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Optimizing maize yield and nutritional quality through synergistic use of guinea pig manure and mineral fertilization: a sustainable approach for coastal Peru

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Introduction: Excessive reliance on mineral fertilizers in maize cultivation has raised environmental concerns, highlighting the need for more sustainable alternatives. This study evaluated the effects of guinea pig (*Cavia porcellus* L.) manure and the application of N, P and K fertilizers on the yield and nutritional quality of hybrid maize grown in the central Peruvian coast.

Methods: A split-plot design with three replications, was implemented, testing four manure doses (0, 2, 5, 10 t ha^{-1}) in combination with four mineral fertilizer levels (0, 50, 75, and 100% of recommended N, P and K).

Results: The 5 t ha^{-1} manure + 75% mineral fertilizer treatment achieved the highest yield (8.82 t ha^{-1}), representing a 28.38% increase relative to the full mineral fertilization treatment, accompanied by a grain weight of 152.80 g and an ear weight of 171.31 g. Nutritional quality peaked at 5 t ha^{-1} manure + 100% mineral fertilizer, with 7.85% protein and 363 kcal 100 g^{-1} energy content. Multivariate analysis revealed strong positive correlations between combined organic-mineral inputs and key productivity parameters. These findings demonstrate that the strategic integration of 5 t ha^{-1} of guinea pig manure with a 25% reduction in mineral fertilization (i.e., 75% of the recommended dose) enhanced both grain yield and nutritional value.

Discussion: This combination offers a practical, cost-effective pathway for smallholder farmers to improve yellow maize production under coastal Peruvian conditions while reducing dependence on chemical fertilizers. These results demonstrate a clear synergistic interaction between organic and mineral fertilization, leading to improved crop productivity under conditions of limited soil organic matter in the coastal soils of Peru. This finding supports the use of guinea pig manure as a sustainable and environmentally friendly agricultural input.

KEYWORDS

circular economy, grain quality, integrated fertilization, multi-variate analysis, sustainable agriculture

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1 Introduction

Maize (*Zea mays* L.) is recognized as one of the three most important cereals globally, surpassed only by wheat and rice (Kandil et al., 2020). It plays a fundamental role in human nutrition, animal feed, and industries applications (Choudhary et al., 2021). In Peru, maize is cultivated across 254,743 ha producing approximately 1.27 million tons annually (Barandiarán, 2020). However, the 20% of maize produced in the Amazon region (INEI, 2022) is insufficient to meet national demand, resulting in dependence on imports and compromising food security. This challenge is further exacerbated by the high nutritional requirements of the crop. Under high yielding conditions (>16 t ha^{-1}), maize requires between 250–300 kg N ha^{-1} (Biswas et al., 2022), which often leads to excessive use of mineral fertilizers. Such overreliance has resulted in well-documented environmental consequences, including soil degradation, nitrate leaching (Liu B. et al., 2022), and reductions in organic matter (Wang et al., 2019). To address these issues, the combined use of organic and mineral fertilizers has emerged as a promising alternative (Etesami et al., 2023), particularly in coastal soils, where improvements in physical properties and microbial activity have been reported (Sheoran et al., 2019; Liu X. et al., 2022).

While compost is widely studied and recognized for its high nutritional content (2.84% N, 52.56% organic matter, C/N ratio of 11.06) (Vallejos-Torres et al., 2022; Kandil et al., 2020), little is known about the agronomic potential of guinea pig (*Cavia porcellus* L.) manure—an abundant yet underutilized resource in Peru—despite its exceptional composition. The benefits of guinea pig manure as an organic amendment to increase crop productivity remain largely untapped, primarily due to limited awareness among producers. Recent analyses, highlight its high organic matter content, ranging from 52.56% to 72.77 ± 6.27% (Barreda-Del-Carpio et al., 2022; Calero-Rios et al., 2025), suggesting strong potential for agricultural application. Maize is a crop of great socioeconomic importance worldwide. Nevertheless, declining soil fertility is contributing to yield reductions and a significance decrease in overall production (Kabré et al., 2025). The decline in soil productivity due to intensive cultivation, unbalanced fertilization, and the impacts of climate change represents a major challenge for future food security (Abbas et al., 2024).

The need for alternative, affordable, and accessible nutrient sources to improve soil fertility in degraded agricultural lands has become a major concern for soil scientists, agronomists, and local farmers (Hafez et al., 2021). The present study was conducted in the coastal region of Peru, characterized by sandy loam soils, alkaline pH (8.3), and moderate electrical conductivity (37.4 mS m^{-1}). These edaphic conditions impose agronomic constraints that require solutions adapted to local socioeconomic and ecological contexts. Unlike most existing studies focusing on generic organic amendments (Abbas et al., 2024; Wang, J. et al 2025; Wang N. et al., 2025), this research is the first to evaluate the combined effects of multiple doses of guinea pig manure (0, 2, 5, and 10 t ha^{-1}) and mineral fertilization levels (0, 50, 75, and 100% of N, P and K) on the agronomic performance and nutritional quality of hard yellow maize.

In this context, we hypothesize general: that the strategic application of guinea pig manure, in combination with reduced mineral fertilization, can simultaneously improve the yield and nutritional quality of the commercial hybrid DEKALB® maize, while promoting soil health and consumer wellbeing. Accordingly, three specific hypotheses were proposed:1) The agronomic traits and yield of yellow maize were influenced by guinea pig manure and the application of N, P, and K fertilizers under the conditions of the central Peruvian coast, 2) The nutritional quality of yellow maize grain was influenced by guinea pig manure and the application of N, P, and K fertilizers in the central Peruvian coast and 3) The combined effect of guinea pig manure and N, P, and K fertilization was associated with improved nutrient-use efficiency and nutrient assimilation in yellow maize grown in the central Peruvian coast.

These hypotheses are supported by evidence showing that organic management enhances nitrogen use efficiency, mitigates abiotic stress (Zhai et al., 2024; Duan et al., 2023), and increases productivity and profitability—particularly for smallholder systems (Dubey et al., 2022). Furthermore, organic input–based agriculture aligns with sustainable food systems and supports circular economy principles. Specifically, this study addresses three key significant gaps: first, the paucity of research on local livestock residues; second, the absence of effective protocols to reduce mineral fertilizers use in maize cultivation; and third, the limited characterization of how nutritional management influences the protein and energy content of maize grain, a key factor determining its suitability for animal feed.

The objective of this research is to generate robust, context-specific evidence to support viable, sustainable, and cost-effective alternatives for maize production. These findings aim to contribute to improved cropping systems and to the strengthening of national food security—a pressing concern in the current global context.

2 Materials and methods

2.1 Study area

The study was conducted at the facilities of the Universidad Nacional Agraria La Molina, located in the district of La Molina, province and department of Lima, Peru. The experimental site is geographically located at 76°56′21″ W longitude and 12°04′55″ S latitude, at an elevation of 247 meters above sea level. During the study period, the site experienced an average temperature of 19.89 °C, relative humidity of 79.43%, and minimal precipitation, with only 0.8 mm h^{-1}. In this region, annual precipitation typically ranges from 0.4 to 20.2 mm year^{-1}. Soil properties were analyzed at the Soil, Water, and Foliar Laboratory (LABSAF) of the National Institute of Agrarian Innovation (INIA). Soil texture was determined using the Bouyoucos method (AS-09) (RECNAT-2000, 2022). Soil pH was measured following the EPA 9045 method (USEPA, 2004). Electrical conductivity was determined using the saturated paste extract method (AS-18). The cation exchange capacity (CEC) was determined by ammonium acetate extraction (AS-12) (RECNAT-2000, 2022). Available phosphorus (P) was analyzed using the Olsen method (AS-10), and available potassium (K) following the AS-12 protocol (RECNAT-2000, 2022). Organic matter (OM), total carbonates, and organic carbon (OC) were analyzed according to ISO 10694 (ISO 10694, 1995), whereas total nitrogen (N) was determined according to ISO 13878 (ISO 11272, 2017). In addition, the guinea pig manure used in this study was obtained from the facilities of the National Guinea Pig Program at the National Institute of Agrarian Innovation (INIA).

The guinea pig diet was primarily based on green forage, mainly alfalfa and maize fodder. Feed was supplied twice daily, with approximately 30–40% provided in the morning and 60–70% in the afternoon, preferably as wilted forage to prevent digestive disorders.

The physicochemical properties of the soil and guinea pig manure are presented in Supplementary Table 1. The materials exhibited a pH of 7.1, EC of 832 mS.m^{-1}, an OM of 52.56%, and total nitrogen content of 2.84%, with K and P contents of 2.51% and 1.01% respectively.

2.2 Experimental procedure

The soil used in this study was classified as sandy loam and corresponds to an Entisol (young or sandy/desert soils). In addition, Supplementary Table 1 presents the analysis of soil properties at the site where the maize crop was established, as well as the characteristics of the guinea pig manure used in this study. The field experiment followed a split-plot design with three replications. The main plots were assigned four applications rates of guinea pig manure (0, 2, 5, and 10 t ha^{-1}), while the subplots received four levels of granular mineral fertilizer (0, 50, 75, and 100%) based on N, P and K composition. The 100% of mineral fertilization level corresponded to 240 kg N ha^{-1}, 120 kg P ha^{-1} and 140 kg K ha^{-1} which aligns with the nutritional requirements for high-yield maize production under local conditions. This factorial arrangement resulted in a total of 16 treatment combinations. Each main plot covered an area of 120 m², and each subplot measured 30 m² (Supplementary Figure 1).

2.3 Agronomic management

Prior to sowing, standard soil preparation practices were performed, including pre-irrigation, plowing, harrowing, and furrowing. Before planting, manure was applied directly to the furrow ridge at the assigned dose to each experimental unit. This organic amendment was allowed to stabilize in the soil for a period of 15 days to ensure its proper integration and minimize potential phytotoxic effects. Sowing was conducted during the first week of June 2023 using the DEKALB® B-7088 maize hybrid. The planting configuration consisted of 0.30 m spacing between ridges and 0.80 m between furrows. The total experimental area covered 1,440 m², subdivided into 48 plots of 30 m² (5 m × 6 m) each, with seven furrows per plot. Mineral fertilization was applied manually at 30 days after sowing (DAS), corresponding to the V4 vegetative stage of maize. Fertilizers were incorporated by digging a small hole in the ridge with a hand shovel, placing the fertilizer, and covering it with a thin layer of soil. Nitrogen was applied in two equal split doses: the first at 30 DAS, together with phosphorous (P) and potassium (K), and the second one month later, during the V10 stage. Diammonium phosphate, urea, and potassium chloride were used as sources of phosphorus, nitrogen, and potassium, respectively.

Nitrogen was applied of 120 kg N ha^{-1}. During the first application (30 DAS), all phosphorus was supplied using Diammonium Phosphate (DAP, 18–46–0). The amount of DAP required to deliver 120 kg P ha^{-1}, which simultaneously contributed approximately 47 kg N ha^{-1}. The remaining nitrogen needed to complete the first 120 kg N ha^{-1} dose was supplemented with Urea (46–0–0). The second nitrogen dose (60 DAS) was applied exclusively with urea to supply the remaining 120 kg N ha^{-1}. Pest and disease management during the crop cycle involved the pre-emergence application of a broadleaf herbicide, atrazine (50% suspension concentrate), and a fungicidal mixture of azoxystrobin (250 g kg^{-1}) and tebuconazole (500 g kg^{-1}). Insect management was carried out using spinosad (12% soluble concentrate) and emamectin benzoate (19 g L^{-1}) both applied as foliar sprays.

2.4 Morphological evaluations and yield

Agronomic and nutritional assessments were conducted at physiological maturity (210 DAS, R6 stage), following the methodology of Calero-Rios et al. (2025). At harvest, plant height was measured, and after ear collection, the following traits were recorded: ear length and diameter, number of rows per ear, grains per row, and the weights of ear, grains, and cob. All weights were adjusted to a standardized moisture content of 14% for the estimation of grain yield per hectare. Yield was calculated according to the protocol described by Verhulst et al. (2012).

$$\text{Yield (kg ha}^{-1}\text{)} = \frac{(100 - measured \;\; moisture(\%))}{(100 - 14)} \times plot \;\; yield \;\; (g)$$

In addition, the following formula was used to convert the plot weight (g) into kilograms per hectare.

$$\text{Yield (kg ha}^{-1}\text{)} = \frac{Weight(g) \times 10}{Area(m^2)}$$

The nutritional composition of maize was analyzed at the Physicochemical Laboratory of the Institute for Nutritional Research. Protein was determined by the Kjeldahl method, ash and fat were assessed in accordance with Peruvian Technical Standards NTP 205.004 and 205.006, respectively. Dietary fiber was quantified using the AOCS Ba-6 method. Carbohydrate content was calculated by difference, and total energy was estimated based on the Atwater conversion factors for protein, fat, and carbohydrates.

2.5 Nutrient use efficiency of N, P, K and synergy assessment

The efficiency of nitrogen (N), phosphorus (P), and potassium (K) was calculated to determine the amount of maize yield (t ha^{-1}) produced per kilogram of nutrient applied. Nutrient use efficiency (E) was computed using the following formula (Fageria et al., 2011).

$$E = \frac{Y_{Treatment} - Y_{Control}}{Nutrient\ \ applied\ \ (Kg\ \ ha^{-1})}$$

where $Y_{Treatment}$ is the yield in the fertilized treatment and $Y_{Control}$ is the yield in the unfertilized control.

To evaluate potential nutrient interactions, a synergy index was calculated using the equation of Wen et al. (2016).

$$Synergy\ \ (Kg\ \ ha^{-1}) = Y_{Observed} - Y_{Expected}$$

where $Y_{Observed}$ is the yield obtained from the combined application of nutrients, and $Y_{Expected}$ is the sum of yields from individual nutrient application.

2.6 Statistical analysis

The data satisfied the assumptions of normality and homogeneity of variance, as verified by the Shapiro–Wilk and Bartlett tests, ($p< 0.05$). Mean comparisons were conducted using Tukey's test ($p< 0.05$) implemented in the "agricolae" package (Mendiburu, 2010). Principal component analysis (PCA) was performed using the FactoMineR (Lê et al., 2008) and factoextra (Kassambara and Mundt, 2020). Additionally, the corrplot package (Wei and Simko, 2021) was used to assess the relationships among variables and generate graphical representations of the correlation matrices. Boxplots were created using the ggplot2 package. All statistical analyses were performed in RStudio (R Core Team, 2024). A split-plot experimental design was used, where Factor A: Guinea pig manure amendment (t ha^{-1}) was assigned to the main plots, and Factor B: Granulated mineral fertilizer (%) to the subplots. The main plots were arranged in a randomized complete block design with three replications. The data were analyzed using an analysis of variance (ANOVA) according to the following linear model (Montgomery, 2017):

$$Y_{ijk} = \mu + \rho_k + \alpha_i + (\rho\alpha)_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}$$

Where: Y_{ijk} is the response variable; μ is the overall mean; ρ_k is the effect of the K-th block; α_i is the effect of the i-th level of Factor A; $(\rho\alpha)_{ik}$ is the main plot error (Error a); β_j is the effect of j-th level of Factor B; $(\alpha\beta)_{ij}$ is the interaction effect A×B; and ε_{ijk} is the subplot error (Error b). The assumptions of error normality (Shapiro–Wilk test) and homogeneity of variances (Levene's test) were verified. Differences among means were compared using Tukey's test at a significance level of 0.05.

3 Results

3.1 Agronomic characteristic and yield

The highest grain yield was obtained with the combination of 5 t ha^{-1} of guinea pig manure and 75% mineral fertilization (8.82 t ha^{-1}), followed by 10 t ha^{-1} of manure plus 75% mineral fertilizer (8.37 t ha^{-1}). Overall, the combined application of organic and mineral fertilizers increased hard yellow maize yield by 27.44% compared with mineral fertilization alone (Table 1). Among the evaluated variables, only grain yield showed statistically significant differences in response to mineral fertilization, whereas the remaining variables did not differ significantly among treatments (Table 2).

The principal component analysis (PCA) (Figure 1A) shows that Factor A corresponds to the applied guinea pig manure doses (0, 2, 5, and 10 t ha^{-1}), display a clear positive association, indicating that plants with longer and wider ears tend to produce a higher number of kernels. Similarly, PG, PM, and PC cluster together, positioned closer to Dim2 but still well represented in Dim1, suggesting that these variables are positively related and collectively describe production components. Yield (R), represented by the red arrow, shows a strong correlation with PG and PM, reinforcing the role of these traits as direct predictors of productivity. The distribution of individual observations, colored according to manure dose, shows that the red ellipse (10 t ha^{-1}) clusters toward the right side of the biplot, in the same direction as the production variables (R, PM, PG). This pattern suggests a positive association between the highest manure dose and key yield-related attributes. In contrast, treatments with 0 and 2 t ha^{-1} (blue and orange) are more dispersed toward the left and center of the graph, indicating lower performance and reduced productivity. The principal component analysis (Figure 1B) illustrates Factor B, which corresponds to the levels of granulated mineral fertilization (0, 50, 75, and 100%) evaluated across the agronomic variables, indicating that these variables are positively correlated and respond similarly to fertilizer levels. The variables PM (ear weight), PG (100-kernel weight), and PC (kernel weight per ear) also group together, forming a more horizontal pattern, while yield (R)—represented by the red arrow—is strongly aligned with PG and PM, suggesting that yield is directly influenced by these weight-related components. Regarding the treatments, the points corresponding to 100% fertilizer (red) cluster towards the right of the graph, in the same direction as the yield-related variables, indicating a strong positive association between full fertilization and improved production performance. Overall, the PCA results indicate that increasing rates of granulated mineral fertilizer—particularly the full recommended dose (100%)—significantly enhance yield-related traits, confirming its central role as a key nutritional input in maize production.

The principal component analysis (Figure 2) enables the visualization of how treatments simultaneously influence multiple agronomic attributes. Meanwhile, LM (ear length), DM (ear diameter), and NGM (number of kernels per ear) also contribute to Dim1 but in a more dispersed pattern, reflecting complementary information related to ear morphology. Regarding the distribution of treatments (represented by color-coded circles and borders), treatments receiving higher doses of both manure and mineral fertilizer (e.g., E5–F100 and E10–F100) cluster toward the right side of the biplot, within the positive region of Dim1, indicating a clear association with higher yield, kernel weight, and larger ear size.

3.2 Nutritional quality of maize kernel

The highest ash content (1.40%) was obtained in the treatment without manure or mineral fertilizer. The highest protein (8.42%) and fiber (2.70%) contents were recorded with the application of 2 t ha^{-1} of manure combined with 100% mineral fertilization. Fat (4.35%) and energy (363 kcal 100 g^{-1}) contents were highest under

TABLE 1 **Agronomic composition and the yield of DEKAL B® hybrid maize combined with guinea pig manure and mineral fertilizer.**

Treats	LM (cm)	DM (cm)	HM (cm)	NGM	PM (g)	PC (g)	PG (g)	R (t ha^{-1})
E0-F0	13.00	4.53	16.73	548.37	171.31	18.51	152.80	7.33
F50	14.02	4.50	17.00	569.80	169.10	18.06	151.04	7.53
F75	14.24	4.57	16.81	564.49	164.61	18.45	146.16	8.08
F100	13.77	4.50	16.6	534.08	163.01	17.66	145.35	7.68
E2	13.81	4.42	16.93	562.33	149.10	17.13	131.97	6.40
E2-F50	14.22	4.45	16.90	553.67	157.39	16.69	140.70	7.61
E2-F75	14.06	4.55	16.40	540.92	155.12	16.60	138.52	7.98
E2-F100	13.52	4.45	16.53	536.61	161.4	16.50	144.91	8.22
F50	13.31	4.45	17.27	553.37	158.85	16.27	142.58	7.01
E5-F50	14.04	4.39	16.47	549.96	162.67	17.64	145.03	7.86
E5-F75	13.97	4.55	17.01	567.18	166.24	16.99	149.25	8.82
E5-F100	14.00	4.54	16.20	528.12	168.24	17.66	150.58	8.11
E10	13.83	4.38	16.93	555.20	156.86	15.86	140.99	7.55
E10-F50	13.72	4.45	16.70	541.58	162.23	16.59	145.64	7.63
E10-F75	14.05	4.46	16.20	539.71	167.34	17.44	149.91	8.37
E10-F100	14.37	4.58	16.53	547.41	164.15	17.44	146.71	6.98

LM, Ear length; DM, Ear Diameter; HM, Ear row; NGM, Number of grains per ear; PM, Ear weight; PC, Cob weight; PG, Grain weight; R, Yield.
E0-F0, Control; F50, 50%, mineral fertilizer; F75, 75%, mineral fertilizer; F100, 100%, mineral fertilizer; E2, 2 t ha^{-1} manure guinea pig; E2-F50, 2 t ha^{-1} manure guinea pig + 50%, mineral fertilizer, E2-F50, 2 t ha^{-1} manure guinea pig + 50%, granulated mineral; E2-F75, 2 t ha^{-1} manure guinea pig + 75%, mineral fertilizer; E2-F100, 2 t ha^{-1} manure guinea pig + 100, mineral fertilizer; F50 ,50%, mineral fertilizer; E5-F50, 5 t ha^{-1}, manure guinea pig + 50%, mineral fertilizer; E5-F75, 5 t ha^{-1}, manure guinea pig + 75%, mineral fertilizer; E5-F100, 5 t ha^{-1}, manure guinea pig + 100%, mineral fertilizer; F100 ,100%, mineral fertilizer; E10-F50, 10 t ha^{-1}, manure guinea pig + 50%, mineral fertilizer; E10-F75, 10 t ha^{-1}, manure guinea pig + 75%, mineral fertilizer; E10-F100, 10 t ha^{-1}, manure guinea pig + 100%, mineral fertilizer.

the 5-t ha^{-1} manure + 100% mineral fertilizer treatment. The treatment with 2 t ha^{-1} of manure and 100% mineral fertilizer showed the highest values of protein-derived and fat-derived energy (E_prot and E_fat), with averages of 33.67% and 39 kcal 100 g^{-1}, respectively. Conversely, the highest carbohydrate content (74.13%) and carbohydrate-derived energy (297.67 kcal 100 g^{-1}) were obtained with 2 t ha^{-1} of manure (Table 3). No significant differences were observed for ash, fat, fiber, energy, E_fat, or E_CHO. However, granulated mineral fertilizer showed significant effects on protein (Prot), carbohydrate (CHO), and protein-derived energy (E_prot) (Table 4).

The principal component analysis (Figure 3A) illustrates the distribution of grain nutritional traits under the different guinea pig manure doses applied to the crop. Energy, fat, and protein—together with their corresponding derived indices (E_fat and E_prot)—are strongly correlated with one another and cluster in the right quadrant of the biplot, particularly in the direction of the 10-t ha^{-1} manure treatment (red). This pattern indicates that higher manure doses are associated with increased concentrations of these nutritional components. In contrast, carbohydrates (CHO) are positioned on the opposite side of the biplot, toward the left quadrant, suggesting that higher carbohydrate levels occur in treatments without manure or with

TABLE 2 **Two-way F and probability (P) values examining the effects of combining guinea pig manure and granular mineral fertilizer on the agronomic composition of maize.**

Variable	Guinea pig manure (t ha^{-1})		Granular mineral fertilizer (%)		Guinea pig manure x mineral fertilizer	
	F	*p*	F	*p*	F	*p*
LM	0.190	0.901	1.330	0.282	0.490	0.869
DM	0.600	0.621	1.690	0.189	0.530	0.842
HM	0.280	0.838	1.900	0.149	0.850	0.575
NGM	0.130	0.939	0.860	0.473	0.390	0.932
PM	2.500	0.077	0.580	0.634	0.520	0.847
PC	1.610	0.207	0.130	0.939	0.340	0.955
PG	2.580	0.071	0.630	0.602	0.620	0.774
R	1.17	0.335	4.760	0.007*	0.21	0.941

LM, Ear length; DM, Ear Diameter; HM, Ear row; NGM, Number of grains per ear; PM, Ear weight; PC, Cob weight; PG, Grain weight; R, Yield. Significance levels: *$p < 0.05$.

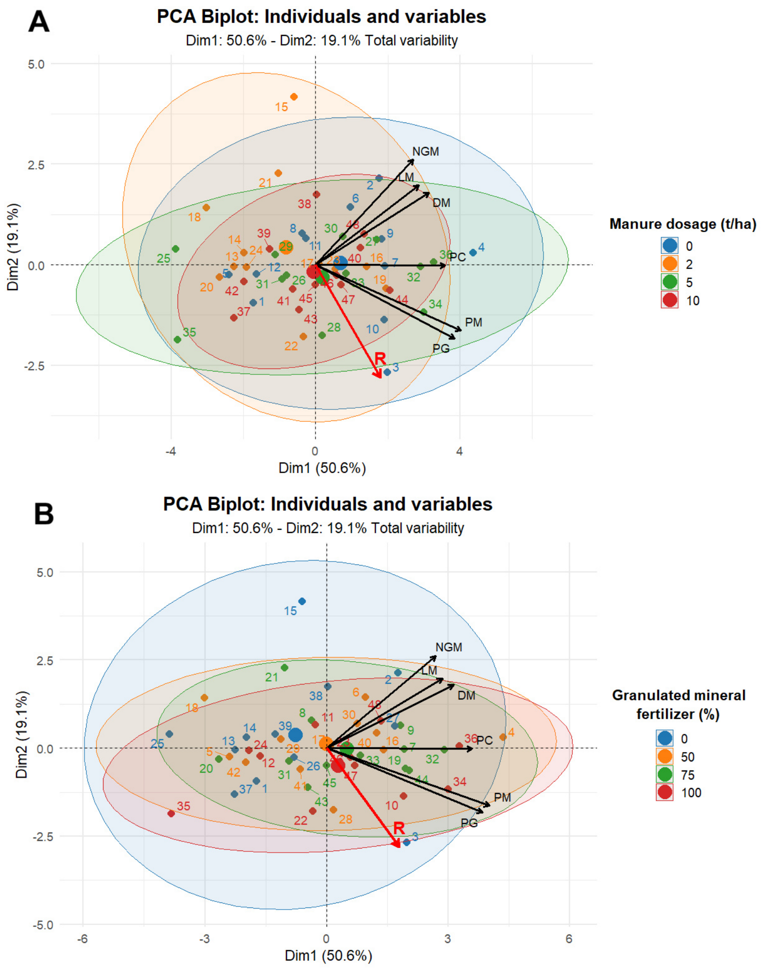

FIGURE 1
Principal component analysis between agronomic variables and yield. **(A)** Mediated by the different dose levels of guinea pig manure and **(B)** Granulated mineral fertilizer in maize (*Zea mays* L.) LM, Ear length; DM, Ear Diameter; HM, Ear row; NGM, Number of grains per ear; PM, Ear weight; PC, Cob weight; PG, Grain weight; R, Yield.

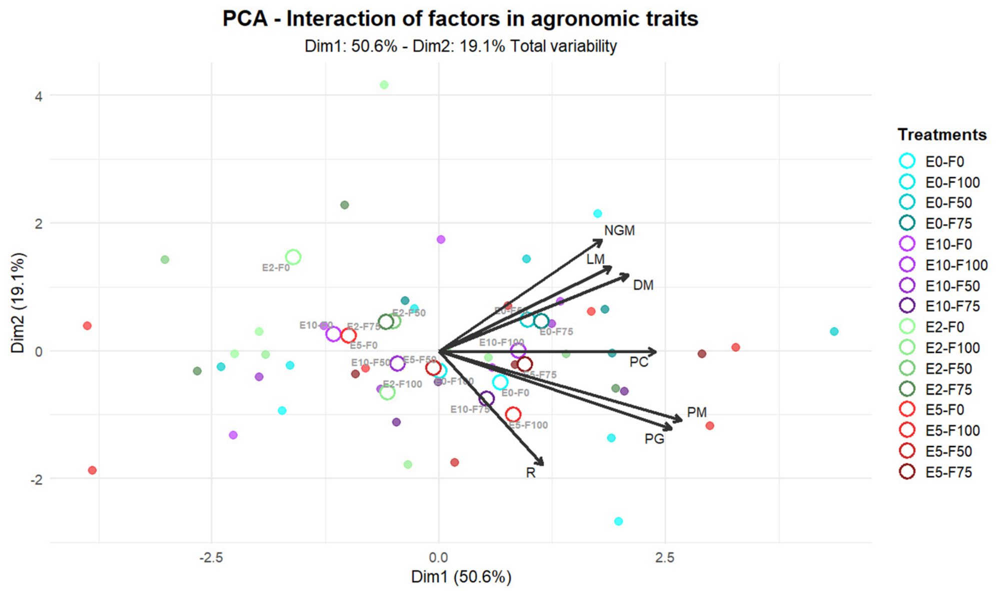

FIGURE 2
Interaction between mineral fertilization and the dose of guinea pig manure on corn yield.

TABLE 3 **Nutritional composition of the maize combined with guinea pig manure and mineral fertilizer.**

Treats	Ash	Fat	Prot	Fiber	CHOs	Energy	E_prot	E_fat	E_cho
	g. 100 g^{-1}. N					Kcal. 100 g^{-1}			
E0-F0	1.4	4.07	7.27	2.61	73.59	360	29	36.67	294.33
F50	1.28	3.97	7.08	2.63	73.93	360	28.33	35.67	296
F75	1.31	4.27	7.15	2.46	73.4	361	28.67	38.67	293.67
F100	1.23	4.17	8.07	2.51	72.91	361.67	32.33	37.67	291.67
E2	1.33	4.32	6.63	2.58	74.13	361.67	26.33	38.67	297.67
E2-F50	1.37	4.11	7.36	2.6	73.5	360.67	29.33	37	294.33
E2-F75	1.27	3.99	7.56	2.6	73.48	360	30	36	294
E2-F100	1.17	4.31	8.42	2.7	72.38	362.33	33.67	39	289.67
F50	1.31	4.05	6.62	2.65	74.1	359.67	26.67	36.33	296.67
E5-F50	1.3	4.16	7.1	2.62	73.7	360.33	28.33	37.33	294.67
E5-F75	1.3	4.23	7.46	2.73	73.08	360	30	38	292
E5-F100	1.25	4.35	7.85	2.51	73.01	363	31.67	39	292.33
E10	1.37	4.16	7.19	2.67	73.51	360.67	29	37.67	294
E10-F50	1.36	4.09	7.17	2.72	73.75	360 ± 2	28.33	36.67	295
E10-F75	1.19	4.07	8	2.48	73.44	362	31.67	36.67	203.67
E10-F100	1.34	4.3	8.27	2.67	72.31	360.67	33	38.67	289

Ash, Grain ash; Fat, Grain fat; Prot, Grain prot; Fiber, Grain fiber; CHOs, Grain carbohydrates; Energy, Grain energy.

low application rates (blue and orange). The principal component analysis (Figure 3B) indicates that the variables Fat, E_fat, Energy, Prot, and E_prot are clustered in the right quadrant of the biplot, showing a high contribution to the explained variance and a positive correlation between them. In contrast, carbohydrates (CHO) are positioned on the opposite side, revealing an inverse relationship with these nutrient-dense variables. Observing the clustering ellipses, it can be seen that the treatments with 100% mineral fertilizer (red ellipse) are mainly located in the area associated with a higher concentration of protein, fat, and energy, indicating a positive effect of this dose on the nutritional quality of the grain. Conversely, unfertilized treatments (blue ellipse) are clustered closer to the carbohydrate vector, suggesting that the absence of fertilizer favors its accumulation, but to the detriment of other nutrients. Intermediate doses (50 and 75%) occupy intermediate positions, in the PCA, indicating a progressive transition in nutritional composition as fertilization increases.

The principal component analysis (Figure 4) reveals a clear relationship between treatments and nutritional characteristics. For example, the Fat and E_fat vectors are oriented toward the upper right quadrant, indicating that samples located in this region are positively associated with higher fat and lipid-derived energy content. This pattern is observed primarily in some treatments with intermediate to high fertilizer rates, such as “5-100” and “10-100,” suggesting a synergistic crop response to the combined nutrient input. Similarly, the variable Prot and its corresponding energy variable E_prot are oriented towards the lower right quadrant, implying that treatments located in

TABLE 4 **Two-way F and probability (*p*) values examining the effects of combining guinea pig manure and granular mineral fertilizer on the nutritional composition of maize.**

Variable	Guinea pig manure (t ha^{-1})		Granular mineral fertilizer (%)		Guinea pig manure x mineral fertilizer	
	F	*p*	F	*p*	F	*p*
Ash	0.190	0.901	2.520	0.076	0.900	0.533
Fat	0.130	0.940	0.770	0.517	0.350	0.951
Prot	1.530	0.226	15.300	<0.001	0.950	0.499
Fiber	0.830	0.486	0.670	0.577	1.260	0.295
CHOs	0.220	0.879	6.340	0.002	0.480	0.880
Energy	0.110	0.952	1.280	0.299	0.510	0.857
E_prot	1.060	0.381	15.790	<0.001**	0.950	0.499
E_fat	0.070	0.973	0.830	0.486	0.360	0.948
E_cho	1.050	0.382	1.040	0.387	0.930	0.514

Ash, Grain ash; Fat, Grain fat; Prot, Grain prot; Fiber, Grain fiber; CHOs, Grain carbohydrates; Energy, Grain energy. Significance levels: **$p < 0.01$.

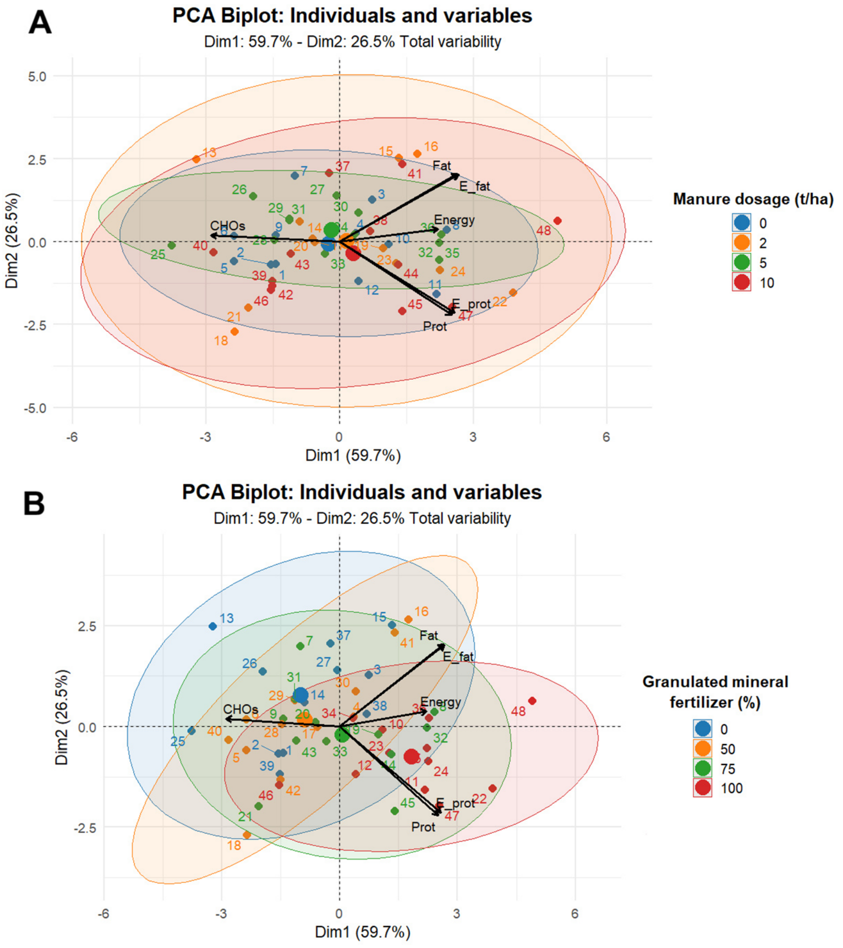

FIGURE 3
Principal Component Analysis between Nutritional quality of maize kernel. **(A)** Mediated by the different dose levels of guinea pig manure and **(B)** Granulated mineral fertilizer in maize (*Zea mays* L.) Fat, Grain fat; Prot, Grain prot; CHOs, Grain carbohydrates; Energy, Grain energy.

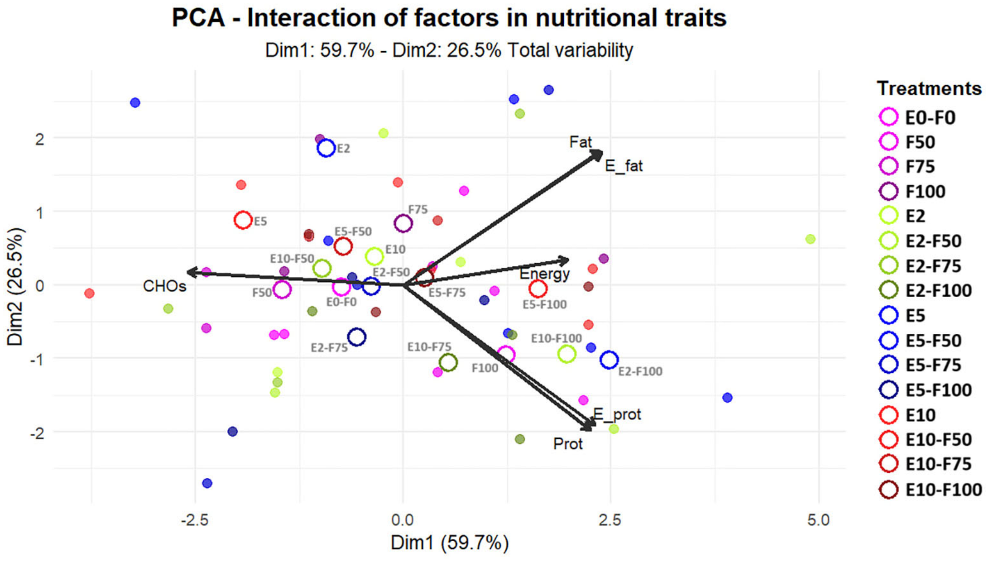

FIGURE 4
Interaction between mineral fertilization and guinea pig manure dose on Nutritional quality of maize kernel.

this area are characterized by higher protein levels. This behavior could be related to nitrogen availability, since plant protein is closely linked to nitrogen metabolism, and treatments with higher fertilizer input could be favoring this synthesis. On the other hand, the vectors assigned to CHOs are projected to the left quadrant of the graph, reflecting an inverse relationship with the other variables, particularly lipids and proteins. Treatments located in this region, such as “2-0” or “0-0,” likely represent a lower nutrient availability. It is important to note the partial separation of treatments along the principal axes, indicating structural differences in grain nutrient composition under the various fertilization combinations. This discrimination, although not completely categorical, reflects the sensitivity of PCA to identify general trends in the data and suggests that certain treatments could offer specific advantages depending on the nutritional parameter of interest, such as protein or energy content.

3.3 Nutrient use efficiency and synergistic effects

3.3.1 N, P, and K use efficiency

Nutrient use efficiency (NUE) for N, P, and K exhibited consistent and comparable agronomic responses across treatments, as shown by the quadratic regression curves in Figures 5A–C. Although these nutrients were analyzed individually, their response patterns were remarkably similar, which is explained by the strong correlations (r = 0.95–0.98) among the total amounts of nitrogen, phosphorus, and potassium applied. This high degree of association reflects the factorial structure of the guinea pig manure–mineral fertilizer combinations, where increasing the dose of either input source proportionally increased the supply of all three nutrients, resulting in a coupled crop response. Nutrient use efficiency decreased as total nutrient input increased, as indicated by the progressively flatter slopes of the curves, reflecting a diminishing marginal yield per additional unit of nutrient applied. These findings indicate that NUE is maximized at intermediate application rates and that strategically balanced source combinations can achieve high yields while reducing input requirements per ton of grain. The polynomial regression models provided a realistic approximation of the nonlinear soil–plant dynamics observed under experimental conditions, enabling the identification of agronomic thresholds beyond which the marginal benefit of nutrient addition declines. Consequently, these models not only quantify the technical efficiency of the system but also support the development of rational fertilization strategies aimed at optimizing resource use efficiency.

The nutrient use efficiency (NUE) can be determined from a quadratic curve such as the one presented in the manuscript (Figures 5A–C) by analyzing the shape and parameters of the regression equation.

Where:

$$y = \text{yield (t ha}^{-1}\text{)};\ x = \text{nutrient (N, P and K) applied (kg ha}^{-1}\text{)}$$

Instant agronomic efficiency (IAE) is obtained by deriving the equation with respect to x (*dy/dx*). This indicates how many kilograms of maize yield are gained for each additional kilogram of N, P, or K applied.

For 240 kg N ha^{-1} applied in the experiment, we have:

$$\text{N applied (kg ha}^{-1}\text{)} = 240;\ \text{IAE (kg grain/kg N)} = 4.1$$

For 120 kg of P ha^{-1}, applied in the experiment, we have:

$$\text{P applied (kg ha}^{-1}\text{)} = 120;\ \text{IAE (kg grain/kg P)} = 9.2$$

For 140 kg of K, applied in this experiment, we have:

$$\text{P applied (kg ha}^{-1}\text{)} = 140;\ \text{IAE (kg graino/kg P)} = 6.2$$

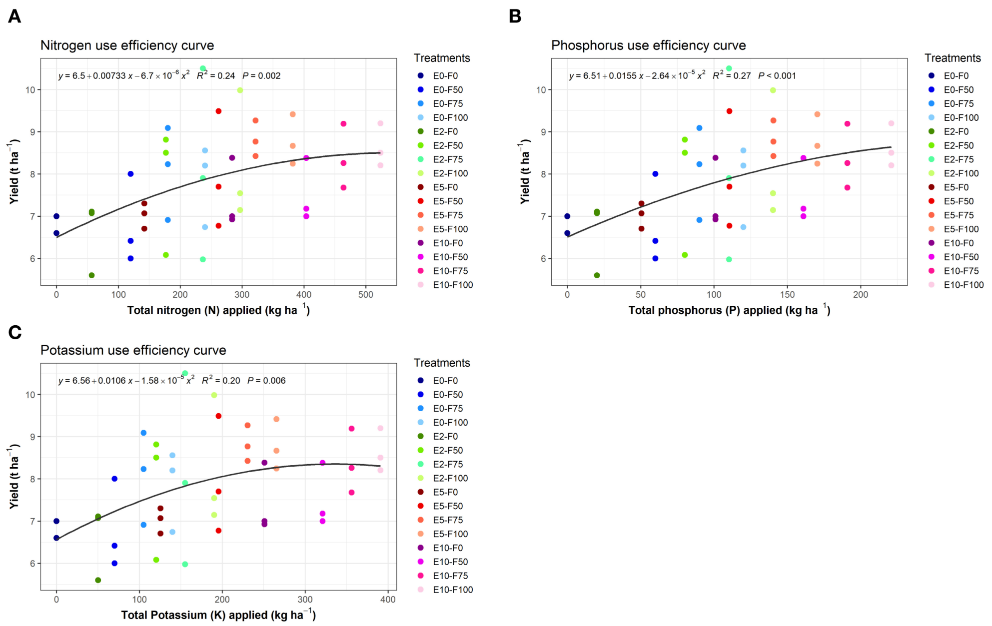

FIGURE 5
Nutrient use efficiency curves for **(A)** nitrogen, **(B)** phosphorus, and **(C)** potassium across the treatments evaluated.

The integrated quadratic curve reflects the overall response pattern to N, P, and K application across all treatments.

Nitrogen use efficiency (expressed as kilograms of grain produced per kilogram of N applied) was the highest under the F50 and F75 fertilization levels. Excessive N application (F100) did not markedly increase yield and may reduce efficiency while heightening environmental risks. Therefore, F75 appears to offer the best compromise between maize productivity and nitrogen use efficiency. A similar pattern was observed for phosphorus: the F75 treatment provided an optimal balance between mineral P inputs and maize yield, indicating that at least a moderate P dose is required to unlock the crop's productive potential. In this context, it is essential to evaluate not only absolute yield but also the kilograms of grain produced per kilogram of P applied. Moderate mineral fertilization rates (F50–F75) also showed the highest efficiency when integrated with organic amendments. In contrast, excessive mineral inputs (F100), whether N, P, or K, did not result in further yield gains, suggesting diminishing returns and lower nutrient use efficiency. Thus, a balanced management strategy that incorporates potassium and mineral fertilizers at moderate levels is recommended to maximize yield while ensuring efficient nutrient use.

Spatial mapping of agronomic synergy (Figure 6) further identified optimal regions within the treatment matrix. The greatest positive synergy clustered in intermediate combinations—particularly E2–F75, E5–F50, and E10–F50—where integrated nutrient sources appeared to trigger complementary edaphic and physiological processes, including improved soil structure, greater moisture retention, stimulation of beneficial microbes, and synchronized nutrient supply. In contrast, extreme treatments, such as E0–F0 (no inputs) and E10–F100 (maximum inputs), produced near-zero or negative synergy, underscoring that both nutrient deficiency and excessive supply restrict the crop's yield response. The partial symmetry observed in the synergy surface suggests that, despite the collinearity among N, P, and K inputs inherent to the factorial design, specific source ratios generate nonlinear, emergent responses that cannot be predicted from single-factor effects. This spatial visualization serves as a practical decision-support tool for designing sustainable and balanced fertilization strategies that maximize agronomic returns while preventing unnecessary resource use.

4 Discussion

4.1 Agronomic characteristic and yield

The ear length of hybrid yellow maize obtained in this study, grown in sandy loam soil (pH 8.3) under a mean temperature of 19.89 °C, was shorter than values reported by Hossain et al. (2024) for hybrid maize grown under comparable edaphoclimatic conditions (27.55 °C, sandy loam soil, pH 7.27), where the application of organic amendments resulted in an average ear lengths of 20.8 cm. Similarly, Thapa et al. (2024) reported ear lengths of 20.57 cm and 17.62 cm in sweet corn cultivated under similar conditions (20.25 °C, sandy loam soil, pH 6.89) with manure applications of 448 kg N ha^{-1} and 224 kg N ha^{-1}, respectively. In contrast, Kandil et al. (2020) observed an average ear length of 16.7 cm in the yellow maize hybrid 'Pioneer SC 30N11' under conditions similar to those of the present study similar (24 °C, sandy loam soil, pH 7.99) following the application of 5 t ha^{-1} of compost. The cob diameter obtained in this study is consistent with the findings of Budiastuti et al. (2023), who reported an average of 4.74 cm when applying a maize cob amendment at a rate of 12.5 t ha^{-1}. Similarly, Calero-Rios et al. (2025) recorded an average diameter of 4.11 cm with the application of 10 t ha^{-1} of guinea pig manure combined with 50% of the recommended granulated mineral fertilizer rate in maize (INIA 619 hybrid). The number of grain rows per cob observed in this study agrees with Gao et al. (2020), who reported that fertilizer application increased the average number of grain rows. Likewise, Calero-Rios et al. (2025) reported an average of 13.71 grain rows per cob with 5 t ha^{-1} of guinea pig manure in maize (INIA 619 hybrid), while Shah et al. (2016) documented 18.13 row per cob in the Dk-6724 hybrid with organic amendments.

The greatest values for ear length, cob diameter, and grain rows per cob were obtained with the application of the organic amendment guinea pig manure (GPM). The high organic matter

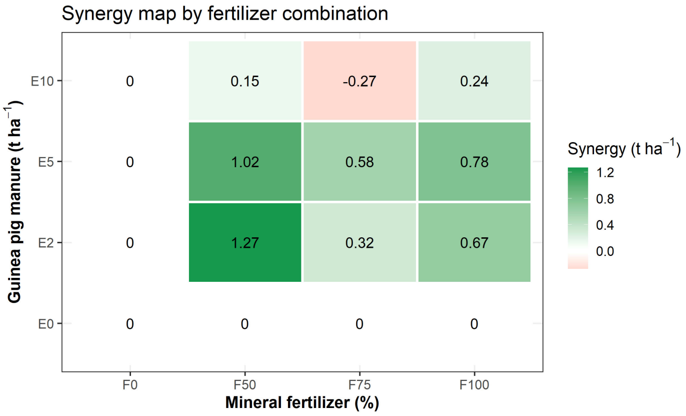

FIGURE 6
Heatmap of synergistic responses for the comparison of fertilization sources (mineral fertilizer vs. guinea-pig manure).

content of GPM likely contributed to these results by enhancing phosphate solubility, and thereby increasing soil phosphate availability for plant uptake (Qiu et al., 2022). Their use has been shown to increase soil fertility and achieve higher yields (Abdelhameed and Metwally, 2019; Xu et al., 2024). Espejo et al. (2021) reported that GPM increased soil nitrogen, phosphorus, and potassium contents by more than 100% related to untreated soils. Likewise, Murray-Núñez et al. (2023) documented an organic matter content of 68.4%, total nitrogen of 3.42%, and a pH of 6.93 in GPM—values comparable to those obtained in the present study.

In 2023, the application of 10 t ha^{-1} of compost combined with vermiculite resulted in a maximum plant height of 189.1 cm and a cob length of 21.6 cm while the highest hybrid maize grain yield-, approximately 10 t ha^{-1}- was achieved with 15 t ha^{-1} of NPK plus compost. This exceeded the yield of the compost-only control (< 8 t ha^{-1}). These results were obtained in sandy loam soil (pH 7.0) at 247 m a.s.l., with a mean temperature of 19.89 °C and a relative humidity of 79.43% (Hossain et al., 2024). Collectively, these findings demonstrate that integrating organic compost with mineral fertilizers is an effective strategy for sustainable agricultural production systems in various regions (Etesami et al., 2023. Compost organic matter enhances essential biological and physicochemical soil properties, which likely explain the substantial improvements in maize growth parameters when high compost rates are applied or when compost is combined with chemical fertilizers rather than using mineral fertilizers alone (Nigussie et al., 2021). Furthermore, the higher number of kernels observed with the application of 50% granulated mineral fertilizer supports the conclusion that mineral fertilizers remain essential for achieving maximum maize yields (Aguilar et al., 2016).

Essilfie et al. (2024) also reported that while sole NPK and integrated NPK–chicken manure applications produced comparable vegetative responses, integrated fertilization resulted in significantly higher grain yields across two agroecologies. Similarly, Hossain et al. (2024) demonstrated that both organic and mineral fertilizers improve maize growth and yield compared with the control. In the present study, however, some variables—such as yield and protein content—did not exhibit significant differences among treatments. This observation aligns with Jjagwe et al. (2020), who reported no statistically significant differences in maize yield across fertilization regimes. In another study, compost application enhanced vegetative growth and yield (Imran et al., 2021), reinforcing that treatment effects may vary depending on soil conditions, compost composition, and hybrid characteristic.

Although the highest yellow maize yield (8.82 t ha^{-1}) was obtained under the E5-F75 treatment (5 t ha^{-1} of manure guinea pig + 75% mineral fertilizer), no significant differences were observed in agronomic traits or grain yield among treatments. This lack of significance may be attributed to certain limitations, including the relatively low number of replicates. This may have reduced the statistical power to detect true differences between treatments. In addition, the evaluation was conducted during a single cropping season and at a single site; therefore, the results may not be extrapolated to other edaphoclimatic conditions or agricultural cycles, limiting their long-term applicability. Furthermore, only specific combinations of organic and mineral fertilization were assessed, and thus it cannot be ensured that these doses represent the optimal fertilization strategy for maximizing yellow maize yield.

4.2 Nutritional quality of maize kernel

Regarding the nutritional quality of DEKALB® hybrid maize kernels, Yankah et al. (2020) reported an ash content of 0.79%, while Qamar et al. (2016) documented values ranging from 0.81% to 1.35% for the same hybrid. Similarly, Langyan et al. (2022) recorded a range of 0.73–1.93%, with a mean of 1.33%, which is comparable to the values obtained in this study. Carbohydrate contents reported in the literature also closely match our findings, with Kumar et al. (2016) reporting 74.3%, Saleh et al. (2013) reporting 73.0%, and Yankah et al. (2020) reporting 73.94%. These results reaffirm that locally produced maize remains a rich source of carbohydrates. Protein content values reported by Kumar et al. (2016) (9.4%) and Yankah et al. (2020) (8.90%) are likewise consistent with those observed in the present study. Variability in fat composition across studies may be attributed to differences in storage conditions, post-harvest handling, and processing methods (Ahmed et al., 2014).

Hwang et al. (2016) and Nankar et al. (2020) reported fat contents in brown rice ranging from 1.70% to 5.77%. In the current research, the fat content of maize was 3.28%, compared with 4.70% reported by Kumar et al. (2016), whereas Yankah et al. (2020) also documented 3.28% in maize nutritional composition. Fiber content in rice, according to Enyi et al. (2025), ranged from 0.7 to 5.5%. Calero-Rios et al. (2025) reported fiber values of 2.50–2.56% under conditions involving 75 and 0% of the recommended granular mineral fertilizer dose. Regarding energy value, the same authors obtained 357.17–360.83 kcal 100 g^{-1} for maize cultivated under these fertilization schemes, whereas Verma and Srivastav (2017) reported an average of 365.23 kcal 100 g^{-1}. The significant effects of guinea pig manure (GPM)-based amendments on certain nutritional variables may be attributed to the ability of organic fertilizers to enhance maize yield and through improvements in soil physicochemical properties and nutrient uptake, even under drought stress conditions (Shah et al., 2016). In this study, GPM contained 52.56% organic matter, 2.84% nitrogen, 2.51% potassium, and 1.01% phosphorus pentoxide, with a pH of 7.1; parameters that likely contributed to the observed improvements in both the nutritional quality of DEKALB® maize grain and the associated soil properties.

Maize yield reached 8.82 t ha^{-1} with the application of 5 t ha^{-1} of GPM combined with 75% mineral fertilizer, followed by 8.37 t ha^{-1} with 10 t ha^{-1} of GPM plus 75% mineral fertilizer. The lowest yield, 6.40 t ha^{-1}, was obtained with the application of 2 t ha^{-1} of GPM alone. These findings confirm that combining mineral fertilization with GPM at rates of 5–10 t ha^{-1} and 75% of the mineral fertilizer recommendation significantly increases the yield of DEKALB® hard yellow maize (Calero-Rios et al., 2025).

Furthermore, reducing mineral fertilizer inputs by through the application by 25% through the application of 5 t ha^{-1} of organic fertilizer maintains high productivity, highlighting the importance of balanced nutrient management in maximizing yield in DEKALB® hard yellow maize. Excessive use of mineral fertilizers in maize production, aimed at ensuring high yields, can lead to elevated production costs, soil fertility depletion, and environmental pollution, thereby constraining sustainable agricultural development. Such practices also promote nitrogen losses to the environment with undesirable ecological consequences (Devi et al., 2025; Lv et al., 2020). Therefore, scientifically grounded fertilization strategies must simultaneously consider crop productivity and agro-environmental sustainability (He et al., 2022). The 27.44% yield increase achieved through the combined application of organic and mineral fertilizers aligns with the results of Yang et al. (2021), who reported enhance maize yield and quality when sheep manure was integrated with mineral fertilization.

The nutritional composition of yellow maize exhibited distinct variations among treatments. Specifically, the E2 treatment showed the highest carbohydrate content, E2–F100 presented the highest protein content, and E5–F100 resulted in the highest grain energy content. These variations can be attributed to several limitations, including the assessment being conducted during a single cropping cycle and/or at a single site. The response of the maize hybrid in terms of carbohydrate, protein, and energy accumulation may vary substantially under different environmental conditions, thereby limiting the generalizability of the results. Moreover, the internal redistribution of carbon and nitrogen during grain development makes it difficult to attribute nutritional changes to a single fertilization factor. Additionally, another limitation to be addressed in future studies is the evaluation of the effects of azoxystrobin and tebuconazole on the microbiota of guinea pig manure and on the microbial communities naturally present within this organic input.

4.3 Nutrient use efficiency and synergistic effects

The nitrogen (N) application responses observed are consistent with previous research, which has shown that higher N rates increased maize grain yield (Dew et al., 2024; Sharma et al., 2024), with comparable responses also reported for phosphorus (P) and potassium (K) (Drescher et al., 2021). However, nitrogen use efficiency is typically maximized at intermedium application rates. Consequently, exceeding 176.8 kg N ha^{-1} would not represent an economically viable option for maize producers. This finding aligns with Gajula et al. (2025), who reported that applying more than 180 kg N ha^{-1} is not economically feasible and may exacerbate financial constraints for farmers. Partial substitution of mineral fertilizers with organic sources-provided that both inputs are applied in adequate and balanced proportions-represents a promising strategy to sustain high productivity while improving production stability (Selim, 2020). These results indicate that the strongest synergistic responses occurred at intermediate application rates. Particularly when organic and mineral fertilizers were combined, yields were greater than expected from their individual effects. This synergy not only enhances maize yield but also contributes to maintaining long-term soil fertility (Wang, F. et al., 2025).

Guinea pig manure combined with N, P, and K application showed an efficient association in terms of nutrient use by yellow hard maize; however, no significant differences were observed among treatments. It is well established that organic manure improves soil structure, microbial activity, and nutrient availability. Moreover, microbial consortia such as arbuscular mycorrhizal fungi (AMF), together with compost application, have been shown to exert positive effects on plant morphological development (Vallejos-Torres et al., 2019). Therefore, within a single cropping cycle, the magnitude of these effects may be limited. In addition, the lack of foliar analysis or nutrient monitoring in the soil throughout the crop cycle restricts a more comprehensive understanding of how and when maize assimilated nutrients. Future studies are recommended to evaluate the effects of microbial activity and environmental conditions on guinea pig manure production.

Under the treatment without the incorporation of guinea pig manure or mineral fertilizer (E0–F0), the benefit–cost ratio reached 1.022, indicating a marginal gain of S/. 0.022 for every sol invested. In contrast, the application of the E5–F75 treatment increased the benefit–cost ratio to 1.276, corresponding to a return of S/. 0.276 per sol invested in maize production, thereby demonstrating a clear net economic benefit. These results indicate a favorable economic performance of 27.61% (Supplementary Table 2).

5 Conclusions

The combined application of guinea pig manure and mineral fertilizers markedly enhanced both the agronomic performance and nutritional quality of DEKALB® yellow maize. In particular, treatments with 5 t ha^{-1} of guinea pig manure plus 100% of the recommended mineral fertilizer dose (E5-F100), and 10 t ha^{-1} of manure with 100% mineral fertilization (E10-F100), achieved the highest yields, along with increased grain weight and larger ear size. These results demonstrate a clear synergistic interaction between organic and mineral fertilization, leading to improvements in agronomic traits directly linked to productivity. Furthermore, grain nutritional quality - specifically protein, fat, and energy content - improved significantly with increasing manure doses, whereas carbohydrate levels decreased, indicating a favorable shift in the nutritional density of yellow maize. These findings support the use of guinea pig manure as a sustainable, cost-effective, and environmentally friendly input that complements rather than replaces, mineral fertilization in maize production.

Future research should explore the long-term impacts on soil fertility, with an emphasis on microbial communities. Additionally, trials under different planting dates and across diverse edaphoclimatic regions of Peru are recommended to assess the reproducibility and scalability of these results. This contributes to the development of context-specific technical recommendations that foster sustainable agriculture and strengthen national food security.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EC-R: Investigation, Visualization, Conceptualization, Data curation, Formal analysis, Methodology, Resources, Validation, Writing – review & editing. JC: Investigation, Methodology, Resources, Funding acquisition, Project administration, Writing – original draft. RS: Funding acquisition, Methodology, Writing – original draft, Conceptualization, Formal analysis. NG-J: Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. GV-T: Visualization, Investigation, Project administration, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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