply becoming a significant concern. Fertilizer application has been identified as a potential solution for improving agricultural production (Chen et al., 2021). Nitrogen is a vital nutrient that often limits crop yield; however, its excessive application has led to nitrogen use inefficiency and environmental problems (Khan et al., 2022). Coating urea with renewable compounds such as polymers (Kaneko et al., 2019), chitosan (Essawy et al., 2016), cellulose (Costa et al., 2013), starch (Zhao et al., 2021), alginate (Sathisaran and Balasubramanian, 2020), and lignin (Chen et al., 2021) offers a solution for the slow or controlled release of nitrogen, thereby improving its efficiency.

Slow-released sulfur-coated urea (SCU) and urea-formaldehyde (UF) have gained attention for their ability to release nutrients gradually, reducing the need for frequent applications and improving nutrient use efficiency (Chandran et al., 2021). These coated fertilizers also enhance soil fertility and reduce nutrient losses (Yamamoto et al., 2016).

Soil texture and other factors influence the fertilizer-crop productivity relationship. Studies have demonstrated the positive effects of coated urea fertilizers on wheat and maize plants in different soil types (Shivay et al., 2019). Additionally, the N fertilizer tends to be conveyed according to different soil structures, original soil properties, and climate status (Quan et al., 2020).

Optimization techniques are crucial for the efficient fertilization of crops, allowing for the optimal use of resources and the improvement of crop productivity (Goulding et al., 2008). Researchers can adjust application rates by identifying the optimal levels and interactions of fertilizers while minimizing waste and environmental impacts (Seppelt and Voinov, 2002). Optimization also has economic implications, enabling farmers to allocate resources efficiently and reduce input costs (Goulding et al., 2008). The wheat-maize rotation is a prominent agricultural practice in Egypt that considers the main cycle receiving N fertilizers. This study aimed to investigate the impact of coated urea fertilizers, comprising formaldehyde and sulfur as organic and inorganic coating materials, on two key aspects: (1) the properties of different soil types (clayey, loamy, and sandy) and (2) the productivity of wheat (*Triticum aestivum* L. var. Giza 168) and maize (*Zea mays* L. SC 168 hybrid) crops.

Materials and Methods

Sampling site

Three soil types were collected from different sites and classified according to the FAO classification (IO, 1947), which categorizes soils as sandy (S), loamy (L), and clayey

(C). The sandy soil (Haplic Arenosols type) was collected from El-Bostan village in El-Bahira Governorate, Egypt (30°69′10″ N, 30°33′25″ E, altitude 6.54 m). The loamy soil (Haplic Calcisols type) was calcareous and gathered from the Kilo 48 desert road of Alexandria-Cairo, Nubaria, El-Bahira Governorate, Egypt (29°82′12″ N, 31°06′43″ E, altitude 29.82 m). The final soil sample was clayey (Eutric Vertisols type) collected in EL-Gemmeiza, Middle Delta, El Gharbia Governorate, Egypt (31°47′22″ N, 30°43′33″ E, altitude 8.02 m). The soil samples were transported to the laboratory and air-dried at an ambient temperature of 25 °C. Subsequently, the dried soil samples were sieved through a 2-mm screen in preparation for various analyses.

Optimization procedure

A factorial experiment was conducted to optimize the pretreatment method for maximizing grain yield in plants. The experiment employed a central composite face-centered (CCFC) approach and included three factors: Factor A = plant type coded (one, two types), Factor B = soil type coded (one, two, three types), and Factor C = coated urea levels coded (50, 100, and 150 % doses). The levels and range of each factor are specified in Table 1.

Experimental layout

Lysimeter experiments were conducted over consecutive winter seasons of 2019/2020 and summer seasons of 2020/2021 in EL-Gemmeiza, Middle Delta, El Gharbia Governorate, Egypt. The primary objective of this study was to assess the impact of urea fertilizers, both coated and uncoated with different materials, on soil biochemical characteristics and plant productivity. The study employed wheat (*T. aestivum*) and maize (*Z. mays*) plants, which represent a traditional rotation practiced in the region for decades during the winter/summer seasons.

The results of the optimization experiment, which elucidated the use of the recommended dose of N to maximize the grain yield, indicated that the experiment should be performed in a split-plot design with three replicates. The main plot considered independent was the three types of soils. Each group was divided into three sub-groups as follows: T1 = recommendation rate (100 %) of urea (46 % N) fertilizer for wheat (179 kg ha^{-1} N) and maize (286 kg ha^{-1} N); T2 = sulfur-coated urea (SCU, 37.86 % N: 30 % S) at the recommended rate of 100 % for wheat (89.50 kg ha^{-1} N) and maize (143 kg ha^{-1} N); T3 = urea-formaldehyde (UF, 30 % N with molar ratio of 1.2) at a rate of 100 % of the recommended dose for wheat (89.50 kg ha^{-1} N) and maize (143 kg ha^{-1} N). The lysimeters were divided into three groups, each with nine lysimeters to be studied in both seasons. Each group was repeated thrice. The dimensions of the lysimeters were (0.5 m length × 0.8 m width × 1.00 m depth) and accommodated about 600 kg of soil.

Table 1 – The optimization factors and coding ranges.

Factor	Name	Level	Low level	High level
A	Plant type	1.50	1.00	2.00
B	Soil type	2.80	1.00	3.00
C	Coated urea	100.00	50.00	150.00

Wheat var. Giza 168 seeds were sown on 20 Nov 2019 at a rate of 120 kg ha^{-1}. The crop was harvested on 15 May 2020 at the end of the ripening stage for the winter season. Phosphorus (46 kg P ha^{-1}, $Ca(H_2PO_4)_2.H_2O$) was applied during the preparation of the field, while potassium (95.2 kg K ha^{-1}, K_2SO_4) was applied after 60 and 90 days of sowing. Nitrogen fertilizers were added in three equal portions at heading stages after one month and two months of sowing. Regarding the summer season, maize seeds SC 168 hybrid were planted at a rate of 33 kg ha^{-1} on 28 May 2020 and harvested after full maturity on 22 Sept 2020. Urea was applied in three equal doses after 20, 40, and 60 days of planting. Potassium (46 kg K ha^{-1}, K_2SO_4) was supplied at the second irrigation. The wheat and maize grains were then detached from the straw and weighed individually.

Soil analysis

Surface soil samples (0-30 cm) were collected from the experimental area and analyzed for various physical and chemical properties (Table 2). Soil pH was determined using a soil-water suspension, while soil EC was measured in soil paste extract (Page et al., 1982; Klute, 1986). The total carbonate content was determined using a Collin's calcimeter (Şenlikci et al., 2015). The OM content was quantified using the Walkley and Black method, and the cation exchange capacity (CEC) was analyzed using

Table 2 – Chemical and physical characteristics of the three soil types used in the experiment.

Properties	Types of soils		
	Sandy	Loamy	Clayey
Clay (%)	4.99	17.12	50.45
Silt (%)	7.11	35.01	29.18
Fine sand (%)	39.49	25.01	12.32
Coarse sand (%)	48.41	22.86	8.05
Textural class	Sand	Loam	Clay
pH (1:2.5)	8.02	8.11	7.93
ECe (dS m^{-1})	1.09	1.90	1.7
CEC (cmol$_c$ kg^{-1})	16.8	43.27	65.65
Bulk Density (g cm^{-3})	1.65	1.51	1.24
Total porosity (%)	37.8	43.02	53.21
OM (%)	0.72	0.94	1.15
$CaCO_3$ (%)	3.61	24.70	2.88
N available (mg kg^{-1})	13.45	39.78	49.05
P available (mg kg^{-1})	2.18	4.05	6.19
K available (mg kg^{-1})	55.15	128	286

ECe = electrical conductivity measured in soil paste; CEC = cation exchange capacity; OM = organic matter; N = nitrogen; P = phosphorus.

$CH_3CO_2NH_4$, as indicated by Cottenie et al. (1982). The available K and N were determined using the methods of AOAC (2005), and the available P was quantified using the method of Olsen et al. (1954), as reported by Liu et al. (2023). The soil microbial populations of bacteria, fungi, and actinomycetes were quantified following the established methodologies of Vieira and Nahas (2005) and Allen (1958). The fertility index was calculated according to the methodology proposed by Abdellatif et al. (2021), as detailed in Eq. (1):

$$FI = (FN \times FP \times FK \times FOM)^{1/5} \quad (1)$$

where: FI = fertility index; FN = available nitrogen content (mg kg^{-1}); FP = available phosphorus content (mg kg^{-1}); FK = available potassium content (mg kg^{-1}); and FOM = organic matter percentage.

Activities of soil enzymes, such as the magnitude of soil health and the indicator for biochemical changes in the soil, have been determined (Paz-Ferreiro et al., 2012). The DHA was quantified using the method described by Casida et al. (1964), while the urease activity was determined using the method proposed by Tabatabai (1983).

Plant sampling and analyses

Plant samples (straw and grain) of maize and wheat were harvested at the maturity stage to determine plant characteristics. The biomass (grain yield and straw yield) of the plants was measured, as well as plant height and grain weight. Grain and straw samples were oven-dehydrated at 70 °C, ground, and wet digested using (H_2SO_4 + $HClO_4$), as described by Cottenie et al. (1982). Total N was analyzed using the Kjeldahl method, as reported by Page et al. (1982), and the content of crude protein was calculated by multiplying the % N by 6.25. The vanadate-molybdate method he determined the total P, as described by Chapman and Pratt (1962). In brief, reagent A is prepared by dissolving 20.0 mg of ammonium molybdate tetrahydrate in 250 mL deionized water (DIW). Reagent B is prepared by dissolving 1.0 mg of ammonium metavanadate (NH_4VO_3) in 40 mL nitric acid and 200 mL DIW.

Subsequently, reagents A and B were combined with 100 mL of nitric acid and diluted with DIW to 1 L. A 5 mL aliquot of the mixture was then transferred to a volumetric cuvette and mixed with an aliquot of plant-digested extract. The intensity of the yellowish color was then measured spectrophotometrically using a wavelength of 470 nm. Total K was determined using a flame photometer according to the method described by Cottenie et al. (1982). The nutrient uptake of N, P, and K by the grains and straw was calculated by multiplying the nutrient percentages by the biomass of the dry yield per plant and expressing the result as kg ha^{-1}. The chlorophyll a and b content were estimated using the method described by Ritchie (2006).

Statistical analysis

The data obtained was analyzed using Design Expert software (version 12.0.3) for regression and graphical analyses. The multiple coefficients of determination, R^2, were employed to elucidate the variability of dependent variables. The model equation derived from the analysis was utilized to predict the optimum amount and examine the interaction between the factors within the defined range, in accordance with the approach described by Zulkali et al. (2006). The analysis of variance (ANOVA) was conducted using the PROC GLM function of SAS 9.4M8 software. The Fisher's protected least significant difference (LSD) test at the 0.05 level and PCA were conducted using the Minitab software (2022).

Results

Optimization experiment results

The design aimed to identify the highest rate of grain yields. To this end, a quadratic equation model was employed to predict the optimal point. The model is expressed as follows Eq. (2):

$$\text{Grain yield} = 4.4033 + 0.495088\,A + 0.618997\,B + 0.987276\,C - 0.37875\,AB - 0.06125\,AC + 0.11125\,BC + 0.113854\,A^2 + 0.03784\,B^2 - 0.70639\,C^2 \quad (2)$$

where: A = plant type; B = soil type; and C = coated urea doses. This equation provides a coded representation, allowing factor coefficients to be compared to identify their relative impact.

The regression results indicated a high significance level at a 99 % confidence level, with a determination coefficient (R^2) recorded as 0.89.

The Pareto diagram, which presents the proportionate impact of individual factors in the model, was obtained using the effect tools box of a 2^x factorial level design expert and is illustrated in Figure 1 A-D. The chart shows the influence of different levels of coated urea on grain yield. The fraction of design space (FDS) statistics in Figure 1D provide valuable insights into the relationship between the factors and their interactions in the experimental design. In this case, three factors were considered: Factor A = plant types; Factor B = soil types; and Factor C = concentrations of coated urea. The power values (90.7 and 71.2 %) between each factor and its interaction, respectively, indicate the adequacy of the model for predicting the response based on the specified factors. This suggests that the quadratic effects of the factors have a strong influence on the response variable. The standard error values (0.45, 0.5, and 0.55) between factors A and B in the design graphs indicate the variability in the estimated effects of these factors.

The Design Expert model employed a central composite design approach, generating 20 test formulations. This experimental design allowed for

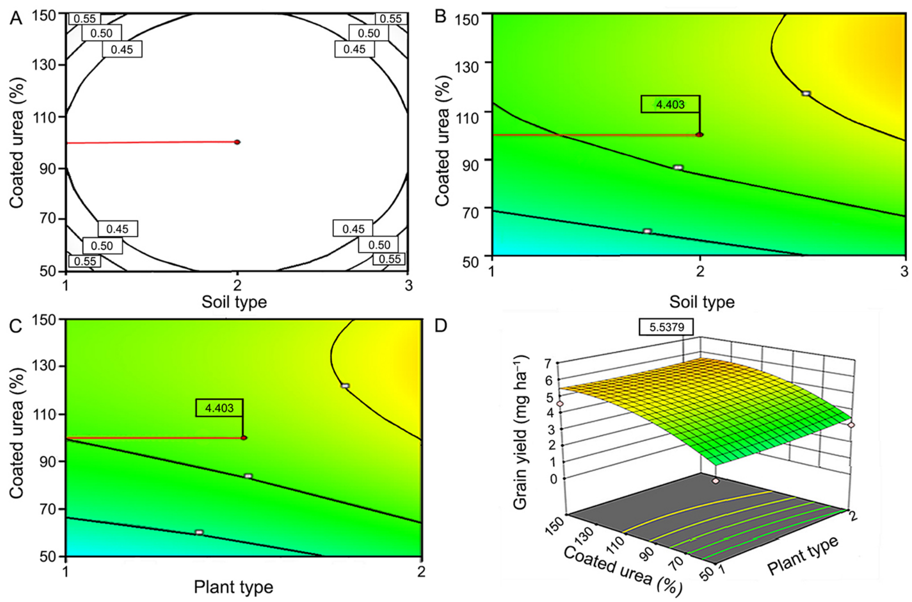

Figure 1 – A) Standard error of the factorial design through fraction of design space (FDS) statistics for grain yield between coated urea and soil type; B) Response surface contour plot correlation between coated urea and plant type; C) Response surface contour plot correlation between coated urea and soil type; D) 3D surface plot with optimization point for maximizing grain yield using coated urea and plant type factors. A = plant type; B = soil types; and C = concentrations of coated urea.

systematically exploring various factors and their interactions to optimize a specific outcome. Statistical analyses were conducted based on prediction-based metrics, particularly using FDS statistics to identify the best-fitting model among the trials. Through these analyses, the model sought to identify the independent variables that would yield optimal responses.

The present study focused on the interplay between the coated urea level, soil, and plant types to maximize grain yield. The results of this investigation are presented in Figure 1 A-D, which illustrate the interactions between these factors. The key finding of this study was the remarkable impact of the 100 % coated urea level, as evidenced by its highly significant *p*-value ($p < 0.001$). This factor emerged as the primary driver for achieving the maximum grain yield, which amounted to approximately 4.403 Mg ha^{-1}. Furthermore, the study employed a 3D response surface plot, as depicted in Figure 1D, to provide a comprehensive view of the relationships between the three influencing factors: coated urea level, soil, and plant types. The plot facilitated the identification of the design point that predicted the highest grain yield, approximately 5.55 Mg ha^{-1}. Notably, this optimal yield was associated with the utilization of a 100 % dose of coated urea fertilizers.

The empirical experimental results

Soil properties

The urea coating types exhibited varying influences on the chemical properties of the soil (Table 3). The soil and plant species demonstrated effects on the soil properties ($p < 0.01$). The pH was influenced by the plant type-coated fertilizer interaction. The availability of the macronutrients (P and K) was affected by the treatment-soil type interaction, while the N availability was influenced by soil type-plant type interaction. The SCU and UF treatments reduced pH and EC compared to the uncoated urea. The T2 treatment demonstrated a positive impact on soil salinity and pH. The sandy soil exhibited the lowest values of available NPK in both seasons compared to other soil types, as evidenced in Table 3.

Furthermore, the availability of nutrients was reduced in the second season, with the exception of K, which increased after harvesting maize plants. The SCU treatment enhanced soil available NPK, and its application in clayey soil recorded the highest values in both plants. SMB and soil OM were influenced by the treatments, and the SCU treatment recorded the highest values in both plants (Figure 2). The DHA enzyme exhibited a similar polynomial trend with both plants (Figure 3). Applying urea-coated fertilizers resulted in an increase in DHA with both plants in different soil types.

The maximum value of DHA was recorded in the loamy soil treated with SCU (T2), with an increase rate of 11.41 and 13.71 % for both wheat and maize plants, respectively, in comparison to the uncoated urea. With regard to urease enzyme activity, the two plants exhibited divergent trends from those observed in the wheat data, which displayed a curved polynomial trend (Figure 3). In contrast, the maize data exhibited a linear, straight pattern. The application of SCU resulted

Table 3 – Effect of urea-coated types on pH, electrical conductivity (EC), available nitrogen (N), phosphorus (P), and potassium (K) in three soil types after harvesting wheat and maize plants.

Soil type	Treatment	Wheat					Maize				
		EC	pH (1:2.50)	NPK available			EC	pH (1:2.50)	NPK available		
				N	P	K			N	P	K
		dS m^{-1}		-------------- mg kg^{-1} --------------			dS m^{-1}		-------------- mg kg^{-1} --------------		
Sandy soil	T1	0.91^{fg}	8.07^{a}	34.50^{ef}	2.22^{e}	78.32^{e}	0.82^{e}	8.01^{a}	24.50^{f}	2.96^{d}	92.50^{f}
	T2	0.77^{g}	7.91^{c}	40.12^{def}	2.95^{e}	97.15^{d}	0.61^{f}	7.88^{c}	29.08^{ef}	3.99^{d}	114.27^{de}
	T3	0.82^{g}	7.91^{c}	34.08^{f}	2.46^{e}	83.67^{de}	0.71^{ef}	7.94^{abc}	25.35^{ef}	3.30^{d}	102.97^{ef}
Loamy soil	T1	1.66^{a}	8.02^{ab}	41.63^{de}	3.92^{d}	116.37^{c}	1.51^{a}	7.91^{bc}	28.32^{ef}	4.24^{d}	119.30^{de}
	T2	1.37^{bc}	7.88^{c}	46.42^{cd}	5.02^{c}	131.37^{c}	1.24^{bc}	7.86^{c}	36.07^{ab}	6.53^{c}	147.83^{c}
	T3	1.51^{ab}	7.91^{c}	43.47^{d}	4.16^{d}	124.52^{c}	1.39^{ab}	7.89^{c}	30.52^{cde}	5.83^{c}	134.20^{cd}
Clayey soil	T1	1.31^{cd}	8.05^{a}	51.03^{bc}	6.72^{b}	322.13^{b}	1.24^{bc}	7.99^{ab}	32.58^{bcd}	8.10^{b}	333.89^{b}
	T2	1.08^{ef}	7.93^{bc}	62.75^{a}	8.79^{a}	366.00^{a}	1.00^{d}	7.90^{bc}	40.50^{a}	9.50^{a}	374.01^{a}
	T3	1.14^{de}	7.94^{bc}	55.45^{b}	7.28^{b}	336.33^{b}	1.10^{cd}	7.91^{bc}	34.85^{c}	8.19^{ab}	363.70^{a}

Means in the same columns without the same letter are different (0.05 level). Difference at 0.05 and 0.01 probability levels. T1= nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde.

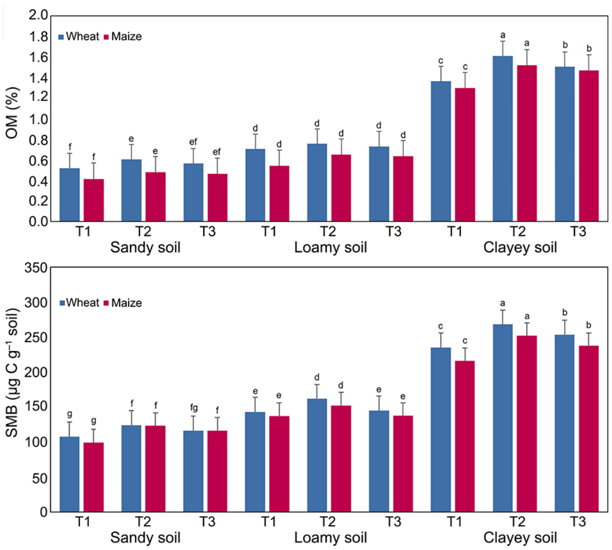

Figure 2 – Effect of coated urea fertilizers on organic matter (OM) and soil microbial biomass (SMB) of soil types after harvesting of wheat and maize plants. The column values with different letters are different (Duncan Multiple Range Test (DMRT), $p < 0.05$). T1 = nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde.

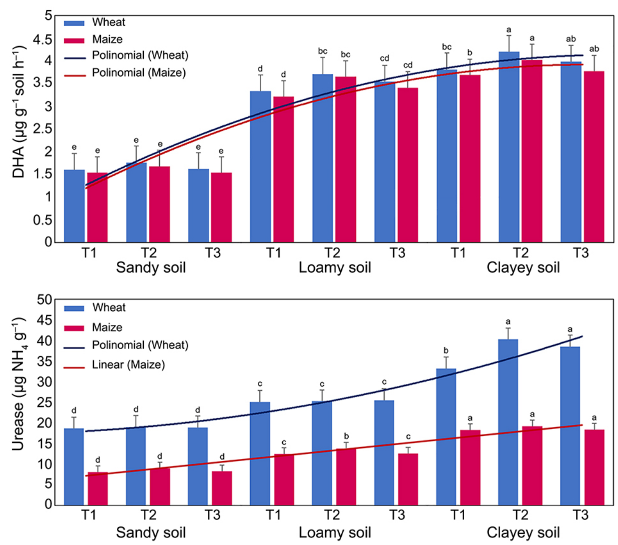

Figure 3 – Effect of coated urea fertilizers on dehydrogenase (DHA) and urease enzymes activity of soil types after harvesting of wheat and maize plants. The column values with different letters are different (Duncan Multiple Range Test (DMRT), $p < 0.05$). T1 = nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde.

in increased urease activity in different soil types with both plants. Therefore, the maximum urease activity was recorded for wheat plants in clayey soil treated with SCU with an increase of 21.16 % in comparison to the uncoated urea, while the sandy soil treated with SCU recorded the highest value of the urease activity with maize plants with a rise of 11.33 %.

The sandy soil exhibited the lowest population diversity of microbes, while the clayey soil exhibited the highest one (Figure 4). The coating fertilizers did not affect the total counts of bacteria, fungi, and actinomycetes in either sandy or loamy soil for both plants (Figure 4). The application of T3 in clayey soil increased the total counts of bacteria, fungi, and actinomycetes with colony-forming units (CFU) values of 8.12, 6.88, and 6.35 log CFU g^{-1} for wheat plants and values of 8.15, 4.89, and 4.57 log CFU g^{-1} for maize plants, respectively.

The total counts of microbes (TC) decreased with the second season (maize plant) under all soil types except the bacterial population. The application of UF recorded the highest difference with an increase of 15.54 % in comparison to the first season. The fertility index of different soil types after harvesting wheat and maize plants is presented in Table 4, demonstrating that

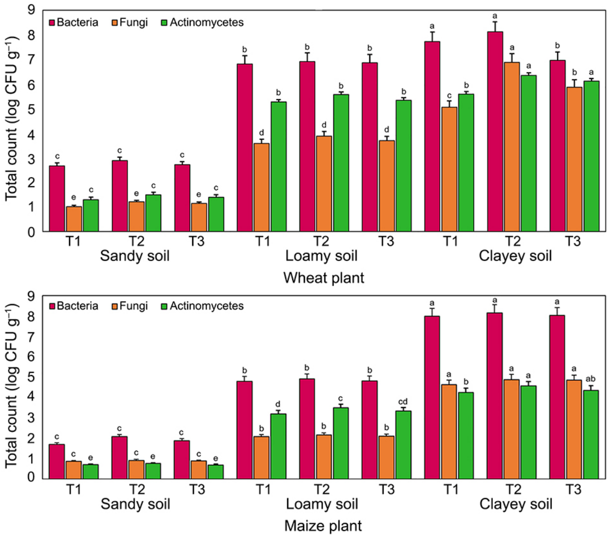

Figure 4 – Total count of bacteria, fungi, and actinomycetes in soil types as affected by coated urea fertilizers after harvesting of wheat and maize plants. The column values with different letters are different (Duncan Multiple Range Test (DMRT), $p < 0.05$). T1 = nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde.

Table 4 – Effect of different coated urea fertilizers on fertility index (FI) of different soils after harvesting of wheat and maize plants.

Soil types	Treatments	Wheat	Maize
Sandy soil	T1	4.98^{h}	4.88^{h}
	T2	5.86^{g}	5.76^{f}
	T3	5.24^{h}	5.24^{g}
Loamy soil	T1	6.68^{f}	5.98^{f}
	T2	7.46^{d}	7.43^{d}
	T3	6.97^{e}	6.85^{e}
Clayey soil	T1	10.85^{c}	10.26^{c}
	T2	12.66^{a}	11.69^{a}
	T3	11.53^{b}	10.88^{b}
LSD (0.05)		0.27	0.50

Means in the same columns without the same letter are different (0.05 level). T1 = nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde. LSD = least significant difference.

SCU ameliorated the soil properties. T2 exhibited the highest rate in clayey soil with an increment percentage of 154.22 and 139.55 % for wheat and maize plants, respectively, in comparison to the lowest values recorded with T1 in sandy soil.

Plant biomass and productivity

The grain yield of wheat and maize plants was affected by coated urea, soil type, and plant season (Table 5). Clayey soil exhibited the highest grain yield, with increases of 25.60 and 39.04 % for wheat and 12.52 and 25.20 % for maize compared to loamy and sandy soil, respectively. The SCU and UF treatments increased yield. Additionally, urea coating, soil type, and plant type affected grain weight and plant height. While coated urea did not affect chlorophyll a, it critically affected chlorophyll b. The plant type and soil type were affected ($p < 0.01$) individually or in combination with chlorophyll with both plants. Hence, clayey soil had the highest chlorophyll content.

The SCU exhibited higher nitrogen uptake ($p < 0.01$) in all soil types (Table 6). The nitrogen uptake in wheat grains was nearly double that in straw, while the nitrogen uptake in maize straw ranged from 41.63 to 81.92 % of that in grains. Phosphorus uptake was lowest in sandy soil, and the SCU increased uptake in all soil types. The SCU also increased potassium uptake in all soil types, with the highest values recorded in clayey soil, with average values of 29.64 and 109.49 kg ha^{-1} in wheat plants and 62.79 and 109.49 kg ha^{-1} in maize plants, respectively.

Discussion

The dilemma of increasing soil available nutrients throughout the plant period in a way that is both suitable and efficient is a primary concern for crop producers and soil researchers. The study results validated the quadratic equation model in Eq. (1) for predicting grain yield based on plant type, soil type, and coated urea level. The analysis of variance (ANOVA) demonstrated the high significance of the model ($p < 0.01$) with an R^2 of 0.89, which explained 89 % of the yield variation. The lack of fit was non-significant, confirming the model validity (Zulkali et al., 2006).

The Pareto charts in Figure 1A illustrated the contribution of each factor to grain yield. The FDS statistics in Figure 1B and C provide insights into factor relationships. Power values of 90.7 % for factors A, B, and C indicated the model accuracy in estimating individual factor effects. The 71.2 % power value for interactions suggests slightly lower accuracy. The 99.9 % power value for squares indicated strong quadratic effects (Siemsen et al., 2010). Standard error values (0.45, 0.5, and 0.55) between factors A and B indicated variability. The small standard error implied precise estimates, suggesting reliable effects (Asiamah et al., 2017; Yi et al., 2022).

The relatively small standard error values indicate that the estimated effects of factors A and B are precise, suggesting a reliable estimation of their effects on the response variable. This implies that the coated urea level of 100 %, the recommended dose of N, influences the grain yield of the plants with greater accuracy. Furthermore, the interaction between the coated urea level, soil type, and plant type significantly influenced grain yield ($p < 0.001$), with the 100 % coated urea treatment achieving the highest yield of 4.403 Mg ha^{-1}. The 3D response surface plot in Figure 1D predicted a maximum yield of approximately 5.55 Mg ha^{-1} with the 100 % coated urea dose.

Table 5 – Biomass parameters of wheat and maize plants as affected by urea-coated fertilizers in three soil types.

Soil type	Treatment	Wheat						Maize					
		Grain yield	Straw yield	1,000 grains weight	Plant height	Chl *a*	Chl *b*	Grain yield	Straw yield	100 grains weight	Plant height	Chl *a*	Chl *b*
		------ Mg ha^{-1} ------		g	cm	------ mg g^{-1} ------		------ Mg ha^{-1} ------		g	cm	------ mg g^{-1} ------	
Sandy soil	T1	2.75^{e}	4.86^{d}	45.09^{d}	71.07^{c}	2.39^{d}	0.94^{d}	4.61^{e}	5.93^{g}	35.35^{f}	275.00^{cd}	1.44^{e}	0.69^{c}
	T2	3.03^{de}	5.13^{d}	45.86^{cd}	71.87^{c}	2.41^{d}	0.98^{d}	4.77^{e}	6.17^{f}	37.20^{de}	276.67^{bcd}	1.44^{e}	0.73^{abc}
	T3	2.66^{e}	4.92^{d}	45.20^{d}	72.25^{c}	2.46^{cd}	1.01^{cd}	4.61^{e}	5.85^{g}	35.79^{ef}	273.33^{d}	1.43^{e}	0.70^{bc}
Loamy soil	T1	3.29^{cd}	5.69^{c}	46.19^{bc}	80.19^{b}	2.53^{bc}	1.09^{bc}	5.31^{d}	6.58^{e}	38.50^{cd}	280.33^{bcd}	1.64^{cd}	0.68^{c}
	T2	3.52^{c}	5.85^{c}	46.94^{ab}	80.53^{b}	2.55^{b}	1.11^{ab}	5.66^{c}	7.19^{d}	39.76^{bc}	283.00^{b}	1.65^{bcd}	0.73^{abc}
	T3	3.49^{c}	5.81^{c}	46.44^{abc}	81.20^{b}	2.50^{bc}	1.09^{bc}	5.39^{d}	6.43^{e}	39.36^{c}	281.33^{bc}	1.61^{d}	0.74^{abc}
Clayey soil	T1	4.35^{b}	6.38^{b}	47.14^{a}	86.15^{a}	2.72^{a}	1.15^{ab}	6.07^{b}	7.62^{c}	41.24^{ab}	294.33^{a}	1.68^{abc}	0.78^{abc}
	T2	4.82^{a}	6.78^{a}	47.28^{a}	87.63^{a}	2.75^{a}	1.18^{a}	6.47^{a}	8.15^{a}	42.23^{a}	292.33^{a}	1.70^{ab}	0.81^{a}
	T3	4.65^{ab}	6.53^{ab}	47.20^{a}	86.87^{a}	2.68^{a}	1.19^{a}	6.15^{b}	7.93^{b}	42.12^{a}	292.78^{a}	1.72^{a}	0.80^{ab}

Means in the same columns without the same letter are different (0.05 level). T1 = nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde. Chl *a* = Chlorophyll (a); Chl *b* = Chlorophyll (b).

Table 6 – Effect of urea-coated fertilizers on NPK uptake on both grains and straw of wheat and maize plants grown under three soil types.

Soil types	Treatment	Wheat						Maize					
		Uptake in grain			Uptake in straw			Uptake in grain			Uptake in straw		
		N	P	K	N	P	K	N	P	K	N	P	K
		---------- kg ha^{-1} ----------											
Sandy soil	T1	32.55^{d}	4.59^{e}	8.53^{f}	16.38^{de}	3.53^{g}	54.60^{i}	57.36^{f}	9.54^{e}	22.91^{f}	17.59^{f}	5.81^{f}	7.19^{f}
	T2	36.33^{d}	5.64^{e}	13.07^{e}	17.96^{d}	5.82^{de}	63.79^{g}	61.15^{e}	11.12^{e}	35.78^{de}	21.39^{e}	8.02^{de}	90.50^{d}
	T3	31.07^{d}	5.32^{e}	10.47^{ef}	15.41^{e}	4.78^{ef}	58.66^{h}	57.77^{ef}	9.99^{e}	27.00^{ef}	15.80^{f}	6.43^{ef}	74.10^{e}
Loamy soil	T1	48.12^{c}	4.84^{e}	12.32^{e}	24.28^{c}	4.19^{fg}	69.62^{f}	75.23^{d}	10.97^{e}	30.07^{ef}	26.98^{d}	6.74^{ef}	84.45^{d}
	T2	52.39^{c}	6.09^{de}	23.44^{c}	26.53^{c}	7.80^{ab}	80.98^{d}	81.96^{c}	19.43^{b}	53.05^{bc}	32.61^{c}	13.17^{c}	117.41^{bc}
	T3	50.44^{c}	7.44^{cd}	18.26^{d}	25.40^{c}	6.24^{cd}	73.64^{e}	77.43^{d}	13.82^{d}	43.14^{cd}	26.60^{d}	8.37^{d}	92.21^{d}
Clayey soil	T1	69.60^{b}	8.87^{c}	23.71^{c}	30.62^{b}	6.44^{cd}	95.76^{c}	94.28^{b}	17.01^{c}	55.61^{b}	37.58^{b}	8.89^{d}	109.13^{c}
	T2	79.63^{a}	13.94^{a}	36.58^{a}	34.75^{a}	8.98^{a}	132.56^{a}	103.91^{a}	25.86^{a}	74.36^{a}	47.79^{a}	18.76^{a}	142.68^{a}
	T3	75.56^{ab}	11.44^{b}	28.64^{b}	33.09^{a}	7.18^{bc}	100.14^{b}	95.32^{b}	18.27^{bc}	58.41^{b}	39.68^{b}	16.13^{b}	126.98^{b}
LSD (0.05)		3.68	0.88	1.51	1.30	0.69	5.43	2.02	1.36	5.77	1.71	0.93	5.79

Means in the same columns without the same letter are different at 0.05 level. Difference at 0.05 and 0.01 probability levels. T1 = nitrogen recommended rate from urea fertilizer; T2 = nitrogen recommended rate from sulfur-coated urea; T3 = nitrogen recommended rate from urea-formaldehyde. LSD = least significant difference; N = nitrogen; P = phosphorus; K = potassium.

The results demonstrated a significant effect of soil types on pH and EC (Table 3), and these findings are consistent with previous studies by Wang et al. (2021). The slow-release property of sulfur-coated urea contributes to reduced leaching and maintenance of soil pH, as indicated by Ke et al. (2018). This underscores the necessity of considering soil characteristics in fertilizer management strategies. Applying SCU decreased pH, particularly in loamy soil. This effect may be attributed to the acidifying effects of sulfur and urea composites or shifts in microbial diversity (Hu et al., 2022; Mustafa et al., 2022).

Urea-coated fertilizers exhibited a synergistic effect on nutrient availability, a finding consistent with previous research (Li et al., 2021). The T2 treatment increased P and K availability in sandy soil by 32.88 and 24.04 %, respectively, in wheat plants compared to uncoated urea. In maize plants, the T2 treatment enhanced N, P, and K availability by 27.37, 54.01, and 23.91 %, respectively, in loamy soil, demonstrating the potential benefits of coated fertilizers for different crops. This shows that slow-release fertilizers have exhibited capacity to enhance nutrient content (Ghafoor et al., 2021). Clayey soil exhibited the highest nutrient concentrations, with N, P, and K values of 62.75, 8.79, and 366.00 mg kg^{-1} for wheat plants, and 40.50, 9.50, and 374.01 mg kg^{-1} for maize plants, respectively.

The nutrient concentrations in clayey soil were notably high, aligning with previous research that establishes correlations between clayey content and soil fertility, OM, NPK availability, and microbial diversity (Javed et al., 2022; Zhang et al., 2023). The SCU and urea-formaldehyde (UF) improved soil fertility compared to uncoated urea, as reported by Yin et al. (2017). These results are consistent with the data observed in Figures 2 and 4, which demonstrated the positive effects of coated fertilizers in soil OM and SMB carbon and their impacts on microbial populations in the soil. This aligns with previous studies' findings demonstrating the benefits of coated fertilizers. For instance, previous studies have highlighted the capacity of coated urea, such as SCU, to enhance SMB and OM content, thereby promoting a favorable environment for microbial activity (Lupwayi et al., 2010; Zheng et al., 2016).

The notable enhancement promoted by SCU of SMB, OM, and overall microbial population across diverse soil types, including sandy, loamy, and clayey soils, is consistent with the findings of El-Hassanin et al. (2024) and Khan et al. (2015). These studies collectively support the hypothesis that coated fertilizers contribute positively to soil microbial dynamics, fostering a conducive environment for plant growth and nutrient cycling. Additionally, the positive correlations observed between soil fertility and SMB (R^2 = 0.99, p < 0.05), OM (R^2 = 0.98, p < 0.05), grain yield (R^2 = 0.88, p < 0.05), and microbial population (R^2 = 0.81, p < 0.05) (Figure 5) underscore the overall benefits of coated fertilizers in enhancing soil health and productivity. These data are consistent with those obtained by Seleem et al. (2022). The necessity of coating is further emphasized by the drawbacks associated with granulated urea, such as rapid dissolution leading to nitrogen (N) loss through leaching or volatilization (Rehman et al., 2022). This underscores the importance of adopting coated fertilizers to mitigate nutrient loss and enhance nutrient use efficiency.

N-based coated fertilizers enhanced soil enzyme activities (DHA and urease) in different soil types, with clayey soil showing the highest values (Figure 3). These findings align with previous studies on rice (Mi et al., 2019), maize (Lian et al., 2021), and wheat plants (Ma et al., 2023). The application of coated urea fertilizers significantly impacted the grain yield, straw yield, grain weight, and plant height of wheat and maize plants, and their physiological attributes. The SCU treatment demonstrated the most favorable results (Table 5). These outcomes align with previous studies on rice (Rehman et al., 2022) and cotton plants (Geng et al., 2016). The maximum yields were achieved in clayey soil with the T2 treatment, reaching 11.60 Mg ha^{-1} for wheat and 14.62 Mg ha^{-1} for maize. This observation underscores the significance of soil characteristics in determining the efficacy of coated urea fertilizers (Zheng et al., 2016).

The interaction between the coating material and the soil matrix, particularly in clayey soil, may improve nutrient retention and release dynamics, ultimately enhancing plant growth and productivity (Trenkel, 2010; Vejan et al., 2021). The SCU exhibited a positive correlation with chlorophyll a and b, possibly due to dry matter partitioning and the relation between S and photosynthesis (Rose, 2016). The improvement in soil fertility, regulation of nitrogen efficiency, increased enzyme activity, and enhanced nutrient availability associated with SCU application, as reported by Ma et al. (2023), further supports the importance of coating in optimizing plant performance.

The study also emphasizes the role of soil type in influencing NPK uptake in wheat and maize plants, consistent with findings from Gao et al. (2021). SCU application led to increased total NPK uptake (Table 6), with maximum values recorded for nitrogen (N),

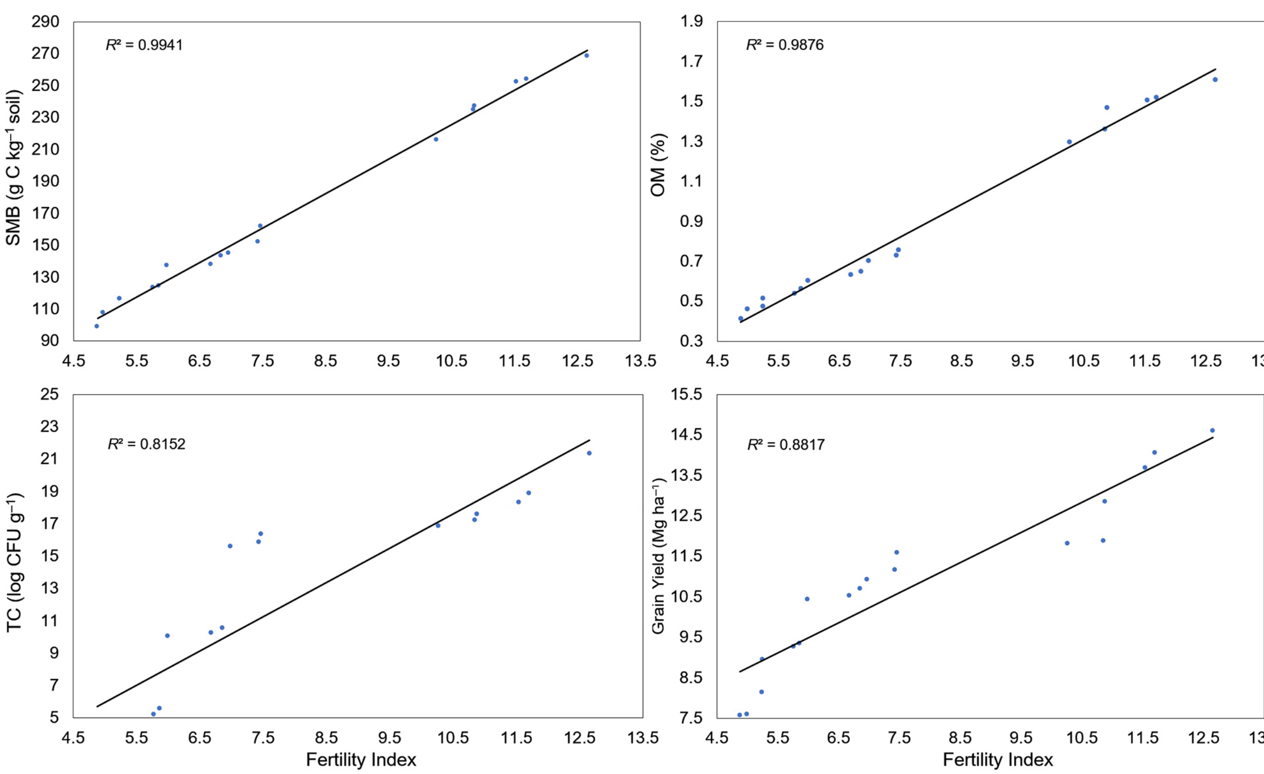

Figure 5 – Correlations of soil fertility index with soil microbial biomass (SMB), organic matter (OM), grain yield, and total count of microbes (TC) in soil types as affected by mid period application of coated urea fertilizers.

phosphorus (P), and potassium (K) in both wheat and maize plants. These results demonstrate the potential of coated urea fertilizers, particularly SCU, in improving nutrient utilization and uptake efficiency, essential for achieving higher yields in different soil types.

The PCA is crucial in elucidating the correlation matrix between the biochemical characteristics of soils and plant biomass in the study (Figure 6A and B). This statistical technique facilitates the identification of patterns and relationships within a multivariate dataset. Principal component (PC) groups identified six components and introduced PC1 and PC2 (Figure 6A) to count the maximum weightage component with 94.30 % of the total components. The eigenvectors in Figure 6B demonstrated that all parameters contributed equally to PC1, with SMB as the most affected parameter, while grain yield was the most effective in PC2. It is essential to recognize the role of soil type in influencing the recorded data.

Different soil types possess distinct physical and chemical properties, which affect nutrient availability, microbial activity, and overall soil health (Cardoso et al., 2013). Such variations may introduce biases into the dataset, potentially influencing the observed correlations between soil characteristics and plant biomass. Additionally, the coating of soil particles may influence the biochemical characteristics measured (Baldock and Skjemstad, 2000). The term "coating" describes organic or mineral materials around soil particles, influencing nutrient retention, water-holding capacity, and microbial activity (Mohammadi et al., 2011).

The composition and thickness of these coatings can vary across soil types, contributing to the observed variability in biochemical parameters (Fertahi et al., 2021). Consequently, the maximum components (PC1 and PC2) were employed to illustrate the correlations between biochemical (i.e., SMB, OM, TC, DHA, and urease) of soil and plant biomass (i.e., grain yield and straw yield) in the principal component analysis described in Figure 6B.

SMB, OM, TC, and DHA are highly positively correlated with each other and have a significant correlation with urease activity in both grain and straw yield. The findings align with similar results reported by Gu et al. (2009), emphasizingthe consistency and reliability of the observed correlations. This consistency across studies strengthens the robustness of the conclusions drawn from the current research.

The use of a quadratic equation model improved the prediction of grain yield based on factors such as plant type, soil type, and coated urea level. The model accounted for 89 % of the variation in grain yield. A key observation emerged regarding the positive impact of coated urea at total dosage on grain yield, particularly in sandy and loamy soils. The application of coated urea not only enhanced grain yield but also exhibited a constructive influence on crucial soil properties, including pH, EC, and nutrient availability. This positive effect was especially pronounced in soil types prone to nutrient leaching and reduced fertility.

Soil amendments with SCU and UF had strong positive correlations with soil fertility and various microbial counts. Clayey soil, characterized by its higher nutrient levels and fertility, showed the most pronounced benefits from these coated urea amendments. Applying coated urea positively influenced soil enzymes, increasing yields and plant attributes for wheat and maize. The most pronounced benefits were observed with sulfur-coated urea in clayey soil, with impressive yields for both crops.

The enhanced soil fertility and nutrient availability resulting from coated urea applications contributed significantly to improved plant biomass and nutrient uptake. The principal component analysis further supported using coated urea fertilizers as a strategic approach to bolster both crop production and soil fertility. These findings provide compelling evidence to support the adoption of coated urea fertilizers as a valuable tool in sustainable agriculture. They offer not only improved crop yields but also substantial benefits to soil health.

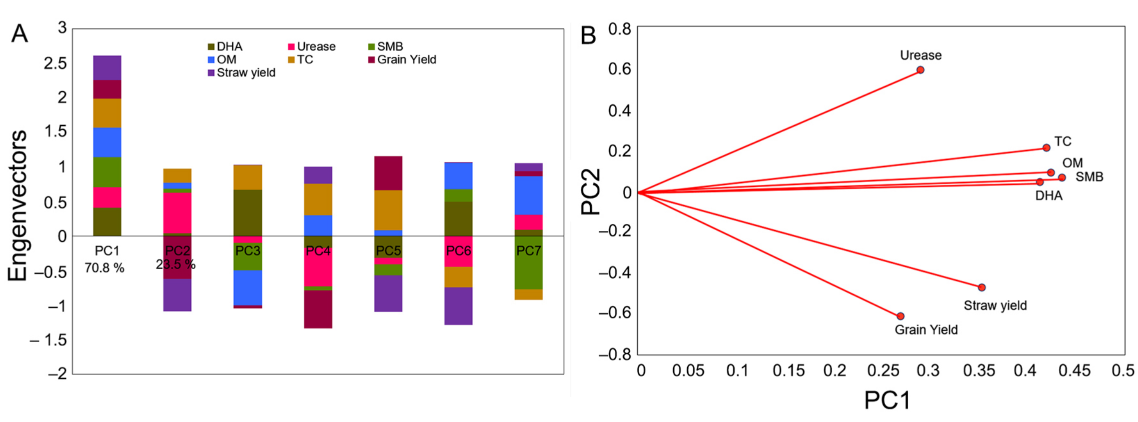

Figure 6 – Correlations between soil biochemical properties of soil types and plant biomass via: A) Eigenvectors groupings and B) Principal component analysis (PCA) for first components (PC1) and second components (PC2) as affected by coated urea fertilizers after harvesting of wheat and maize plants. TC = total counts of microbes; OM = organic matter; SMB = soil microbial biomass; DHA = dehydrogenase enzyme activity.

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