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Production of biochar derived from guinea pig manure as a soil amendment in high Andean and coastal acidic soils in Peru: agronomic potential and cost analysis for sustainable circularity

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Introduction: The valorization of local resources, such as guinea pig manure, allows traditional inputs to be transformed into more stable products with higher added value, such as biochar, rather than being used as raw manure.

Methods: This study evaluated the physicochemical properties, toxicity, and neutralizing capacity of biochar obtained from guinea pig manure, produced by open pyrolysis in a pyrolytic oven in Huancayo, Junin, Peru. Fresh manure was also characterized prior to pyrolysis, and its median lethal dose was determined.

Results: The results indicated that guinea pig manure had an approximate volume of 2,883.99 cm^3 in an uncompacted state and 2,205.41 cm^3 in a compacted state, with densities of 0.293 and 0.380 kg/cm^3, respectively. Guinea pig manure biochar has high N, P, and K contents, as well as a significant percentage of ash (34.6%) and fixed carbon (37.9%). Its alkaline pH (9.17), high cation exchange capacity (48.8 meq/100 g), and high organic matter content (62%) suggest its potential for improving acidic soils. It also has a considerable moisture content (34.8%) and microelements such as Mg, Cu, Ca, and Zn. In economic terms, the production of 1 ton of guinea pig manure has an estimated cost of 231.23 soles, while the sale price of biochar reaches 3,515.31 soles per ton, demonstrating its high added value.

Discussion: Biochar derived from guinea pig manure has a superior nutritional profile compared to biochars obtained from plant biomass, making it a viable alternative for agriculture. Its application, however, must take into account specific safety tests for each crop to ensure both safety and effectiveness.

KEYWORDS

biochar, circularity, guinea pig, manure, physicochemical properties, soil

Introduction

Multiple factors, such as soil fertility loss, drought, erosion, soil acidity, and climate change, pose serious threats to the capacity of soils to sustain food production (Minta et al., 2018). Soil degradation and contamination lead to excessive soil depletion (Abdelhak, 2022) and represent a deterioration of soil quality, structure, fertility, and functionality. Unsustainable agricultural practices can result in alarming rates of soil erosion.

Soil acidification is a critical global challenge that threatens agricultural productivity by limiting nutrient availability and degrading agroecosystems (Regasa et al., 2025). It is the process by which soil pH decreases, causing soils to become acidic (Adane, 2014; Smith and Hardie, 2022). Acid soils negatively affect agricultural productivity and account for approximately 30%–40% of agricultural land worldwide (Bian et al., 2013; Alemu et al., 2022).

Peru is not exempt from this reality, with its intensive agricultural production and increased use of fertilizers, especially in the high Andean areas (Gutierrez et al., 2022). The primary cause of soil fertility degradation is nutrient imbalance, as each crop has distinct nutrient requirements and uptake rates that manifest in identifiable deficiency symptoms (Shrivastav et al., 2020). Continuous cropping can significantly reduce the availability of essential nutrients such as phosphorus and potassium, whereas balanced fertilizer use may be an effective alternative for improving crop development (Chen et al., 2021).

Recently, special attention has been given to a highly valuable species, guinea pigs (*Cavia porcellus*). Guinea pigs are prolific, grow quickly, reproduce efficiently on a varied diet, and adapt to diverse climatic conditions (Lammers et al., 2009). However, the storage of excrement in sheds poses environmental and health challenges, creating unsanitary conditions for the animals and caretakers (Harkness et al., 2007). Although guinea pig manure is easily collected and can be deposited in centralized areas, it is estimated that between 2 and 3 kg are produced per 100 kg of live weight per day, as 60% and 80% of the food consumed is eliminated as manure (Murray-Núñez et al., 2023). In the case of maize, Calero-Rios et al. (2025) reported that the application of guinea pig manure improved nutrient use efficiency, grain yield, and protein quality in maize, while reducing the need for mineral fertilizers by up to 50%, thereby providing a sustainable fertilization strategy for agricultural systems.

However, the relationship between soil and plant nutritional status involves the availability of soil nutrients, especially in temperate climates (Scavo et al., 2022), and the safety of food available to consumers. Organic amendments derived from manure represent a relevant component of integrated livestock farming systems, supporting agricultural sustainability and contributing to circular economy frameworks. When improperly managed, their application may generate adverse environmental effects. Appropriate management practices, supported by technological interventions, can enhance their added value as a rich source of essential nutrients for crop growth. Such practices must ensure balanced application rates and careful monitoring to prevent nutrient overload and the excessive accumulation of compounds such as sterols in the soil (Sadeghpour and Afshar, 2024).

The production of guinea pig manure-derived biochar as an amendment for acidic soils represents a promising agronomic strategy that can significantly reduce the use of commercial inorganic fertilizers and, consequently, lower environmental pollution while maintaining high yields of safe food products (Rombel et al., 2022). Accordingly, biochar has become a valuable product within the bioeconomy, which involves the valorization of biological resources through bioengineering to generate economically valuable products. As a marketable product, biochar has applications in the energy sector, the manufacture of biochar-based materials, and agriculture. Therefore, biochar production not only improves soil quality but also creates new income-generating opportunities (Rizwan et al., 2023).

Biochar is obtained by controlled heating of organic matter under oxygen-limited conditions, generating a highly porous and chemically stable material (Li et al., 2023). In agricultural applications, its use has been shown to improve water retention, increase cation exchange capacity, stabilize soil pH, and provide a favorable habitat for beneficial microorganisms (Adekiya et al., 2020). The hypothesis is that the transformation of guinea pig manure into biochar through pyrolysis significantly improves its physicochemical properties compared with fresh manure, increasing its stability, nutrient content, and ability to improve acidic soils. Therefore, guinea pig manure biochar is expected to be a profitable and efficient alternative for use as an agricultural amendment when applied at optimal doses that maximize its benefits without causing adverse effects.

Material and methods

Location of the experiment

The experiment took place at the Santa Ana Agricultural Experiment Station, located in the province of Huancayo at 3,290 m.a.s.l., with coordinates 12°00′37.4″ S, 75°13′19.8″ W. The climate in the area is temperate and cold, with low humidity. The prevailing weather is cold and rainy, with dry autumns and winters. Temperatures fluctuate between 20°C during the day and below 0°C at night.

The objective of this bioassay was to determine the median lethal dose (LD_{50}) of the biochar using the Probit model for the analysis of binomial data (germinated/nongerminated), in accordance with standard methodologies for the initial assessment of acute toxicity in soil amendment (Duó et al., 2010).

Collection and physicochemical characterization of guinea pig manure

Guinea pig manure was collected from 10 randomly selected pens at the Santa Ana Agricultural Experiment Station (Junín, Peru) to ensure sample representativeness. Approximately 2 kg of fresh manure was collected from each pen and homogenized to form a composite sample. The composite sample was air-dried at room temperature for 7 days and sieved through a 12-mm mesh to remove feed residues and other coarse materials. For physicochemical analyses, a 1-kg subsample was prepared from the sieved material. All laboratory determinations were performed in triplicate at the Chemical Analysis Services Laboratory of the Universidad Nacional Agraria La Molina (UNALM). Analytical methods followed the national guideline for solid waste characterization (Ministerial Resolution No. 457-2018-MINAM). Bulk density was determined using a standardized method: a plastic cylinder of known volume was filled with manure and lightly compacted by dropping it three times from a height of 5 cm, after which the final volume was recorded. Bulk density was calculated as density = mass/volume. This physical test was repeated three times for each condition (compacted and noncompacted). Characterization results are presented as mean ± standard deviation based on analytical replicates.

Biochar production from guinea pig excrement

The open or rapid pyrolysis method was used to produce biochar using guinea pig excrement. For this purpose, a metal tank was used to construct the pyrolytic oven, which served as a reactor, yielding 20 kg of biochar from guinea pig manure. This method is also known as an open-top pyrolytic reactor. Special care was taken to obtain biochar rather than ash or semicharcoal. Biochar was produced by fast pyrolysis using a metallic tank Kon–Tiki-type reactor, which typically operates within a temperature range of 500°C–700°C, according to established technical specifications (Cornelissen et al., 2024). During the process, a flame-free combustion regime was maintained to ensure low-oxygen conditions. The selected temperature range is supported by previous studies reporting optimal biochar properties within this thermal interval (Huang et al., 2018; Murray-Núñez et al., 2023) and is consistent with the final characteristics of the product, including alkaline pH and high fixed carbon content.

At the end of the homogeneous formation of the charcoal, sufficient water was added to cool and stop the heat reaction. The collected charcoal was stored in a polypropylene bag under cool, dry conditions. Afterward, it was ground to produce particles approximately 3 mm thick, ready for application. The fresh guinea pig manure had an approximate volume of 2,883.989 cm^3 in the uncompacted state and 2,205.41 cm^3 in the compacted state. The average density recorded was 0.293 kg/cm^3 in the uncompacted state and 0.380 kg/cm^3 in the compacted state.

Analysis of FT-IR for the determination of biochar functional groups in relation to its raw material

The dry, ground precursor material (guinea pig manure), as well as the dry guinea pig biochar, were manually analyzed using Fourier transform infrared spectroscopy (FT-IR). This technique is based on the absorption of radiation at specific frequencies and allows conclusions to be drawn about the functional groups on the surface of the biochar. A total of 200 scans were taken across a range of 4,000–600 nm to characterize the chemical structure of the sample. The analysis was conducted using a Thermo Fisher Scientific-Nicolet iS10 equipment (USA) in the Laboratory of the Faculty of Sciences—Chemistry at the National Agrarian University La Molina. Radiation spectra within this range were recorded for each sample; potassium bromide was used as a blank, and absorption spectra were subsequently obtained from the radiation spectra.

Biochar cost calculation from guinea pig manure

The economic cost of producing 1 kg of biochar (US$/kg) was calculated by taking into account the following factors: 130% of the market price of guinea pig manure (US$/kg); the conversion ratio of the quantity of biochar produced per kilogram of manure; labor costs (US$/day); the number of days required to produce 1 megagram (Mg) of biochar (day/Mg); and the energy costs for the pyrolysis process, based on the price of wood (US$/kg) and the transformation ratio of the quantity of wood used to produce 1 Mg of biochar.

Biochar assay of the average tolerance limit on corn seed germination tests (*Zea mays*)

The LD_{50} of guinea pig manure biochar was measured using the methodology proposed by Duó et al. (2010), adjusted to our case. A completely random design (DCA) was designed with 11 treatments and three replicates. Each treatment consisted of a mixture of river sand and biochar in increasing biochar volume proportions (0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%). After leaving the pyrolytic reactor, the biochar was ground and passed through a 2-mm sieve before being mixed. The experimental unit was defined as a set of six cells arranged in rows in a seedling tray, containing a mixture of river sand and biochar in the proportions determined for each treatment. These units were arranged in three seedling trays, each containing 72 cells (six rows by 12 columns), with dimensions of 2.5 cm × 3.3 cm × 4.5 cm and a volume of 37 cm^3. The 11 treatments were randomized within each tray. A mark was placed to identify each treatment and its replicate. One

INIA 619 corn seed was sown in each cell at a depth of 1 cm. Over a period of 8 days, the number of seeds that germinated in each experimental unit was recorded daily. The germination percentage for each day was calculated using the following formula indicated in Equation 1:

$$\% \text{ Germination} = \left(\frac{\# \text{ germinated seeds}}{6}\right) \quad (1)$$

Acidity-neutralizing capacity and salinization effect of guinea pig manure

The ability to neutralize acidity (pH) and the effect of salinization (EC) were evaluated according to the methodology proposed by Hailegnaw et al. (2019), with adaptations, using two tests: one in the laboratory and the other in pots. The first laboratory test was designed as a DCA with six treatments and five replicates. Each treatment consisted of a mixture of soil and biochar at proportions of 0%, 3%, 4%, 5%, 6%, and 7% by weight. Agricultural soil from the high Andes mountains at 4,000 m.a.s.l. in the Junín province of Peru was used to calculate the neutralizing capacity of guinea pig manure biochar on soil. This soil had an average pH of 6.33, which is considered slightly acidic. The biochar used had an average pH of 9.8, which is alkaline. The experiment began with a 20-g soil sample being weighed in a test tube. Biochar was then added to the soil in different quantities (see Table 1). The mixture was stirred, and 40 ml of distilled water was added. After shaking and mixing, the mixture was left to settle before the electrode was inserted, and the pH was recorded (Scavo et al., 2022). This process was repeated five times for each percentage and/or dose of biochar (Table 1).

For the second test assessing the neutralizing capacity of guinea pig biochar, soil was collected from agricultural land in Pachacamac, Lima. The soil was supplied by a testing laboratory accredited by the INACAL-DA accreditation body (registration number LE-200) and had a pH of 5.296 and an aluminum content of 9.954. This soil was mixed with guinea pig manure biochar in capsule form. One kilogram of acidic soil was placed in plastic bags, with biochar added at 0% (0 kg), 10% (0.09 kg), and 20% (0.27 kg) to allow individual mixing within each bag. The bags were then placed in 5 cm × 5 cm pots with a volume of 90 ml and labeled T1 (0%), T2 (10%), and T3 (20%) for a period of 10 days. The pH and EC parameters were measured for each treatment before watering on day 0 and again after 10 days of watering to check for any changes.

TABLE 1 Biochar doses used in the neutralization test.

Treatment	Biochar doses (%)	Biochar weight (g)	Soil weight (g)
T1	0	0.0	20
T2	3	0.6	20
T3	4	0.8	20
T4	5	1.0	20
T5	6	1.2	20
T6	7	1.4	20

Samples were taken from each treatment at the end of the 10-day period. The mixture of acidic soil and guinea pig manure biochar was added to a laboratory flask until the volume of soil solution in the graduated flask reached 90 ml, and the pH and EC parameters were measured in the same manner. To determine the neutralizing capacity, 90 ml samples of the wet mixture were taken from each treatment. These samples were placed in paper bags, which were then placed in an oven for 1 day to begin the drying process. The treatments were divided into graduated flasks, with each treatment consisting of three replicates of 30 ml of the solid mixture. Distilled water was added to each flask, which was then placed in a shaker for 10 min before being left to rest. After this period, the samples were placed on filter paper suspended over a beaker. Finally, the liquid collected from the filter paper was left to rest for a further 15 min. Radish seeds were used for this parameter and were evaluated over an 8-day period.

Method and data analysis

The data obtained were tabulated using data collection forms in Excel spreadsheets. A descriptive statistical analysis was performed and presented in tables and figures showing the mean values. Toxicity was evaluated using Probit analysis. The results of the evaluated variables were analyzed for normality using the Shapiro–Wilk test (Shapiro and Wilk, 1965) and for homogeneity of variances using Bartlett's (1937) test ($p < 0.05$). For the comparison of means, the Tukey test at 0.05% was applied.

Results and discussion

Valorization of guinea pig manure as a by-product in the guinea pig chain for a novel agricultural application: biochar

In 2018 in Peru, there were more than 800,000 small-scale producers dedicated to raising guinea pigs (*Cavia porcellus*), mainly in the regions of Cajamarca, Cusco, Ancash, Apurímac, Junín, Lima, La Libertad, Ayacucho, Arequipa, and Lambayeque. This represented 57.1% of agricultural producers according to the breeding of minor livestock species and reached 60% in 2023 (Figure 1), making it the main breeding activity after chickens (76.4%) (Instituto Nacional de Estadística e Informática [INEI], 2024). The production of this species increased steadily between 2018 and 2022, with a slight growth of 3.23% recorded in 2023. In 2021, Peru was estimated to have produced approximately 25.8 million guinea pigs, with domestic consumption of around 22,000 tons, representing an increase of 8.59% between 2019 and 2021 (Ministry of Agrarian Development and Irrigation, 2023). An analysis of the guinea pig production chain (Figure 2) begins with the supply of inputs. Between January and September 2022, guinea pig meat production alone reached 8.5 MT (Agroperu, 2023).

Table 2 shows the amount of guinea pig manure estimated as a by-product, as well as the yield after transformation into biochar by pyrolysis under controlled conditions at 500°C. In general, the values show an upward trend between manure production and its potential

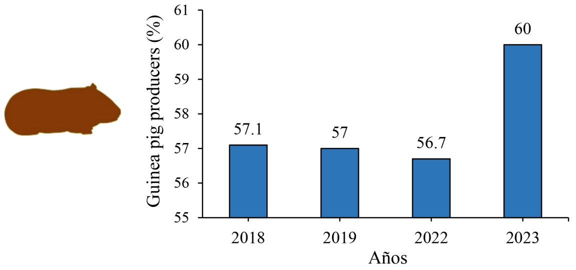

FIGURE 1
Percentage of minor agricultural producers according to the raising of livestock species between 2018 and 2023.

conversion into biochar, closely related to the increase in guinea pig production reported in recent years, despite the decline observed in 2020 due to the coronavirus disease 2019 (COVID-19) pandemic. This increase reflects government support for the guinea pig production chain in the country, particularly in the Andean regions of the central and southern highlands, where production units have experienced parallel growth in the number of animals and in the volume of organic by-products, such as manure. The application of pyrolysis techniques includes the use of artisanal or medium-tech reactors that can transform manure, previously considered waste, into a raw material or precursor for biochar, a product with multiple agronomic and environmental benefits.

The average conversion yield from dry manure to biochar is 30%, with slight variations attributable to manure moisture content, pyrolysis temperature, and process operating conditions. This advancement in the circular economy demonstrates that integrating valorization technologies such as pyrolysis contributes significantly to closing the nutrient cycle and improving the sustainability of the guinea pig production chain. It represents an opportunity for the economic diversification of production units by utilizing a by-product with commercial potential as an agricultural amendment, biofilter, or carbon sink. The following literature review reports on the physicochemical properties of biochar that make it an effective amendment for improving soil quality in agriculture (Table 3).

Table 3 confirms the variability of biochar properties depending on the type of manure, although the pyrolysis temperatures applied (300°C–500°C) are decisive for the concentration or reduction of more volatile materials in the manure used as precursor material. In general, pH increases with temperature, reaching more alkaline values above pH 9 in the case of cow and pig manure. The presence of a higher concentration of ashes rich in carbonates and alkaline oxides (Zhang et al., 2021) allows biochar to be used as an acid soil improver. Nitrogen content (N%) is also higher in rabbit and pig biochar when it is produced at temperatures below 400°C. At higher temperatures, volatile nitrogen compounds are lost (Geng et al., 2022). The cation exchange capacity (CEC) varies significantly, with sheep and rabbit biochar showing higher values at medium temperatures (350°C–400°C), indicating better nutrient retention in agricultural soils due to the conservation of oxygenated functional groups. CEC is maximized at temperatures< 450°C but decreases at higher temperatures due to the removal of oxygenated functional groups that favor cation retention.

The different biochars evaluated have specific applications depending on their origin and neutralizing capacity, highlighting their potential as amendments to correct acidity and improve fertility in degraded soils. The guinea pig manure analyzed exhibited a pH of 7.1, organic matter (OM) content of 52.56%, total nitrogen (TN) of 2.84%, phosphorus (P) of 1.01%, and potassium (K) of 2.51%. These properties may directly influence the nutritional performance of the resulting biochar. Biochar produced exclusively from poultry manure has greater potential to supply P and K to soils than lignocellulosic-based biochars, and feedstock blending can be used to develop engineered biochars that better align soil-test fertilizer values with plant nutritional requirements (Novak et al., 2018). Likewise, biochars pyrolyzed from animal manure feedstocks may contain disproportionately high concentrations of phosphorus and potassium, thereby enhancing soil P and K fertility. Pyrolysis at 600°C also reduces phosphorus losses by transforming biochar into a stable, slow-release nutrient source (Jiang et al., 2024. Table 4 shows relevant information from various authors on the application and efficiency of biochar as a corrective agent or soil improver for acidic soils.

Physicochemical characteristics of biochar from guinea pig manure

The results show that the hydrogen potential was 9.17, indicating a high pH suitable for use in acidic soils (Table 5), acting as an acidity

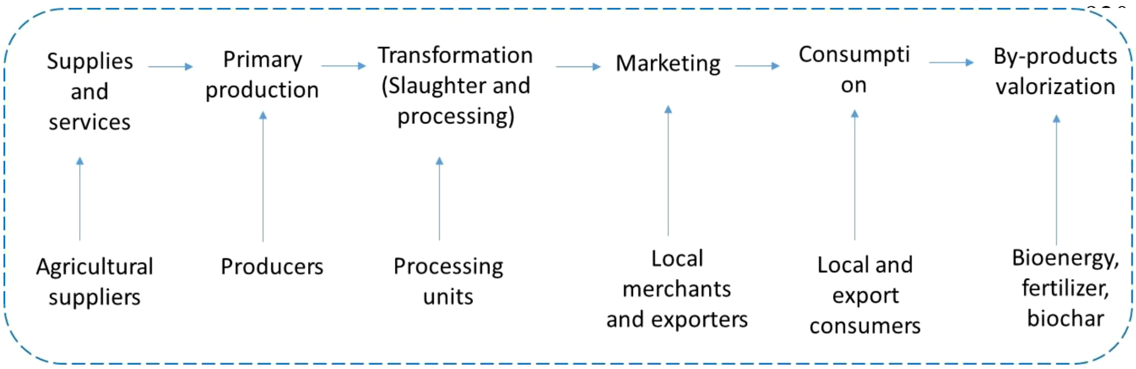

FIGURE 2
Productive chain of the guinea pig.

TABLE 2 Production of guinea pig manure and annual yield.

Year	Population of guinea pig (millions)	Production of manure (kg/year)[a]	Yield in biochar (kg/year)[b]
2015	16.05	406.07	121.8
2016	20.91	529.02	158.7
2017	21.1	533.83	160.1
2018	17.96	454.39	136.3
2019	23.6	597.08	179.1
2020	11.9	301.07	90.3
2021	25.8	652.74	195.8

[a]Each guinea pig produces 25.3 kg of manure until release to market.
[b]Biochar yield: 30%.

compensator, and with potential for environmental remediation of acidic waters. The data obtained in this study are consistent with the findings of Trujillo et al. (2019), who reported an average pH of up to 10.23 using chicken manure; very close to the results found in this study, which obtained a pH of 9.17. Studies on biochar production at different temperatures have reported pH values between 8.92 and 11.14. García et al. (2021), using the slow pyrolysis technique in vine cultivation at the end of its production cycle, reported a pH of 10.5. Singh et al. (2023) investigated biochars in the Peruvian Amazon produced by slow pyrolysis in a furnace and obtained pH values between 7.14 and 10.74.

Murray-Núñez et al. (2023) reported that biochar produced at temperatures from 350°C to 600°C had a pH ranging from 7.97 to 10.35. A pH of 9.17 suggests its potential use for the adjustment of acidic soils. Its high cation exchange capacity (48.8 meq/100 g) and high fixed carbon content (37.9%) render it a material with high stability and nutrient retention, similar to that reported by Singh et al. (2023) for biochar obtained from poultry manure. However, concentrations of heavy metals such as Cr (7.09 mg/kg) and Cd (1.05 mg/kg) were detected, suggesting the need to evaluate their safety before application in sensitive crops (Bolan et al., 2023). Regarding EC, a high value of 17.28 dS/m was observed, directly related to the salt content in the rhytidome, as indicated by Nunes et al. (2021), which could influence the results of the guinea pigs' feeding.

The authors mentioned found that fast and open pyrolysis of plant tissues yielded nitrogen (N) percentages ranging from 0.31% to 0.84%, which contributes to the development of microbial life and soil recovery. The phosphorus content present in biochar obtained from guinea pig manure was 4.0%, which is high compared with studies applying different pyrolysis processes to eucalyptus biomass, where levels of 0.50% were reported, except in biochar produced by slow pyrolysis of branches.

The results of the analysis in Table 5 indicate a notable increase in certain compounds, including Mn, Mg, Cu, Ca, Zn, and Na, and electrical conductivity—closely correlated variables that increase during rapid pyrolysis of guinea pig manure. Several of these

TABLE 3 Physicochemical properties of biochar produced from animal manure.

Biochar source	Temperature (°C)	pH	N (%)	CIC (cmol/kg)	Reference
Cow manure	300	8.62	2.72	185.89	Zhang et al. (2021)
	400	9.86	2.09	169.07	
	500	10.75	1.76	156.91	
	600	10.79	1.72	156.52	
	700	10.83	1.54	147.52	
Cow manure	300	8.48	2.55		Qin et al. (2019)
	400	9.18	2.62	nd	
	500	9.36	2.53	nd	
	600	9.6	2.15	nd	
	700	10.36	1.45	nd	
Cow manure	300	8.62	nd	nd	Nguyen et al. (2024)
	400	9.86	nd	nd	
	500	10.75	nd	nd	
	600	10.79	nd	nd	
	700	10.83	nd	nd	
Sheep manure	500	nd	2.89	nd	Huang et al. (2018)
Rabbit manure	500	nd	2.57	nd	
Pig manure	500	nd	2.23	nd	
Rabbit manure	300	8.6	2.1	146	Cárdenas-Aguiar et al. (2022)
Rabbit manure	600	10.8	0.8	127	
Rabbit manure	550	6.98	2.98	23.1	Medyńska-Juraszek et al. (2022)

TABLE 4 Applications and neutralizing capacity of biochar produced from various types of waste.

Biochar source	Suggested application and neutralizing capacity	Reference
Biochar from waste trees at 550°C for 5 h.	Increase in soil pH and decrease in exchangeable acidity, due to the rise in exchangeable and water-soluble basic cations, as biochar is rich in carbonates and other alkaline substances.	Chen et al. (2023)
Plat debris and cow manure	pH increasing by 1 unit	Geng et al. (2022)
	Increasing soil pH (+ 1), organic matter (120.8%), and CEC (16.2%); soil K availability was improved.	Zhang et al. (2022)
Commercial products	Biochar has a positive effect on reducing soil acidity, raising the initial pH by 1 unit (to 5.56), increasing MOS, releasing available Ca^{2+} and Mg^{2+}, and improving soil fertility.	Dang et al. (2022)
Rice straw	Biochar improves heterotrophic nitrification (pH 4.0–7.4) and promotes nitrogen retention in soil at pH 4.5–6.4. It improves nitrogen use efficiency.	Qian et al. (2023)
Organic wastes	Application of 1.5% biochar to the soil increases the pH value by 0.26–0.47 units.	Guo et al. (2022)
Biochar from Douglas fir	Biochar provides alkalinity and buffering capacity, has greater solubility in water, and increases the availability of bases. Its pH and buffering capacity depend on cation exchange sites.	Arwenyo et al. (2023)

characteristics are replicated to a lesser extent during slow pyrolysis, and their levels are closely associated with changes in pH. This confirms that biochar obtained from animal manure exhibits higher nutrient levels than biochar from plant biomass and that these levels also depend on the type of pyrolysis used, as indicated by Beusch (2021). The concentrations of essential microelements (Mg, Cu, Ca, Zn) fall within the optimal ranges established by international biochar quality standards (IBI, 2023). However, the presence of heavy metals such as Cr (7.09 mg/kg) and Cd (1.05 mg/kg), although below the maximum permissible limits, requires continuous monitoring in long-term applications. Zhang et al. (2024) suggest that these elements can be stabilized in the biochar matrix through complexation and precipitation processes, reducing their bioavailability.

Proximal composition of guinea pig manure biochar

The values shown in Table 6 for ash were 34.6%. This condition allows greater nutrient availability when using biochar as an amendment. Although the high levels of ash could indicate a possible alteration of the physical structure of the biochar, it confirms that the biochar can clearly be used as a product with an alkalizing effect, representing an alternative for environmental remediation (Silva et al., 2024; Nunes et al., 2021). The amount of carbon obtained was 37.9%, confirming biochar's capacity to retain part of the carbon and preserve it in its molecular form (Iglesias-Abad et al., 2020; Dróżdż et al., 2023). Related studies characterizing 60 types of biomass converted into biochar show carbon values ranging from 26.61% to 53.26%, depending on the plant tissue used. The values obtained in this study are consistent with those reported by Trujillo et al. (2019).

The fixed carbon content [37.9% dry material (DM)] favored the formation of biochar with high resistance to degradation. In this context, Meng et al. (2024) reported that the application of manure-derived biochar consistently enhanced both labile and stable components of the carbon cycle, highlighting the potential benefits of this technology for environmental sustainability and agricultural systems. On average, manure-based biochar increased soil organic carbon (SOC) content by 50.5%. Biochar is a carbon-rich material, making it a sustainable alternative to activated carbon; its production therefore represents an effective carbon capture and storage strategy. Moreover, its physicochemical properties render biochar a valuable additive for multiple applications, including the biological treatment of organic waste (García-Prats et al., 2024).

FT-IR functional group analysis in manure and biochar

Figure 3 of the blue spectrum shows that the surface area of the manure contained C–H bonds with peaks in the region 850 to 897/cm, associated with vibrations of aromatic rings, oxygen-rich groups, and aromatic structures. These C–H bonds in the aromatic chains increased in the biochar at the 873/cm peak, similar to the observations reported by Huang et al. (2018) in sheep manure, rabbit feces, and pig manure biochars, all prepared by controlled thermal pyrolysis at 500°C. Near this region, the manure presented a large valley at 986/cm, still related to vibrations of alkene groups (unsaturated) or C–H heterocyclic rings, while the valley at 1,033/cm is associated with stretching of C–O bonds in the form of ethers or similar structures, since the region from 1,100 to 1,300/cm is characterized by the presence of C–O ether bonds. However, in biochar, the functional groups of the original raw material were

TABLE 5 Physicochemical characteristics of guinea pig manure.

pH	EC (dS/m)	CIC (meq/100 g)	OM (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)
9.17	17.28	48.8	62	1	4	3	5	1.7	1.3	4530	72	435	840	15.68	1.05	7.09

EC, electric conductivity; CIC, cation interchange capacity; OM, organic matter; N, nitrogen; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Na, sodium; Fe, iron; Cu, copper; Zn, zinc; Mn, manganese; Pb, lead; Cd, cadmium; mS/m, millisiemens per metro; meq/100 g, miliequivalent per 100 grams; mg/kg, milligrams per kilogram.

TABLE 6 Proximal composition of guinea pig manure.

Humidity (%)	Volatile material (% MS)	Ashes (% MS)	Carbon fix (%MS)
34.8	65.4	34.6	37.9

%MS, dry material percentage.

notably destroyed or reduced during pyrolysis at 500°C (red spectrum), removing heteroatoms and forming a more pronounced valley at 1,000/cm corresponding to aromatic structures of greater polarity (Guo et al., 2021). This effect was observed in the range of 897 to 1,645/cm.

Furthermore, the 1,033/cm peak indicated possible P–O stretching, as also reported by Scavo et al. (2022) for biochar produced from animal manure, which corresponded to the rich presence of P minerals observed in this study. It is important to mention that in the 1,645/cm region, stretching of C=O bonds typically occurs in carbonyl groups of carboxylic acids, amides, or ketones present in proteins and other organic components (Zanutel et al., 2024). Unlike manure, which presented C–H bonds (alcohols, ethers, carboxylic acids, and esters) in the 1,488–1,700/cm region, pyrolysis at 500°C caused the decomposition of these groups, resulting in a decrease in C–H and C–O bands and the formation of more stable structures such as C=C. Furthermore, the 3,630/cm region, characteristic of –OH groups and normally associated with the stretching vibration of nonalcoholic hydroxyl (–OH) groups, also decreased with increasing temperature. In manure, near 3,278/cm, phenolic –OH stretching of hydroxyl groups was observed, whereas in biochar, the signal decreased, attributable to the loss of the –OH groups. This change may be due to O–H vibrations of carboxylic acids, phenols, and alcohols (cellulose/lignin), while the vibrations at 2,920/cm correspond to the symmetric or asymmetric C–H stretching of methyl groups (Dilekoğlu, 2022; Ouyang et al., 2023).

Tolerance limit assay of guinea pig manure biochar on corn seedlings

Toxicity was based on the evaluation of plant mortality associated with the established biochar dose. The physical, chemical, and structural properties of biochar resulted in relatively high levels of both mortality and survival in corn seedlings. Biochar obtained from guinea pig manure tends toward alkalinity (Table 5); however, at high doses, seedling mortality increases, which is unfavorable for seed germination. The results related to radicle sprouting, embryonic gemmule growth, and seedling development are shown in Figure 4. The highest germination percentages were achieved with a LD_{50} of 40%, corresponding to 40 units of biochar per 100 units of soil, quantified by the volume reached in the beaker and mixed at a ratio of 40 solid biochar/100 solid soil. These results are consistent with those reported by Ahmad et al. (2022) in a systematic review of the physicochemical properties of biochar.

Although the determination of LD_{50} using the Probit model provides a clear threshold for acute toxicity, future studies should incorporate measurements of sublethal growth parameters, such as root length, seedling vigor, and biomass, to assess more subtle phytotoxic effects that may influence early crop establishment (Duó et al., 2010).

Biochar applied at a dose of 40% (as described above) showed no lethal effects on corn germination, but higher doses caused a 30% decrease in seedling emergence. These results are consistent with those of Ahmad et al. (2022), who reported adverse effects on cereal germination at high doses of alkaline biochar. Toxicity analysis revealed an LD_{50} of 40%, significantly higher than the 2%–5% range typically recommended for agricultural applications. This unusually high tolerance could be attributed to (1) the effective stabilization of potentially toxic compounds during pyrolysis, (2) the high buffering capacity of the material, which prevents abrupt changes in substrate pH, and (3) the presence of biostimulant compounds that counteract negative effects. However, considering the precautionary principle and the results of long-term studies (Ramírez-Zamora et al., 2022), it is recommended to limit application to a maximum of 30% for agricultural use.

Neutralizing capacity of biochar

The results shown in Figure 5 indicate that the greatest increases in soil pH occurred in acidic and neutral soils, consistent with the findings of García et al. (2021), who reported an increase in soil pH following biochar application when the initial pH was low. Biochar significantly increased the pH of acidic soils, reaching alkaline values (> 7) at an application rate of 7%, thereby confirming its liming effect (Figure 6). Its application in soils with neutral or alkaline pH may not be advisable,

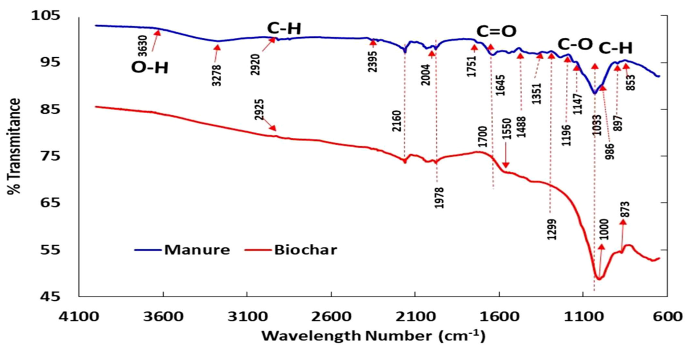

FIGURE 3
Infrared spectrum of present functional groups in the guinea pig manure and biochar from guinea pig manure.

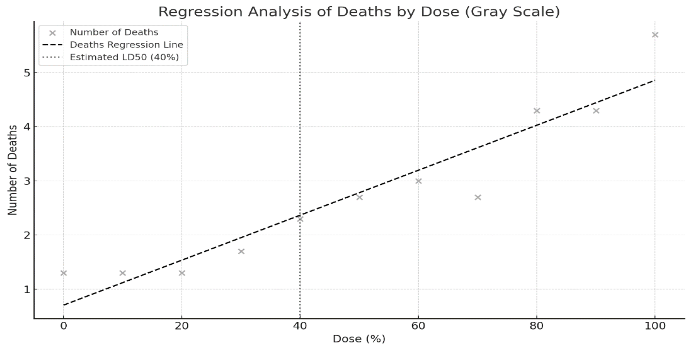

FIGURE 4
Corn seedling mortality.

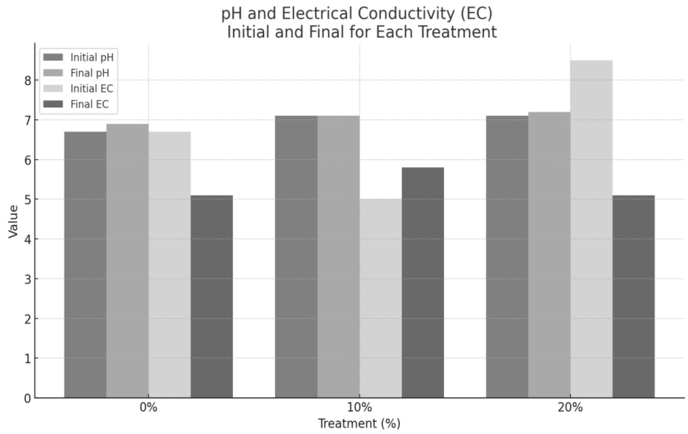

FIGURE 5
Measurement of pH and electrical conductivity at biochar doses of 0%, 10%, and 20%.

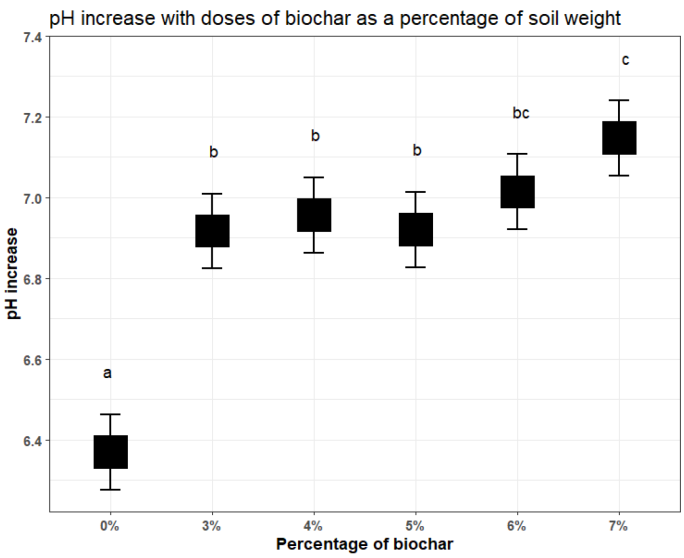

FIGURE 6
Soil pH evaluated at different biochar doses.

as it could lead to imbalances in nutrient availability. The 7% dose produced the greatest increase in pH, consistent with previous reports showing maximum neutralization efficiency between 5% and 8%. The mechanism of action involves (1) the initial release of carbonates and basic oxides, (2) the formation of organo-mineral complexes that increase the buffering capacity of the soil, and (3) the stimulation of microbial activity that favors alkalization. The results reveal a positive and significant effect of biochar dose on pH increase ($p < 0.05$).

TABLE 7 Comparative pH values in relation to biochar application rates.

Characteristic	Percentage of biochar					
	0%	3%	4%	5%	6%	7%
pH	0 (0) a	0.547 (0.025) b	0.587 (0.006) b	0.550 (0.026) b	0.643 (0.074) bc	0.777 (0.072) c

Different letters present significant differences using the Tukey test (P < 0.05).

The use of biochar at a rate of 7% showed the highest pH increase (Table 7) compared with the treatment without biochar. Bolan et al. (2023) reported that biochar is an effective soil amendment because it reduces acidity due to its liming potential. Singh et al. (2023) evaluated dynamic changes in soil pH in relation to the biochar dose and concluded that the addition of the amendment at a rate of 10 t/ha combined with 40 kg of N increased soil pH. They also noted that a higher dose of biochar in the absence of N fertilizer produces a greater increase in soil pH. Biochar derived from organic waste provides a source of carbon input to the soil and offers multifunctional benefits (Bolan et al., 2023). The alkalinity of biochar depends on the type of precursor material and the processing conditions.

Biochar can be alkaline in nature and can neutralize released protons, thereby reducing soil acidity. Soil acidification occurs due to an increase in protons (H^+) released from the transformation reactions of compounds containing carbon (C), N, and sulfur (S). Finally, Meng et al. (2021) noted that soil pH and EC are influenced by biochar (pyrolyzed at 600°C) due to a higher concentration of K^+ ions and a lower CEC. This effect results from the increase in exchangeable and soluble K^+ and the decrease in soil buffering capacity caused by the high rate of biochar application.

Many studies (Table 8) reported pH values ranging from 9 to 10 at a pyrolysis temperature of 300°C, with values exceeding 10 at 600°C. Similarly, EC values between 5 and 7.6 dS/m were observed at 300°C, while higher EC values, ranging from 6 to 9.2 dS/m, were reported at pyrolysis temperatures between 600°C and 700°C when animal manure was used as feedstock.

Table 9 represents the cost analysis of guinea pig manure. For this purpose, data reported by other authors and production values from the Santa Ana experimental station (INIA-Junín, Peru) were used, along with the production data of this species. The most important values considered were the cost of feed and the amount of manure produced by the guinea pig over 24 h. The price of feed was based on the cost of forage, balanced feed, or other inputs, depending on the type of breeding and/or production. In the research by Yamada et al. (2019), feeding expenses with balanced feed and forage were reported as S/. 1.61 per guinea pig until sale, also referred to as an achieved guinea pig. Considering the amount of manure produced per guinea pig, which is 230 g, the price of guinea pig manure per ton was calculated at S/. 83; Likewise, in the study by Cayetano (2019), higher feeding expenses were reported, with S/. 7.97 spent on balanced feed and forage per guinea pig until sale, resulting in a cost of S/. 409.5 per ton of guinea pig manure. Finally, at the Santa Ana Experimental Station, where guinea pigs are fed with green forage, the average feeding cost until sale was S/. 4.5, corresponding to a price of S/. 231.2 per ton of manure. In Table 7, a price increase of 30% was applied to estimate the real cost per kilogram of guinea pig manure, considering potential wholesale, taxes, or other future costs.

Meanwhile, Table 10 presents the cost analysis for producing biochar from guinea pig manure. The cost of fresh manure is a significant factor in this process. Regarding biochar production costs, values of S/. 662.7 were reported by Yamada et al. (2019), S/. 989.5 by Cayetano (2019), and S/. 811.2 based on experimental station data. These costs correspond to the use of fresh manure per ton until biochar was obtained. A 30% increase in cost per kilogram of biochar was then considered, reaching prices of S/. 2.87, S/. 4.29, and S/. 3.5/kg of biochar, respectively. Finally, the price per ton of biochar was subsequently calculated, resulting in costs of S/. 287, S/. 1.82, and S/. 4,287.94. In the experimental station, the cost per ton was estimated at S/. 3,515.3. In American currency, the estimated cost per ton of guinea pig manure biochar would be US$774.1 and US$1,155 based on the feeding systems used in the studies by Yamada et al. (2019) and Cayetano (2019), respectively, and US $947.5 for the experimental station. Costs vary depending on the type of material used to produce the biochar, as shown by Roy et al. (2024).

This last one produced biochar from a derivative of Miscanthus (a perennial herb), estimated at 513.1 Canadian dollars per ton. In this study, various components are included, such as the collection, harvesting, and transportation of Miscanthus, crushing to reduce

TABLE 8 pH and EC values of different types of biochar at varying pyrolysis temperatures.

Reference	Almutairi et al. (2023)				Keskinen et al. (2019)			de Oliveira et al. (2024)		Ali and Fahmi (2024)	
Material / properties	BEV				BEP			BEP		BEO	
Properties	Pyrolysis temperatura (°C)										
	300	400	500	600	350	400	450	300	750	300	700
pH	9	9.3	9.2	10	10	11	10	9.6	12	7.8	11
CE (dSm^{-1})	5	5.1	6.1	6	5.4	6.7	6.8	6.6	9.2	7.6	8.2

BEV, biochars derived from cattle manure; BEP, biochars derived from poultry manure; BEO, biochars derived from sheep manure.

TABLE 9 Comparison of guinea pig manure production in different locations.

Production cost of guinea pig manure		Yamada et al. (2019)	Cayetano (2019)	EEA Santa Ana- INIA
Description	Unit	Quantity	Quantity	Quantity
Time from feeding to market release	Days	110.00	110.00	110.00
Cost from feeding to market release (kg de carne)	S/.	1.61	7.97	4.50
Amount of manure (kg/Guinea pig)	Day	0.23	0.23	0.23
Total manure produced per guinea pig until market release	kg	25.3	25.3	25.3
Production cost of waste per kg	S/.	0.06	0.32	0.18
Calculated sale price (30% additional) per kg	S/.	0.08	0.41	0.23
Calculated price per ton of manure	S/.	82.73	409.53	231.23

the material to chips, and transportation costs within the process. In addition, it covers the cost of pyrolysis, which transforms Miscanthus into biochar, bio-oil, and noncondensable gas, as well as the necessary inputs, such as diesel to start the pyrolysis. A profit margin of 20% is also considered for the costs of each stage of the process. The production cost of biochar also depends on the system used. The Biochar Solutions Incorporated (BSI) costs US $745,000, and the air curtain burner (ACB) costs US$601,168. Costs include equipment, logistics, labor, maintenance, inputs (fuels, electricity), and palletization. The total cost and minimum selling price are US$1,674–1,909 for the BSI and US$528–1,051 for the ACB (Bergman et al., 2022). Finally, the biochar production cost includes fixed costs (equipment, vehicles, storage) of US $754.68/ton and variable costs (fuel, labor) of US$717.76/ton, adding up to a total of US$1,542.16/ton. The cost varies between US$448.78 and US$1,846.96/ton, depending on uncertain factors (Nematian et al., 2021). Although economic análisis was not a primary objective of the study, the calculated production costs (US $1,990.23/ton) are competitive, considering the high added value of the product. Wang et al. (2023) have reported similar costs for semi-industrial production systems, suggesting the economic viability of the process.

Guinea pig manure: a circular solution for acidic soils

Despite the negative impact of the COVID-19 pandemic, Peru has made efforts to increase guinea pig meat production. Genetic improvement of the species by INEI has strengthened the local market in the five regions with the largest populations, including Cajamarca (18.9%), Cusco (13.6%), Ancash (12.9%), Apurímac (7.9%), and Junín (7.6%) (MIDAGRI, 2023). Its entry into the international market, considering that slaughtered guinea pigs can cost between $30 and $80 (MIDAGRI, 2023), highlights the need for Peruvian export companies to improve supply chain management and waste utilization. However, this initiative must reach the most disadvantaged communities and small entrepreneurs, especially considering that Peruvian guinea pig meat production grew by

TABLE 10 Comparison of the cost of producing biochar from guinea pig manure in different locations.

Producing cost of biochar from guinea pig manure		Yamada et al. (2019)	Cayetano (2019)	EEA Santa Ana- INIA
Description	Unit	Quantity	Quantity	Quantity
Cost of one ton of fresh guinea pig manure	S/.	82.73	409.53	231.23
Operator - Screening, drying, collection, and packaging (1 ton)	Unidad	500.00	500.00	500.00
Energy (Pyrolytic oven) (1 ton)	S/.	80.00	80.00	80.00
Total, production cost		662.73	989.53	811.23
Biochar obtained (30%)	kg	300.00	300.00	300.00
Cost of guinea pig manure biochar per kg	S/.	2.21	3.30	2.70
Estimated sale price (30% additional) per kg of biochar	S/.	2.87	4.29	3.52
Sale price of total biochar production		861.55	1286.38	1054.59
Cost of wood charcoal per kg	S/.	6.00	6.00	6.00
Cost of wood charcoal 300 kg	kg	1800.00	1800.00	1800.00
Difference between guinea pig manure biochar and wood charcoal per kg	S/.	3.13	1.71	2.48
Difference between guinea pig manure biochar and wood charcoal per 300 kg	S/.	938.45	513.62	745.41
Cost per 1 ton of biochar	S/.	2871.82	4287.94	3515.31

183% in 2024. More comprehensive and inclusive agricultural policies are needed to support these developments.

In this context, it is important to identify the actors involved in the supply chain and those leading the way toward sustainable use: individual producers and associations/cooperatives, input suppliers (seeds, fodder, medicines), agricultural and veterinary technicians, food processors, marketers, intermediaries and retailers, restaurants and catering companies, public institutions (INIA, SENASA, regional governments), and universities and research centers. Figure 7 presents a comprehensive circularity based on the role of each actor. The practical inclusion of thermochemical conversion of waste into biochar to produce a soil quality improver, especially for acidic soils, contributes to environmental sustainability (Ali et al., 2025). This approach improves crop quality by enhancing the efficiency of agricultural waste, including guinea pig manure, which in turn promotes a reduction in Greenhouse Gases (GHG) emissions.

In this way, small-scale pyrolysis pilot modules are favorable near areas of guinea pig production, particularly in the high Andean regions and parts of the high jungle. Greater integration is needed among knowledge management actors, research centers, universities, and NGOs to expand training for guinea pig producers and agricultural technicians in the production and use of biochar. INEI is leading this process and needs to broaden its coverage through collaborative work with universities and civil society. Introducing the circular economy approach into agricultural and nutritional management systems is important (Roy et al., 2024). This also involves developing technical protocols for the application of biochar in crop soils that are particularly sensitive to acidity. Peru has a significant production of potatoes, coffee, and citrus fruits. Depending on the type of soil, the optimal dose must be established, which requires expanding research aimed at improving productivity and food security through soil conservation.

Incentives for rural development policies, including subsidies or public–private partnerships, will be necessary to implement manure valorization technologies with potential applications in other types of livestock farming that are expanding in the country. However, integrating this proposal within a portfolio of national strategies for sustainable agriculture and climate change mitigation is crucial, as it will enable the fulfillment of commitments to reduce GHG emissions and adapt to climate change. The development of biochar systems is a long-term challenge due to their complexity; while initial funding and international experience are important at the outset, education, awareness, and consistent practice are key to maintaining sustainability (Fridahl et al., 2021).

Conclusion

The economy based on the guinea pig production value chain is promising, given its growing productivity, which is increasing local, regional, and international consumption. The generation of waste, such as guinea pig manure, represents potential for a circular and sustainable economy. Using guinea pig manure as a precursor for biochar production is a strategic opportunity, as this practice not

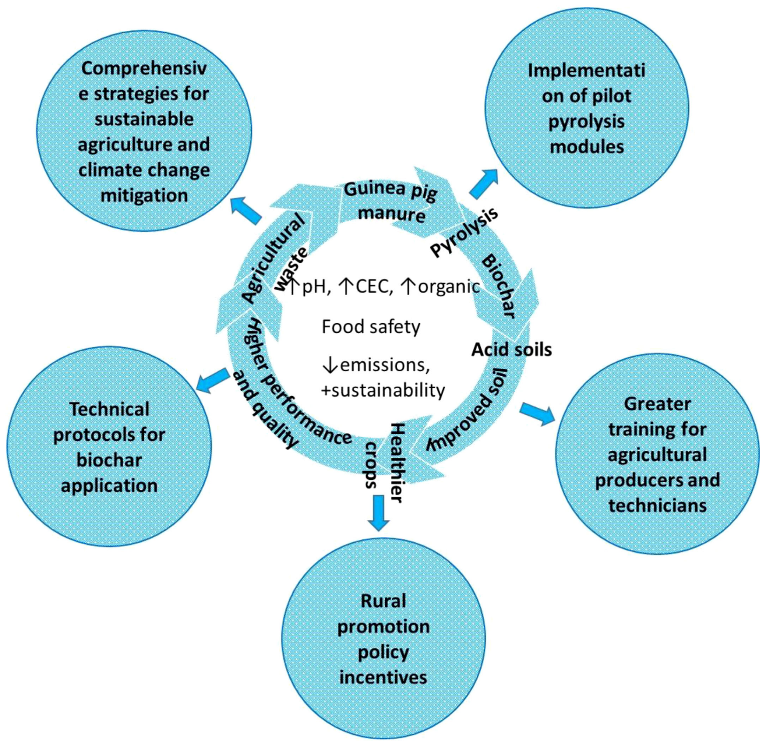

FIGURE 7
Relevant factors in the development of the circular economy in the transformation of guinea pig manure into biochar for the restoration of acidic soils.

only allows valorization of an underutilized agricultural waste but also represents an ecological alternative that significantly improves soil quality, enhances carbon sequestration, and supports the sustainability of agricultural systems—primarily in high Andean areas, where guinea pig farming is traditional and widespread, and even in coastal soils.

Biochar serves as an amendment that, at appropriate doses, is convenient and nontoxic. This research demonstrated that guinea pig manure biochar has an LD_{50} of 40%. However, within the probability of finding plants with no signs of toxicity, doses ranging from 0% to 30% mixed with the substrate are safe. Regarding nutrient content, manure biochar stood out for its high levels of Mn, Mg, Cu, Ca, Zn, and Na. The fixed carbon content (37.9% DM) obtained in this study indicates a substantial proportion of potentially stable carbon, favoring the formation of biochar with high resistance to degradation. Guinea pig manure biochar has a salt concentration that gives it a significant CEC (48.8 meq/100 g) and an EC of 17.28 dS/m, making it suitable for agriculture. The neutralizing capacity of guinea pig manure biochar is manifested as an increase in soil alkalinity with increasing dose. This effect is more pronounced at low doses than at higher ones. The application of biochar is therefore more effective in improving alkalinity in soils with an acidic tendency than in soils with an alkaline tendency.

However, implementation requires the development of sustainable value chains based on agricultural waste, through economic incentives, training programs, and support schemes for applied research. Peru presents a unique opportunity to lead rural circularity models by leveraging local resources such as guinea pig manure; achieving this requires multisectoral coordination that integrates innovation, inclusive policies, and community participation to overcome existing barriers and transform this waste into a model for other types of agricultural/agroforestry residues.

Data availability statement

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

Author contributions

RS: Writing – review & editing, Methodology, Writing – original draft, Funding acquisition, Conceptualization, Investigation, Resources, Data curation, Project administration. LD: Writing – original draft, Investigation, Resources, Validation, Methodology. SH: Data curation, Writing – review & editing, Validation, Visualization, Software. RP-G: Project administration, Writing – review & editing, Supervision, Resources, Investigation. RC-T: Software, Visualization, Data curation, Project administration, Writing – review & editing. CP-C: Investigation, Writing – original draft, Methodology, Visualization, Formal analysis. AA: Supervision, Writing – original draft, Investigation, Visualization. AC: Investigation, Methodology, Formal analysis, Visualization, Writing – original draft. GV-T: Formal analysis, Methodology, Visualization, Conceptualization, Writing – review & editing.

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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.

Correction note

A correction has been made to this article. Details can be found at: 10.3389/fagro.2026.1824018.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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