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Guinea Pig Manure and Mineral Fertilizers Enhance the Yield and Nutritional Quality of Hard Yellow Maize on the Peruvian Coast

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Abstract: Sustainable fertilization using local resources such as manure is crucial for soil health. This study evaluated the potential of guinea pig manure to replace mineral fertilizers in hard yellow maize (hybrid INIA 619) under Peruvian coastal conditions. A split-plot design tested four doses of guinea pig manure (0, 2, 5, 10 t·ha^{-1}) and four levels of mineral fertilization (0%, 50%, 75%, 100%). The study assessed plant height, ear characteristics, yield, and nutritional quality parameters. The results indicated that 100% mineral fertilization led to the highest plant height (229.67 cm) and grain weight (141.8 g). Yields of 9.19 and 9.08 t·ha^{-1} were achieved with 5 and 10 t·ha^{-1} of manure, while 50% mineral fertilization gave 8.8 t·ha^{-1}, similar to the full dose (8.7 t·ha^{-1}). The protein content was highest with 10 t·ha^{-1} of manure combined with mineral fertilization. However, no significant differences were found between the 50%, 75%, and 100% mineral fertilizer doses. In conclusion, applying guinea pig manure improved nutrient use efficiency, yield, and grain protein quality in maize, reducing the need for mineral fertilizers by up to 50%. This provides a sustainable fertilization strategy for agricultural systems.

Keywords: *Cavia porcellus*; inorganic fertilizer; flint corn; proximate analysis; corn grain protein

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1. Introduction

Fertilizers, both organic and mineral, are essential in modern agriculture, as they enhance crop productivity and contribute to food security. Among mineral fertilizers, nitrogen, phosphorus, and potassium are the most commonly applied to meet crops' nutritional requirements [1]. However, excessive and prolonged use of these inputs has been linked to soil degradation, affecting its physical, chemical, and biological properties [2]. Intensive agronomic practices that depend heavily on mineral fertilizers can exacerbate this degradation, compromising soil health and long-term agricultural sustainability [3]. Physically, the continuous application of chemical fertilizers may increase the soil's bulk density, which reduces porosity and impedes water infiltration, leading to surface runoff and erosion [4]. Chemically, such practices can alter soil pH and decrease cation exchange capacity (CEC), diminishing the soil's ability to retain and supply essential nutrients to plants [5]. Biologically, excessive use of mineral fertilizers can disrupt microbial communities, reducing microbial diversity and activity, which are crucial for organic matter decomposition and nutrient cycling [6]. Despite these drawbacks, many farmers continue to rely on chemical fertilizers for crop management due to their rapid effectiveness and ease of application [7].

To mitigate these adverse effects, sustainable fertilization practices have gained attention [8]. One such approach is the application of organic amendments, such as animal manure, which not only supply nutrients, but also improve soil structure, water-holding capacity, and microbial activity [9]. These amendments promote long-term soil fertility and contribute to environmental sustainability by recycling agricultural waste [10]. Among the various organic amendments, guinea pig manure has shown potential as an effective soil input, with multiple studies supporting its integration into agricultural systems [11–13]. It enhances soil water retention capacity and aggregate formation, facilitating root development and promoting healthy crop growth, which ultimately improves yields [14,15]. Additionally, guinea pig manure supplies essential nutrients such as phosphorus, potassium, and nitrogen, contributing to soil fertility [16]. Its nitrogen and micronutrient content further enhance crop nutritional quality [17,18].

However, the exclusive use of organic amendments may not suffice to meet the full nutrient requirements of nutrient-demanding crops such as hard yellow maize (*Zea mays* L.) [19,20]. Therefore, integrated nutrient management—combining organic manure with mineral fertilizers—has emerged as a promising strategy. This approach enhances nutrient use efficiency, improves soil health, and sustains high crop yields and quality [21,22].

Hard yellow maize is one of the most important annual crops globally, noted for its high productivity per unit area compared to other cereals [23]. In Peru, it is cultivated by over 201,000 farmers across 272,709 hectares, representing 14% of the country's agricultural area, with a total production of 1,330,989 $t \cdot ha^{-1}$ [24,25]. The crop is essential to the agrarian economy, serving as a staple for human consumption and animal feed [26]. Its high energy content and nutritional value make it ideal for formulating balanced diets for pigs, poultry, and other livestock [27], with protein, fat, and fiber contents influencing its value as animal feed [28,29]. These nutritional attributes are affected by both genetic and environmental factors [30].

Thus, this study aims to evaluate the influence of varying doses of guinea pig manure in combination with different mineral fertilization levels on the grain yield and nutritional quality of the hard yellow maize variety INIA 619 on the Peruvian coast.

2. Materials and Methods

2.1. Trial Location

The research was conducted at Universidad Nacional Agraria La Molina, in the district of La Molina, Lima Province, Department of Lima, Peru. The experimental plot is located at 76°56′21″ W and 12°04′55″ S, with an altitude of 247 m.a.s.l. The average temperature during the study period was 19.89 °C, with a relative humidity of 79.43% and no recorded rainfall (0.8 $mm \cdot h^{-1}$). The Alexander Von Humboldt Meteorological Station provided the meteorological data (Figure 1).

2.2. Soil Characteristics

A soil characterization analysis was performed at the Soil, Water, and Foliar Laboratory (LABSAF) of the National Institute for Agrarian Innovation. Soil texture was determined using the Bouyoucos method (AS-09) [31], resulting in 56% sand, 19.3% silt, and 24.7% clay, classifying the soil as sandy loam. The pH was measured according to EPA Method 9045 [32], with a value of 8.3, while electrical conductivity was 37.4 $mS \cdot m^{-1}$, determined using the saturation extract method (AS-18) [31]. The cation exchange capacity (CEC) was 12.8 $meq \cdot 100\ g^{-1}$, assessed through ammonium acetate extraction (AS-12) [31]. The exchangeable cations were as follows: calcium (Ca), 6.1 meq·100 g^{-1}; potassium (K), 3.9 meq·100 g^{-1}; magnesium (Mg), 2.6 meq·100 g^{-1}; and sodium (Na), 0.2 meq·100 g^{-1}. The phosphorus (P) content was 22.8 mg·kg^{-1}, determined using the Olsen method (AS-10) [31], while the available potassium content was 110.3 mg·kg^{-1}, following method AS-12 [31]. The organic matter (OM) content was 1.4%, total carbonate—1.5%, and organic carbon (OC)—0.81%, all measured according to ISO 10694 [33]. Total nitrogen (N) was 0.02%, determined using ISO 13878 [34].

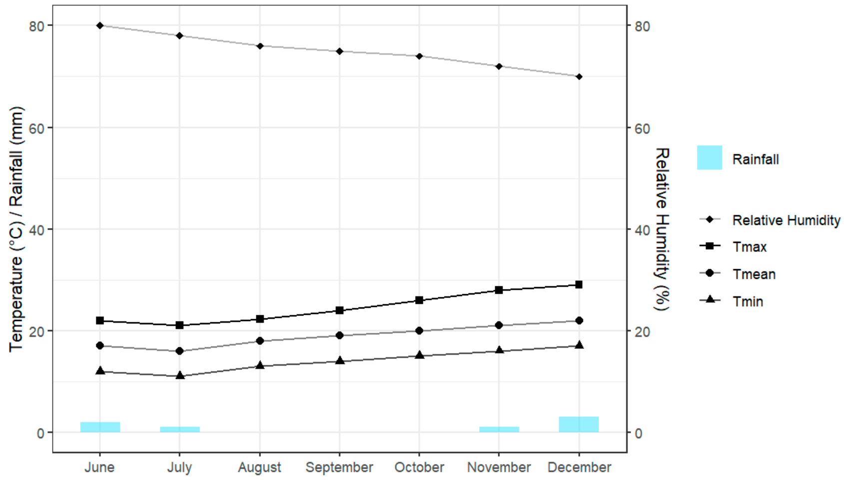


Figure 1. Monthly climatological data of the project site, including precipitation (rainfall), maximum temperature, minimum temperature, and relative humidity.

2.3. Experimental Design

The experiment used a randomized complete block design with a split-plot arrangement and three replicates. The main plot, with an area of 120 m^2, corresponded to the application of guinea pig manure at four rates, while the subplot, covering 30 m^2, consisted of the application of four percentages of the recommended $N–P_2O_5–K_2O$ fertilization dose (Figure 2). The combination of these two factors resulted in a total of 16 treatments.

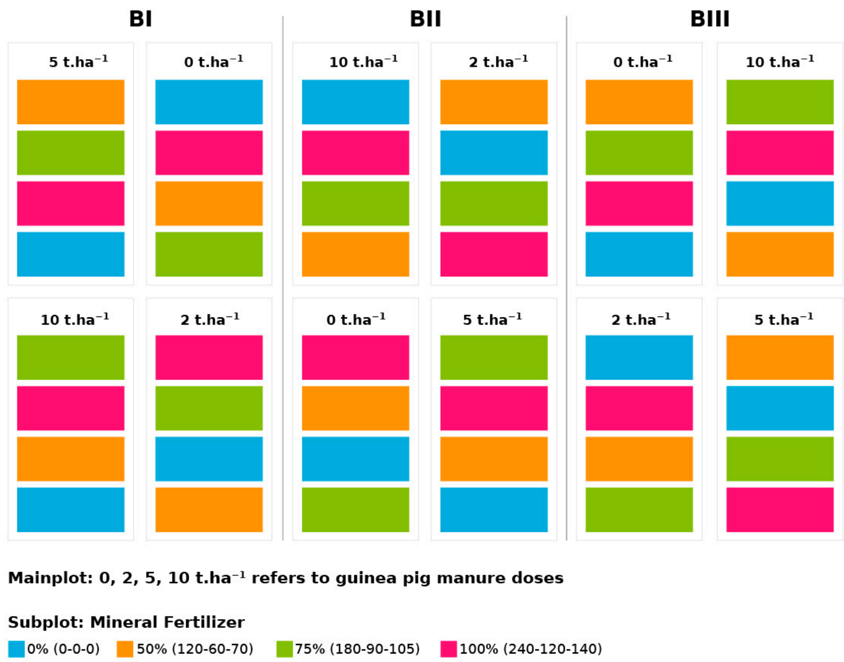


Figure 2. Field distribution of the treatments.

2.4. Characteristics of Guinea Pig Manure

The guinea pig manure was sourced from the National Guinea Pig Program sheds at the Institute for Agrarian Innovation. Its physical and chemical characteristics were as follows. The pH was measured according to EPA Method 9045 [32], resulting in a value of 7.1, while electrical conductivity was 832.0 mS·m^{-1}, determined using ISO 11265 [35]. The organic matter content was 52.56%, and nitrogen (N) concentration was 2.84%, both analyzed using a LECO® CN828 carbon–nitrogen analyzer following ISO 10694 [33] and ISO 13878 [34], respectively. The potassium oxide (K_2O) content was 2.51%, phosphorus pentoxide (P_2O_5) –1.01%, and the carbon-to-nitrogen (C/N) ratio was 11.06.

2.5. Crop Fertilization

Manure fertilization was applied before sowing on the furrow ridge, following the designated doses for each plot, and was allowed to stabilize for 15 days. Mineral fertilization was carried out manually 30 days after sowing (DAS), during the V4 vegetative stage of maize. During this process, a small hole was made on the furrow ridge using a shovel, the fertilizer was applied, and then covered with a thin layer of soil.

Nitrogen fertilization was split into two equal applications. The first was conducted at 30 DAS, along with the application of P_2O_5 and K_2O doses, incorporating half of the nitrogen assigned to each treatment. The second application was performed one month later, during the V10 stage, applying the remaining half of the nitrogen dose. Diammonium phosphate, urea, and potassium chloride were used as sources of P_2O_5, N, and K_2O, respectively.

2.6. Agronomic Management

The experimental field was previously utilized for intensive agriculture, having been planted with hard yellow maize for the past three years. Soil preparation involved initial irrigation, plowing, harrowing, and furrowing. The hard yellow maize hybrid employed in the trial was Megahíbrido Simple INIA 619, derived from two tropical lines (line 451 × line 287) exhibiting a high inbreeding degree. This hybrid was developed at the Vista Florida Agricultural Experiment Station in Chiclayo by the National Institute for Agrarian Innovation (INIA) between 2006 and 2009, with contributions from Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) in Mexico.

Planting was carried out during the first week of June 2023 at a distance of 0.30 m between hills and 0.8 m between furrows in a 1440 m^2 area, distributed in 48 plots of 30 m^2 (5 m × 6 m) with 7 furrows each.

For phytosanitary management throughout the crop growth period, a pre-emergent broadleaf herbicide, atrazine (50% concentrate suspension), was applied alongside a fungicide combination of azoxystrobin (250 g·kg^{-1}) and tebuconazole (500 g·kg^{-1}). An insecticide treatment included spinosad (12% soluble concentrate) and emamectin benzoate (19 g·L^{-1} concentrate).

2.7. Evaluated Parameters

It should be noted that the term cob refers to just the central axis of the maize structure, without the husk and grains, while the term ear refers to the complete structure, including the cob, grains, and husks.

Upon reaching full physiological maturity, which occurred at 210 DAS at the R6 phenological stage, plant height measurements were conducted at harvest. Following the ear harvest, several characteristics were assessed, including ear length and diameter, number of rows per ear, number of grains per row, ear, grain, and cob weight. All weights were standardized to a moisture content of 14%, allowing corn grain yield per hectare calculation.

The yield was calculated as follows [36]:

$$Yield\left(\frac{kg}{ha}\right) = \frac{Total\ corn\ grain\ weight - Moisture\ content}{Area} \times 10$$

The Physicochemical Laboratory of the Institute for Nutritional Research conducted a proximate analysis to evaluate the nutritional composition of maize. The following determinations were performed: protein content—using the Kjeldahl Method [37], ash content—following Peruvian Technical Standard 205.004 [38], and fat content—according to methodology 205.006 [39]. Additionally, fiber was analyzed based on the AOCS Ba-6 method [40], while the carbohydrate content was estimated by difference in dry matter (MS-INN) [41]. The total energy value was calculated by summing the caloric contributions from fat, carbohydrates, and protein.

2.8. Statistical Analysis

The statistical analysis was conducted using a randomized complete block design in a split-plot arrangement. To ensure the validity of the models, the assumptions of normality and homoscedasticity were tested using the Shapiro–Wilk and Bartlett's tests, respectively, implemented through the stat package in R [42]. Analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$. When significant differences were detected, multiple comparisons of the means were conducted using the least significant difference (LSD) test ($\alpha = 0.05$), applying the LSD.test function from the agricolae package in R [43], with adjustments based on the Benjamini–Hochberg procedure.

3. Results

3.1. Vegetative Characteristics

The variance analysis revealed no significant interaction effects; however, significant differences were observed in the main effect between mineral fertilization doses over plant height (p-value < 0.01). The plants receiving 75% and 100% mineral fertilization showed the greatest heights, reaching 229.67 cm and 231.25 cm, respectively (Figure 3).

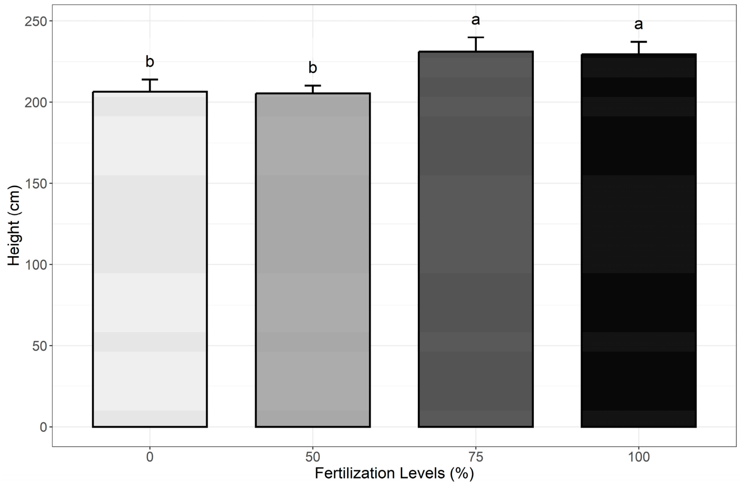


Figure 3. Mineral fertilization effect on INIA 619 plant height (R6). Means with the same lowercase letter are statistically equal according to the LSD test ($\alpha = 0.05$). Data present as the means ± standard error (SE).

3.2. Ear Characteristics

An analysis of variance was conducted, in which the guinea pig manure factor showed significant effects solely on ear diameter (ED) ($p < 0.01$), with the largest diameters observed at application rates of 5 and 10 t·ha^{-1}. In contrast, mineral fertilizer doses had a significant influence on the number of rows per ear (RE), the number of grains per row (GR), ear weight (EW), and grain weight (GW). The highest values for these traits were obtained under the treatment with 100% of the recommended mineral fertilization. However, in specific cases such as the number of grains per row and ear weight, the 50% fertilization dose did not differ significantly from the full dose (Table 1).

Table 1. Ear characteristics of INIA 619.

Factor	EL (cm)	ED (cm)	RE	GR	EW (g)	GW (g)	CW (g)
t·ha^{-1}				**Guinea pig manure (G)**			
0	15.51 ± 2.27	4.01 ± 0.26 c	13.45 ± 1.07	28.84 ± 4.77	141.04 ± 35.77	116.56 ± 30.06	24.49 ± 6.79
2	15.54 ± 2.47	4.04 ± 0.24 c	13.87 ± 1.12	28.52 ± 5.35	146.75 ± 38.35	121.69 ± 32.33	25.58 ± 8.06
5	16.31 ± 2.12	4.19 ± 0.22 a	13.73 ± 1	29.85 ± 4.93	160.63 ± 34.75	132.69 ± 28.37	28.18 ± 7.24
10	16.08 ± 2.47	4.11 ± 0.21 b	13.62 ± 1.17	29.71 ± 5.85	154.06 ± 35.4	127.29 ± 29.96	26.77 ± 5.99
(%)				**Fertilization (F)**			
0	15.69 ± 2.15	4.07 ± 0.22	13.58 ± 0.33 b	28.16 ± 2.36 b	142.89 ± 11.49 b	122.59 ± 10.05 c	24.98 ± 5.99
50	16.15 ± 2.43	4.11 ± 0.24	13.53 ± 0.31 b	30.51 ± 2.34 a	155.21 ± 13.16 a	125.2 ± 10.94 bc	28.01 ± 8.24
75	15.98 ± 2.44	4.08 ± 0.28	13.53 ± 0.30 b	28.3 ± 1.75 b	149.97 ± 19.05 ab	132.88 ± 15.42 b	25.68 ± 7
100	15.62 ± 2.37	4.08 ± 0.24	13.87 ± 0.23 a	30.59 ± 2.99 a	155.51 ± 12.29 a	141.8 ± 11.93 a	26.33 ± 7.01
G	0.53	**	0.16	0.65	0.10	0.94	0.18
F	0.19	0.47	**	*	*	***	0.08
GxF	0.35	**	0.43	0.66	0.18	0.10	0.18

Note: ear length = EL, ear diameter = ED, number of rows per ear = RE, number of grains per row = GR, ear weight = EW, grain weight = GW, and cob weight = CW. Husk weight was not considered in the ear weight (only cob + grains weight). Means and standard deviation are shown. Means with the same lowercase letter are statistically equal according to the LSD test (α = 0.05). Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The analysis of the interaction effect between the two study factors revealed highly significant differences in ear diameter across fertilizer doses when 0 and 5 t·ha^{-1} of guinea pig manure were applied. In treatments with 0 t·ha^{-1} manure, the largest ear diameter was observed without mineral fertilization, whereas increasing manure doses reduced the ear diameter. For treatments with 5 t·ha^{-1} of guinea pig manure, the 50%, 75%, and 100% fertilization doses produced statistically significant results, with ear diameters averaging 4.25 cm, 4.23 cm, and 4.22 cm, respectively (Figure 4).

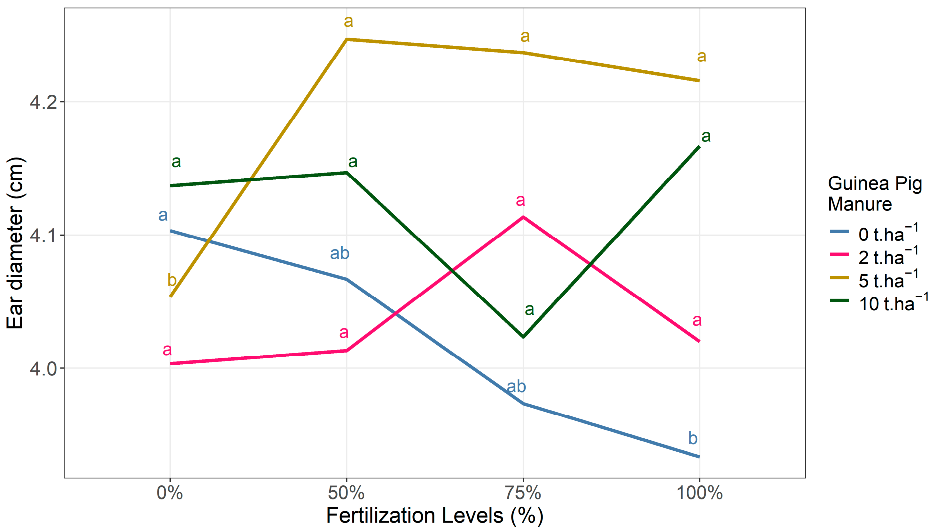
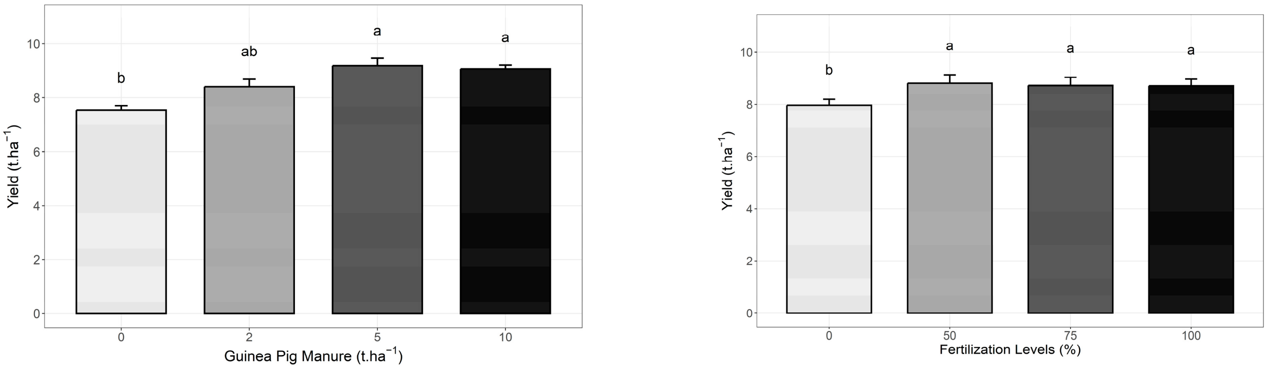


Figure 4. Interaction between mineral fertilization doses (%) and guinea pig manure (t·ha^{-1}) on the ear diameter of INIA 619 maize, which was statistically significant ($p < 0.01$). Means with the same lowercase letter are statistically equal according to the LSD test (α = 0.05).

3.3. Yield

No significant interaction effects were found between the two factors. However, a significant main effect was observed for the guinea pig manure factor (p-value < 0.05). Treatments with 5 and 10 t·ha^{-1} of manure achieved the highest yields, increasing by 18% and 17%, respectively, compared to the treatment without manure (Figure 5a). Regarding the mineral fertilization factor (p-value < 0.01), the highest yields were obtained with 50%, 75%, and 100% of the recommended dose, resulting in up to a 10% increase in yield compared to the unfertilized treatment (Figure 5b).



(**a**) (**b**)

Figure 5. Effect of guinea pig manure (**a**) and mineral fertilization (**b**) on INIA 619 maize yield. Means with the same lowercase letter are statistically equal according to the LSD test (α = 0.05). Data present as the means ± standard error (SE).

3.4. Nutritional Quality

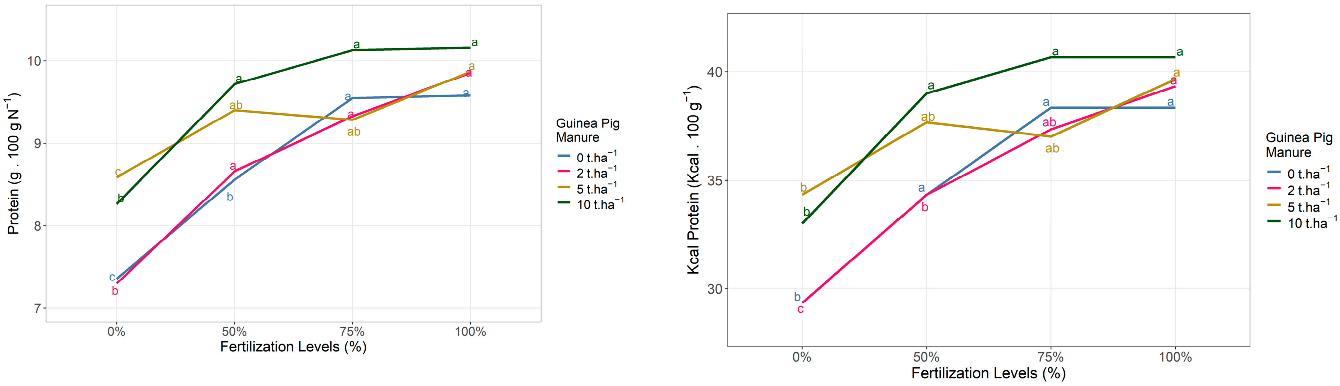
According to the analysis of variance, the application of guinea pig manure did not significantly affect the nutritional quality of maize. However, highly significant differences were observed in the protein content, carbohydrate levels, and total energy in kilocalories derived from proteins and carbohydrates, which were attributed to the mineral fertilization doses applied.

The protein content and its corresponding energy value were notably higher with the application of 75% and 100% of the recommended mineral fertilization, increasing the protein quality by up to 20% compared to the unfertilized treatment. In contrast, the highest carbohydrate content and associated caloric values were recorded in the absence of mineral fertilization. Moreover, the lack of mineral fertilization resulted in significantly lower total energy values than those observed at higher fertilization levels (Table 2).

Finally, at the interaction level, only the protein content and kilocalories of protein variables were statistically significant.

The highest protein contents—10.12, 9.71, and 10.15 g·100 g·N^{-1}—were obtained with the fertilization doses of 50%, 75%, and 100%, respectively, in the treatment involving 10 t·ha^{-1} of guinea pig manure alongside fertilization. However, it is important to note that no significant differences were found between these fertilization doses (Figure 6a).

Regarding the protein content and kcal protein, the highest values were obtained by applying 10 t·ha^{-1} of guinea pig manure, with 40.7 kcal observed at 100% and 75% fertilization levels and 39 kcal at 50%. However, no significant differences were found between these fertilization levels (Figure 6b).



(**a**) (**b**)

Figure 6. Interaction between mineral fertilization and guinea pig manure dosage on (**a**) the protein content and (**b**) kcal protein. Means with the same lowercase letter are statistically equal according to the LSD test (α = 0.05).

Table 2. Nutritional quality of the INIA 619 maize variety.

Level	Prot	Ash	Fat	Fiber	CHO	TE	Kcal Prot	Kcal Fat	Kcal CHO
	$g{\cdot}100\ g{\cdot}N^{-1}$	$g{\cdot}100\ g^{-1}$	$g{\cdot}100\ g^{-1}$	$g{\cdot}100\ g^{-1}$	$g{\cdot}100\ g^{-1}$	$Kcal{\cdot}100\ g^{-1}$	$Kcal{\cdot}100\ g^{-1}$	$Kcal{\cdot}100\ g^{-1}$	$Kcal{\cdot}100\ g^{-1}$
(%)	Fertilization (F)								
0	7.87 ± 0.7 ^{c}	1.13 ± 0.14	3.21 ± 0.32	2.56 ± 0.2	74.22 ± 0.98 ^{a}	357.17 ± 1.99 ^{b}	31.5 ± 2.75 ^{c}	28.92 ± 2.91	296.75 ± 3.84 ^{a}
50	9.08 ± 0.74 ^{b}	1.1 ± 0.13	3.42 ± 0.33	2.51 ± 0.16	73.01 ± 0.9 ^{b}	359.92 ± 3.42 ^{a}	36.33 ± 2.96 ^{b}	30.83 ± 2.98	291.92 ± 3.45 ^{b}
75	9.57 ± 0.57 ^{a}	1.14 ± 0.17	3.56 ± 0.56	2.5 ± 0.14	72.64 ± 0.74 ^{b}	360.83 ± 3.16 ^{a}	38.33 ± 2.39 ^{a}	32 ± 4.94	290.5 ± 2.88 ^{b}
100	9.86 ± 0.73 ^{a}	1.03 ± 0.13	3.43 ± 0.28	2.53 ± 0.18	72.6 ± 0.88 ^{b}	360.75 ± 2.05 ^{a}	39.5 ± 3 ^{a}	30.92 ± 2.54	290.33 ± 3.5 ^{b}
F	***	0.21	0.31	0.82	***	**	***	0.32	***
GxF	*	0.83	0.91	0.59	0.52	0.70	*	0.86	0.54

Note: proteins = Prot, carbohydrates = CHO, total energy = TE, kcal protein = Kcal Prot, kcal Carbohydrate = Kcal CHO. Means and standard deviation are shown. Means with the same lowercase letter are statistically equal according to the LSD test (α = 0.05). Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4. Discussion

Hard yellow maize's critical role in the livestock sector underscores the importance of directing research efforts toward increasing average yields and enhancing grain quality [44].

The study demonstrates that mineral fertilization significantly influences the vegetative growth of hard yellow maize. At the harvest stage (R6), the tallest plants were observed in treatments with 75% and 100% mineral fertilization, reaching 231.25 cm and 229.67 cm, respectively, aligning with the 200.3 ± 0.1 cm height reported in the hybrid's datasheet. This availability of nutrients to the plant promoted its growth and development, as it is associated with an increased production of photosynthates [45]. While inorganic fertilizers are crucial in conventional maize production systems [21], excessive application without organic matter may adversely affect the chemical and microbial richness of the soil [5].

At its release, INIA reported the ear characteristics of hybrid INIA 619 as having a length of 22 cm, a diameter of 7 cm, 16 rows, 40 grains per row, an ear weight of 310 g, and a grain weight of 230 g [46]. However, the trial results presented average ear values of 16 cm in length, 4.1 cm in diameter, 14 rows, 29 grains per row, an ear weight of 151 g, and a grain weight of 125 g. These characteristics more closely resemble those of its parent lines, CML-451 and CML-287, which exhibit ear lengths of 14.2 cm, diameters of 4.29 cm, 13 rows, and 23 grains per row [47]. Understanding the physical characteristics of the ear is crucial due to the focus on maize improvement, particularly the relationship between the number of rows, grain size, and ear width, with the goal of optimizing the total grain weight [48]. In this context, it can be stated that the presence of 5 $t \cdot ha^{-1}$ of guinea pig manure in the soil may improve the ear characteristics of hard yellow maize and positively impact productivity increases.

Regarding maize grain yield, it was found to be significantly influenced by the application of different doses of guinea pig manure, with the highest yields achieved with the highest amendment rates (5 and 10 $t \cdot ha^{-1}$). This result underscores the value of guinea pig manure as a favorable organic fertilizer for maize production. Additionally, the yields obtained with 50% fertilization were similar to those with 100%, likely due to the positive influence of organic matter on the soil. According to Janampa et al. [49], incorporating guinea pig manure into maize crops can enhance yields by improving soil characteristics through an increase of over 90% in the organic matter content. Moreover, guinea pig manure contains a higher nitrogen concentration (3.42%) [50] compared to other commonly used manures, such as cow manure (2.59% N) [51], pig manure (2.04% N) [52], or chicken manure (1.43% N) [53], making it one of the richest nutrient sources for soil. Additionally, the incorporation of carbon and nitrogen present in guinea pig manure promotes microbial activity, increasing soil microfauna and providing biological and chemical stability [54]. It is important to highlight that, currently, Peru leads guinea pig breeding with the largest population size [14], housing 25.82 million guinea pigs [55]. Although primarily raised for meat, their manure is a valuable byproduct commonly used by farmers as a fertilizer, though still in an empirical manner [56]. On average, a rural Peruvian family can collect approximately 564,000 kg of manure annually (L. Chauca, personal communication, August, 2024). Given the results of this study, which demonstrated higher maize yields with an application of 10 $t \cdot ha^{-1}$ of guinea pig manure per hectare, it can be stated that the amount produced is sufficient for guinea pig manure to be considered an accessible and effective organic amendment for improving agricultural production. This makes it an interesting alternative for application as a fertilizer and soil quality enhancer.

As previously mentioned, the importance of mineral fertilization can be emphasized, as it leads to higher grain yields due to its high solubility, ensuring greater nutrient availability for plant absorption [57]. However, these benefits are further amplified when the soil is in a favorable condition, with proper moisture, texture, and organic matter from manure [45]. The combined application of a mineral fertilizer and manure improves soil water retention, enhances the formation of aggregates (>0.25 mm), and increases the content of nitrogen (N), phosphorus (P), potassium (K), and organic matter, thereby improving nutrient availability [58]. Additionally, it leads to greater biomass production throughout the growing season, boosting the plant's photosynthetic activity [59,60]. Relying solely on mineral fertilizers may be insufficient for sustaining high yields due to the potential depletion of the soil's physical and chemical properties, which can affect water retention, stability, and the soil's biological richness [60]. Therefore, farmers should be trained on incorporating manure into their fertilization practices to maintain soil ecosystem sustainability.

Regarding nutritional quality, maize is notable for its high energy content, primarily due to its richness in starch and fat [29]. The average total energy observed in the INIA 619 variety is 397 $Kcal \cdot 100\ g^{-1}$, a higher value than what Maguiña-Maza et al. [61] reported for the same variety. Carbohydrates and ash are abundant within the grain [29]. However, the crude fiber content is low and constitutes less than 5% of the grain's dry weight [62].

Concerning quality, the protein content is approximately 60% at grain maturity, and lysine content is notably high, promoting good consumer digestibility [29]. The highest protein content in this study was observed in treatments with 50%, 75%, and 100% of the recommended mineral fertilizer dose, consistent with the findings of Çarpıcı et al. [63] and Noor et al. [59], who reported that increased nitrogen availability enhances protein synthesis. However, nitrogen levels must remain within a certain range, as excessive and insufficient doses can reduce nitrogen transport to grains before anthesis, affecting their protein content [64]. Tropical lines 451 and 287, progenitors of the INIA 619 variety, are known for their high grain protein quality and increased yield potential [41,65]. Comparatively, nitrogen fertilizer doses of 240 kg·ha^{-1} in a different hybrid under varied environmental conditions produced yields of 8.5 t·ha^{-1}, with the protein content ranging from 8.3% to 10.0%, values below those obtained in the present study with the incorporation of guinea pig manure [65].

The protein content recorded for the INIA 619 variety in this study is considered high [66], making it a valuable genetic material for animal feed production. This high protein content reduces animal husbandry costs by providing a nutritionally rich feed option [44].

These results contribute to the cultivation of hard yellow maize by presenting an agronomic management strategy that enhances grain yield and nutritional quality by combining synthetic fertilizers and guinea pig manure. While such practices are commonly employed in small- and medium-scale agriculture, their combined effects have not been thoroughly studied in the Peruvian agriculture, particularly for the hybrid maize INIA 619.

5. Conclusions

The novelty of this study lies in demonstrating that mineral fertilization and guinea pig manure—a relatively under-researched organic source—significantly influence grain yield. In particular, for the INIA 619 hard yellow maize variety, reducing the synthetic fertilizer dose by 50% did not negatively affect yield. Moreover, the application of 5 or 10 t·ha^{-1} of guinea pig manure markedly improved yields. From a nutritional perspective, the protein content and its energy contribution were higher in treatments with 75% and 100% of the mineral fertilizer dose combined with 10 t·ha^{-1} of guinea pig manure. However, a 50% reduction in fertilizer application produced results comparable to those obtained with the full synthetic fertilizer dose. This study provides essential evidence on the interaction between mineral and organic fertilization, suggesting that an optimal fertilization strategy for hard yellow maize could involve an application of 120–60–70 (N–P–K) from synthetic fertilizers, supplemented with 10 t·ha^{-1} of guinea pig manure. This approach would achieve yields similar to those from the total fertilizer dose while enhancing the grain's nutritional content. Future applications of this strategy could lead to more sustainable crop management and improved grain quality.

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