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Biochar enhances the use efficiency of *guano de isla* and could boost profitability and food security for smallholders in the global south

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Abstract

Guano de isla (seabird guano) is a strategic organic fertilizer in Peru, reserved primarily for economically vulnerable smallholder farmers. However, its availability is declining due to ecological pressures on seabird populations, creating an urgent need to improve its use efficiency. This study tested the hypothesis that biochar can enhance the nutrient use efficiency of guano de isla, allowing reduced application rates without compromising yield or profitability. A randomized complete block experiment (n = 10 replicates per treatment) was conducted in sandy soil in Lurín, Peru, to evaluate lettuce (Lactuca sativa) yield under eight fertilization treatments, including inorganic fertilizer (NPK), guano de isla (400 kg ha^{-1}), biochar (3 t ha^{-1}), and combinations thereof. The biochar + guano de isla (BG) treatment applied 200 kg ha^{-1} of guano de isla (50% of the standard rate). Economic viability was assessed using the value/cost ratio (VCR) under conventional and organic market scenarios, with and without carbon credits. The highest lettuce yields were obtained in the full-rate guano de isla (G) and biochar + guano de isla (BG) treatments, representing a 40% increase compared to the control. Importantly, the BG treatment achieved statistically equivalent yields to the full-rate guano de isla treatment while using 50% less guano de isla. Under conventional market conditions, all treatments resulted in VCR values < 1. However, under organic market conditions, the G, BG, and biochar treatments exceeded the profitability threshold (VCR > 2), with the BG treatment reaching a maximum VCR of 12.9 when carbon credits were included. These findings demonstrate that biochar can significantly enhance the use efficiency of guano de isla in sandy soils, allowing reduced application rates while maintaining productivity. Integrating biochar with guano de isla could help conserve a strategic national fertilizer resource, improve farm profitability, and strengthen food security for smallholder farmers in the Global South.

Highlights

- Biochar significantly increases the use of efficiency of guano de isla, a strategic organic resource reserved for economically vulnerable farmers in Peru.
- By combining guano de isla with biochar, it is possible to reduce the application rate of guano de isla by 50% without compromising yield or food security.

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- Alternatively, biochar could be used to double the effective supply of guano de Isla in Peru.

Keywords Small holder farming, Guano de isla, Biochar, Fertilizer use efficiency, Value/cost ratio

1 Introduction

Biochar is a promising amendment for enhancing the nutrient use efficiency of organic fertilizers such as guano de isla. Its highly porous structure, large specific surface area, and variable surface charge contribute to substantial increases in soil cation exchange capacity (CEC), thereby improving the retention of ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and other nutrient cations that are prone to leaching [11, 20, 32]. Several recent reviews have emphasized the growing importance of biochar as a multifunctional amendment capable of improving soil fertility, nutrient retention, and crop productivity in sustainable agricultural systems [1, 6, 51]. Biochar surfaces also contain functional groups capable of adsorbing both organic and inorganic nitrogen forms, moderating nutrient release dynamics and reducing losses through leaching and volatilization [18, 31]. These processes are particularly relevant in sandy soils, which are typically characterized by low organic matter content, low CEC, and high permeability, conditions that promote rapid nutrient loss and reduce fertilizer use efficiency [9, 35].

Beyond its chemical sorption properties, biochar improves soil physical structure by enhancing aggregation and increasing water-holding capacity, which can mitigate drought stress and facilitate sustained nutrient uptake [2, 33]. Additionally, biochar provides microhabitats that support beneficial soil microbial communities involved in nitrogen mineralization, nitrification, and nutrient cycling [32, 55]. Biochar has also demonstrated considerable potential for remediating agricultural soils contaminated with emerging pollutants and improving long-term soil ecological functioning [24, 49]. Meta-analyses indicate that these combined physical, chemical, and biological mechanisms frequently translate into increased crop yield and improved nutrient use efficiency when biochar is integrated with organic or mineral fertilizers [11, 26, 27]. Collectively, these mechanisms suggest that integrating biochar with guano de isla could reduce nutrient losses, enhance fertilizer use efficiency, and sustain crop productivity even at reduced application rates, particularly in sandy soils vulnerable to nutrient depletion.

Global food security increasingly depends on sustainable intensification strategies capable of maintaining productivity while reducing environmental degradation [21]. This challenge is particularly important for smallholder farmers in economically vulnerable regions who are highly exposed to climate variability and environmental shocks [23, 38, 54]. In Peru and other countries of the Global South, organic fertilization strategies are especially relevant because rising fertilizer prices continue to threaten agricultural profitability and food production systems [8, 48, 52].

Historically, guano de isla has been recognized as one of the most valuable natural fertilizers due to its exceptionally high nutrient concentration and strategic role in Peruvian agriculture [13, 19, 45]. The economic and social importance of guano de isla remains substantial for Peru's agricultural sector, particularly for smallholder farmers who depend on subsidized access to this resource through national agricultural programs [3], 36). However, the dramatic decline in seabird populations caused by avian influenza outbreaks and climatic disturbances now threatens long-term guano availability [12, 16, 22].

Sandy soils were selected for this study because they represent a highly vulnerable and agronomically challenging soil type, particularly in arid coastal regions such as the pacific coast of Peru. These soils are typically characterized by low organic matter content, low cation exchange capacity (CEC), and high hydraulic conductivity, conditions that promote rapid nutrient leaching and reduce fertilizer use efficiency [14, 20]. Similar benefits of biochar amendments in Mediterranean and semi-arid ecosystems have been previously documented by Alonso-Gómez et al. [7]. Nitrogen, especially in nitrate form, is highly mobile in coarse-textured soils and is therefore prone to leaching beyond the root zone, resulting in reduced crop uptake efficiency and increased economic losses [11, 15, 18]. In addition, the limited water-holding capacity of sandy soils can constrain root development and nutrient acquisition under water-limited conditions [14]. Evaluating the integration of biochar with guano de isla under these conditions provides a stringent test of whether biochar can enhance nutrient retention and improve fertilizer efficiency in soils where nutrient losses are expected to be greatest. Demonstrating effectiveness in sandy soils therefore strengthens the practical relevance of this strategy for smallholder farming systems in arid and semi-arid regions Fig. 1.

2 Materials and methods

2.1 Study area

The experiment was conducted in Lurin, Lima, between January and February 2025. The climate is hyper arid, and soils are sandy. The warmest months are December to April, when average temperature is 24–26 °C. Monthly precipitation does not exceed 5 mm per month and is often closer to zero ([46].

2.2 Experimental design

Eight experimental treatments were established using a randomized complete block design, each replicated ten times (Fig. 2). Each experimental replicate contained six lettuce plants (Lactuca sativa) spaced 55 cm apart. The lettuce seedlings were transplanted into the experimental plot two weeks after sowing in cultivation trays. Irrigation was applied every four days, and weed control was performed during the third week following crop establishment. Harvest took place in the fifth week, during which the foliar



Fig. 1 **A**) Bags of guano de isla ready for distribution, **B**) Overview of a guano de isla Island, **C**) Workers harvesting guano de isla



Fig. 2 **A**) Overview of the experiment field in early January 2025 immediately after the beginning of the experiment, and **B**) Overview of the experiment in late January 2025 just prior to harvest and completion of the experiment

portion of the plants (the commercially valuable portion of the plant) was collected and weighed to determine yield. The treatments were:

1. Control (C): No fertilizer
2. Chemical fertilizer (NPK): Inorganic NPC (20–20-20)
3. *Guano de isla* (G)
4. Biochar (BCH)
5. Biomax (BMX): A microbiological soil amendment
6. Biochar + Biomax (BB)
7. Biochar + *Guano de isla* (BG)
8. Biochar + Biomax + *Guano de isla* (BBG)

Each experimental replicate was established in a furrow established using 54 kg of compost (Figs. 2 and 3) supplied by the municipality of Lurin. Fertilizer application rates for each treatment are detailed in Table 1.

The Chemical Fertilizer, and Biomax, were purchased from the local market, while Biochar was obtained from a local biochar producer (www.inkannegro.com) and Guano de Isla was provided by the government institution AgroRural.

The biochar used in this study was produced from municipal green waste. The feedstock consisted primarily of woody pruning residues from urban trees and park maintenance, including eucalyptus (Eucalyptus spp.) and other mixed hardwood species. The chemical properties of the biochar are described in Table 2

The biochar was applied at the rates specified in Table 1 and mixed uniformly into the topsoil of each treatment plot.

2.3 Economic analysis

To assess economic viability of the experimental treatments, the value/cost ratio (VCR) was calculated using the methodology of Roy et al. [44] and Kihara et al. [29]:

$$\mathrm{VCR} = \frac{(\text{yield of amended soil [kg]} \; - \; \text{yield of control [kg]}) \; \star \; \text{price of lettuce (kg)}}{\text{Cost of applied amended (per kilogramo)}}$$

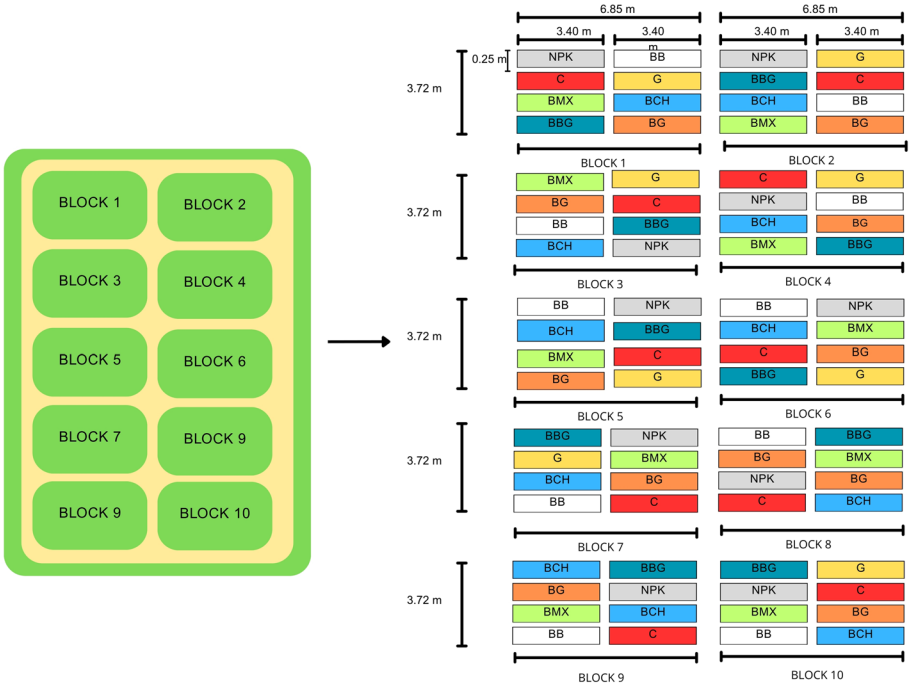


Fig. 3 Distribution of fertilizers combinations by plot for the cultivation of lettuce (*Lactuca sativa*). Color codes: red – Control (C); light blue – Biochar (BCH); green – Biomax (BMX); yellow – Guano de isla (G); gray – Inorganic fertilizer (NPK); white – Biochar and Biomax (BB); orange – Biochar and Guano de isla (BG); dark blue – Biochar, Biomax, and Guano de isla (BBG)

Table 1 Fertilizer dose for each treatment in the randomized complete block experiment. Biomax is a microbiological soil amendment proposed to increase nutrient cycling

Treatment	Dose			
	NPK (20–20-20)	Biochar	Biomax	Guano de isla
Control (C)				
Chemical fertilizer (NPK)	100 kg/ha			
Guano de isla (G)				400 kg/ha
Biochar (BCH)		3 tn/ha		
Biomax (BMX)			500 kg/ha	
Biochar + Biomax (BB)		1 tn/ha	500 kg/ha	
Biochar + *Guano de isla* (BG)		1 tn/ha		200 kg/ha
Biochar + Biomax + Guano de isla (BBG)		1 tn/ha	500 kg/ha	200 kg/ha

A VCR < 1 indicates a financial loss, a VCR between 1 and 2 indicates a net return where costs are recovered, and a VCR > 2 indicates that the investment is fully recovered with at least 100% return.

Four scenarios were considered to evaluate profitability, considering conventional vs. organic markets based on local market prices and the potential for carbon credits to defray the costs of producing biochar (Table 2). Treatments including Biomax were excluded from this analysis as they showed no significant impact on yield.

For the prices of biochar and NPK fertilizers, the local market was used as the reference. In the case of Guano de Isla, the reference price corresponded to the rate at which the state supplies it to small-scale farmers (Table 3) [4].

Table 2 Selected physicochemical properties of the biochar used in the experiment

Property	Value
pH	9.67
Electrical conductivity	7.21 dS m^{-1}
Organic carbon	71.5%
Total nitrogen	0.91%
C:N ratio	78.3
Ash content	17.2%
Calcium (Ca)	2.32%
Potassium (K)	2.64%
Magnesium (Mg)	0.40%
Phosphorus (P)	0.36%
Iron (Fe)	5720 mg kg^{-1}
Manganese (Mn)	165 mg kg^{-1}
Zinc (Zn)	142 mg kg^{-1}
Copper (Cu)	40 mg kg^{-1}
Bulk density	0.22 kg L^{-1}
Moisture content	9.4%

Table 3 Soil amendments prices

Fertilizer	Cost of fertilizer x Tn ($)
NPK	1570
BCH	285
G	285

As a reference, an exchange rate of USD 1 = PEN 3.5 was used. Treatment abbreviations: Chemical fertilizer (NPK), Guano de isla (G), Biochar (BCH)

2.4 Statistical analysis

The fresh weight of the lettuce plants was measured and compared across treatments. Data normality and homogeneity of variances were confirmed using the Kolmogorov-Smirnov and Levene's tests, respectively ($p > 0.05$). A one-way analysis of variance (ANOVA) was performed, followed by Dunnett's post-hoc test for mean comparisons when significant differences via ANOVA were found ($p<0.05$). All analyses were conducted using GraphPad Prism 5.

3 Results

3.1 Yield

The highest average lettuce weights were recorded in the *Guano de isla* (G) and the Biochar + *Guano de isla* (BG) treatments, with no significant statistical difference between them (Fig. 4, $p < 0.05$). These were followed by the biochar treatments (BBG, BB, BCH), and NKP treatments, which also showed no significant differences among themselves. The Control (C) and Biomax (BMX) treatments produced the lowest yields. Notably the BG treatment (that combined biochar with guano de isla) achieved a comparable yield to the pure guano de isla treatment (G) while using only half the dose of *guano de isla*. The microbiological amendment, Biomax (BMX), had no discernible effect on lettuce fresh weight.

3.2 Economic value

The economic analysis, based on the value/cost ratio (VCR), is presented in Table 4. Under conventional market prices (Scenarios S1 and S2), all fertilization treatments

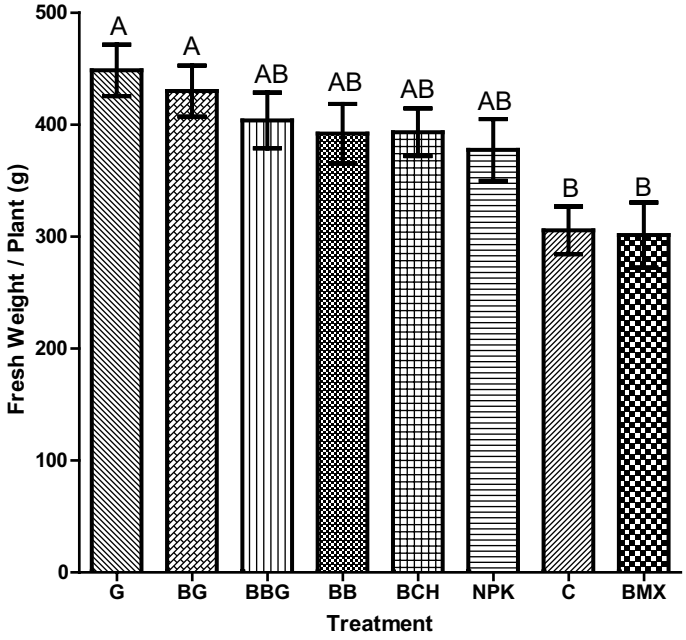


Fig. 4 Average lettuce weight per treatment. The combination of Biochar and guano de isla (BG) produced a yield statistically equivalent to the full-dose guano de isla (G) treatment. Different letters above the bars indicate significant differences ($p < 0.05$) between treatments. Treatment abbreviations: Control (C), chemical fertilizer (NPK), Guano de isla (G), Biochar (BCH), Biomax (BMX), Biochar + Biomax (BB), Biochar + Guano de isla (BG), Biochar + Biomax + Guano de isla (BBG)

Table 4 Scenarios for the economic (value cost ratio, VCR) assessment of lettuce cultivation

System	Scenario	Description
Conventional Agriculture	S1	conventional market prices, without carbon credits.
	S2	conventional market prices, with biochar production cost offset by carbon credits.
Organic Agriculture	S3	organic market prices, without carbon credits.
	S4	organic market prices, with biochar production cost offset by carbon credits.

yielded VCR values below the profitability threshold of 1, indicating they are not economically viable.

However, when evaluated using organic market prices (Scenarios S3 and S4), the VCR for the Biochar (BCH), Biochar + *Guano de isla* (BG), and *Guano de isla* (G) treatments surpassed the profitability threshold of 2. This indicates that the investment is fully recovered with a significant return. The highest VCR was achieved in the Biochar + Guano de isla (BG) treatment under Scenario S4, where organic market prices are combined with biochar and biochar production costs are offset with carbon credits. In contrast, the NPK treatment remained the least profitable option across all scenarios.

To offset the production cost of biochar, the global carbon-credit market for biochar was used as a reference, using the carbon dioxide removal certificate (CORC) (Puro. earth, 2025). In a scenario where access to carbon-credit sales is possible, the production cost of biochar would be nullified Table 5.

Table 5 Economic assessment (Value/Cost Ratio – VCR) of fertilizer treatments on lettuce

Treatment	S1	S2	S3	S4
NPK	0.01			
Biochar (BCH)	0.09		1.76	
Guano de isla (G)	0.41		7.25	
Biochar + Guano de isla (BG)	0.12	0.73	2.15	12.9

S1: Conventional market, no carbon credits. S2: Conventional market, with carbon credits. S3: Organic market, no carbon credits. S4: Organic market, with carbon credits

4 Discussion

4.1 Effect on yield and nutrient use efficiency

Our findings demonstrate that combining biochar with *guano de isla* maintains high crop yields while significantly reducing the requirement for guano de isla. An equivalent lettuce yield was possible with 50% less guano. This improvement in nutrient use efficiency is consistent with previous studies [11, 20, 25, 26, 47], which demonstrate that biochar enhances the physical and chemical properties of soil, increasing nutrient retention and availability for plants [20]. While the initial benefits of biochar can be moderate, long-term application improves soil structure, creating a more favorable environment for root development and efficient nutrient absorption [20], leading to sustained or increased yields over time [28]. Increased benefits from combining and co application of guano de isla and biochar over time is therefore a realistic expectation. Similar circular bioeconomy approaches involving biochar have also been proposed for improving sustainability and reducing agricultural carbon footprints in coffee production systems [30].

4.2 Implications for food security and resource conservation

This strategy is particularly relevant given the current ecological crisis affecting guano-producing seabirds. The dramatic decline in seabird populations along the Peruvian coast, driven by the H5N1 avian influenza and a strong El Niño event, has severely impacted seabird colonies [22, 43]. Guano-producing seabird numbers fell from 4 million in December 2022 to around 0.65 million in March 2025 [4]. Previous ecological studies on guano extraction systems in Peru have already highlighted the vulnerability of seabird reproductive dynamics and the need for sustainable management practices [53]. Consequently, guano production is expected to decrease dramatically, threatening the availability of this critical resource for thousands of small-scale organic farming families who depend on it.

Wile current demand is being met by reserves accumulated before the population collapse of seabirds, these stockpiles are finite. Without recovery of seabird populations, long-term shortages are inevitable. In this context, biochar serves as a viable complementary amendment that can augment the effective supply of limited guano supplies. By integrating biochar into standard fertilization practices, farmers can increase resilience and sustainability mitigating the risk of projected guano shortages, thereby safeguarding agricultural productivity and food security in vulnerable communities.h

Moreover, the production of biochar facilitates the conversion of biomass residues into a high-quality substrate using a methodology that is cost-effective, straightforward, and produces minimal emissions. This makes biochar an ideal solution for smallholder farmers in low- and middle-income countries, particularly in the Global South, where technical expertise and financial resources may be constrained [39]. Low-technology biochar

production systems have also been identified as potentially powerful nature-based climate solutions in developing regions [10]x.

4.3 Economic relevance

The VCR analysis underscores the critical role of market access in the adoption of sustainable farming practices [40]. Under conventional market prices, none of the evaluated amendments were economically viable, offering no incentive for adoption by smallholder farmers. However, when selling into the organic market, where lettuce can fetch significantly higher prices, the investment in organic amendments becomes profitable. This trend is consistent with previous findings demonstrating the long-term financial competitiveness of organic farming systems [17, 34]. In addition, excessive dependence on synthetic fertilizers may contribute to environmental degradation and biodiversity losses in agricultural soils [50].

The G, BG, and BCH treatments all showed a VCR greater than 2 in the organic scenario (S3), indicating a return of over 100% on the investment. The most compelling case is the BG treatment in scenario S4, where the combination of an organic price premium and carbon credits for biochar results in an exceptionally high VCR of 12.9. This demonstrates that organic farming systems supported by mechanisms such as the carbon market can create strong economic incentives for smallholder farmers to adopt practices that are both productive and environmentally beneficial, supporting the idea of the economic potential of using biochar in agriculture [5, 37, 41, 4642 and].

5 Conclusion

This study demonstrates that the addition of biochar to guano de isla allows for a 50% reduction in the application of this strategic fertilizer without compromising lettuce yield. Furthermore, our economic analysis reveals that the combination of biochar and *guano de isla* delivers the highest economic return when sold in the organic market, particularly when the cost of biochar is offset by carbon credits. These findings support the conclusion that combining biochar and guano de isla is a highly effective and economically sound strategy for smallholder farmers. It could promote the conservation of a vital natural resource, enhance farm profitability, and strengthen food security for economically vulnerable communities. Future research should evaluate the long-term effects of this fertilization strategy on soil health and efficacy in other crops commonly cultivated by small-holder farmers.

Supplementary Information

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Supplementary material 1

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Author contributions
Sandro Esteban Lukuy Espejo, contributed to the experimental design, the implementation of the experiment, and the writing of the first and final drafts of the manuscript. *Roberto Carlos Cosme De La Cruz, contributed to the experimental design, lab analyses, and the writing of the first and final drafts of the manuscript.* *Ursula Loret de Mola León* performed critical revision of the manuscript, resolved all raised observations and comments, and ensured the final document's consistency and coherence *and contributed to the writing of the final draft of the manuscript.* *Jean Luc Martin Carruitero, contributed to the experimental design, the implementation of the experiment, and the writing of the first and final drafts of the manuscript.* *Carlos Zavalaga* contributed through critical review of the manuscript and

provided substantive input to the Discussion section regarding implications for food security and resource conservation. *Brenton Ladd, procured funding, contributed to the experimental design and the writing of the first and final drafts of the manuscript.*

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Data availability
All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Adhikari S, Moon E, Paz-Ferreiro J, Timms W. Comparative analysis of biochar carbon stability methods and implications for carbon credits. Sci Total Environ. 2024;914:169607. https://doi.org/10.1016/j.scitotenv.2023.169607.
2. Agegnehu G, Bass AM, Nelson PN, Bird MI. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Sci Total Environ. 2017;543:295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054.
3. Agrorural. Plan anual de comercialización 2024. Agrorural; 2024. https://cdn.www.gob.pe/uploads/document/file/6147020/5427900-rde-n-138-2024-de-plan-anual-de-comercializacion-del-guano-de-las-islas_compressed.pdf?v=1712272572
4. Agrorural. Plan anual de comercialización 2025. Agrorural; 2025. https://www.gob.pe/institucion/agrorural/normas-legales/6763323-113-2025-midagri-dvdafir-agro-rural-de
5. Aisosa B, Oziegbe O, Olawole O. Significance of biochar application to the environment and economy. Ann Agric Sci. 2019;64(2):222–36. https://doi.org/10.1016/j.aoas.2019.12.006.
6. Allohverdi T, Mohanty AK, Roy P, Misra M. A review on current status of biochar uses in agriculture. Molecules. 2021;26(18):5584. https://doi.org/10.3390/molecules26185584.
7. Alonso-Gómez V, Ledesma P, Omondi EO, Lores M, Taggart MA. Biochar as a soil amendment to improve the soil quality of a Mediterranean ecosystem. J Anal Appl Pyrolysis. 2016;122:268–75.
8. Alvarez S. The economics of organic farming. In: Organic farming for sustainable agriculture. Singapore: Springer; 2021. p. 395–408.
9. Anas M, Liao F, Verma KK, Sarwar MA, Mahmood A, Chen Z-L, et al. Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. Biol Res. 2020;53:47. https://doi.org/10.1186/s40659-020-00312-4.
10. Aquije C, Schmidt HP, Draper K, Joseph S, Ladd B. Low tech biochar production could be a highly effective nature-based solution for climate change mitigation in the developing world. Plant Soil. 2022;479(1):77–83. https://doi.org/10.1007/s11104-021-05159-6.
11. Bai SH, Omidvar N, Gallart M, Kämper W, Tahmasbian I, Farrar MB, et al. Combined effects of biochar and fertilizer applications on yield: a review and meta-analysis. Sci Total Environ. 2022;808:152073. https://doi.org/10.1016/j.scitotenv.2021.152073.
12. Blagodatski A, Trutneva K, Glazova O, Mityaeva O, Shevkova L, Kegeles E, et al. Avian influenza in wild birds and poultry: Dissemination pathways, monitoring methods, and virus ecology. Pathogens. 2021. https://doi.org/10.3390/pathogens10050630.
13. Bonilla H. Guano y burguesía en el Perú. Instituto de Estudios Peruanos (IEP); 1974. https://hdl.handle.net/20.500.14660/671
14. Brady NC, Weil RR. The nature and properties of soils. 15th ed. Pearson; 2017.
15. Campos-Astupina C, Loret de Mola-Leon U, Brenton L. Influencia del biocarbón en la disponibilidad de nitrógeno del suelo y el rendimiento de maíz en un Leptosol hiperárido de la costa del Pacífico peruano. South Sustainability. 2025;6(2):e131.
16. Collave L. El impacto de la gripe aviar en las poblaciones de aves guaneras en la costa peruana. Rev Ornitol Peru. 2024;12(1):45–58. https://doi.org/10.1016/j.jclepro.2017.08.086.
17. Crowder DW, Reganold JP. Financial competitiveness of organic agriculture on a global scale. Proc Natl Acad Sci U S A. 2015;112(24):7611–6. https://doi.org/10.1073/pnas.1423674112.
18. Clough TJ, Condron LM. Biochar and the nitrogen cycle: introduction. J Environ Qual. 2010;39(4):1218–23. https://doi.org/10.2134/jeq2010.0204.
19. Cushman GT. Guano and the opening of the Pacific World: A global ecological history. Cambridge University Press; 2013.
20. Ding Y, Liu Y, Liu S, Li Z, Tan X, Huang X, et al. Biochar to improve soil fertility. A review. Agron Sustain Dev. 2016;36(2):36. https://doi.org/10.1007/s13593-016-0372-z.

21. FAO. World food and agriculture – statistical yearbook 2021. Food and Agriculture Organization of the United Nations; 2021. https://doi.org/10.4060/cb4477en.
22. Gamarra-Toledo V, et al. Mass mortality of seabirds along the Peruvian coast linked to HPAI H5N1 outbreak. Avian Dis. 2023;67(2):230–9. https://doi.org/10.3201/eid2912.230192.
23. Guido Z, Knudson C, Finan T, Madajewicz M, Rhiney K. Shocks and cherries: the production of vulnerability among smallholder coffee farmers in Jamaica. World Dev. 2020;132:104979. https://doi.org/10.1016/j.worlddev.2020.104979.
24. Hou R, Zhang J, Fu Q, Li T, Gao S, Wang R, et al. The boom era of emerging contaminants: a review of remediating agricultural soils by biochar. Sci Total Environ. 2024;931:172899. https://doi.org/10.1016/j.scitotenv.2024.172899.
25. Hussain A, Ahmad M, Mumtaz MZ, Nazli F, Farooqi MA, Khalid I, et al. Impact of integrated use of enriched compost, biochar, humic acid and Alcaligenes sp AZ9 on maize productivity and soil biological attributes in natural field conditions. Italian J Agronomy. 2019;14(2):1413.
26. Jaufmann E, Schmid H, Hülsbergen KJ. Effects of biochar in combination with cattle slurry and mineral nitrogen on crop yield and nitrogen use efficiency in a three-year field experiment. Eur J Agron. 2024;156:127168. https://doi.org/10.1016/j.eja.2024.127168.
27. Jeffery S, Verheijen FGA, van der Velde M, Bastos AC. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ. 2011;144(1):175–87. https://doi.org/10.1016/j.agee.2011.08.015.
28. Jiang Y, Li T, Xu X, Sun J, Pan G, Cheng K. A global assessment of the long-term effects of biochar application on crop yield. Current R in Environ Sustainability. 2024;7:100247. https://doi.org/10.1016/j.crsust.2024.100247.
29. Kihara J, Huising J, Nziguheba G, Waswa BS, Njoroge S, Kabambe V, et al. Maize response to macronutrients and potential for profitability in sub-Saharan Africa. Nutrient Cycl Agroecosyst. 2016;105(3):171–81. https://doi.org/10.1007/s10705-015-9717-2.
30. Ladd B, Cornelissen G, Sørmo E, Ortiz R, Anaya de la Rosa R, Borchard N. Circular solutions centered on biochar could improve the carbon footprint of coffee with co-benefits. Food Energy Secur. 2025;14:e70134. https://doi.org/10.1002/fes3.70134.
31. Liu Y, Li H, Hu T, Mahmoud A, Li J, Zhu R, et al. A quantitative review of the effects of biochar application on rice yield and nitrogen use efficiency in paddy fields: a meta-analysis. Sci Total Environ. 2022;830:154792. https://doi.org/10.1016/j.scitotenv.2022.154792.
32. Lehmann J, Joseph S. Biochar for environmental management: science, technology and implementation. 2nd ed. Routledge; 2015.
33. Major J, Rondon M, Molina D, Riha SJ, Lehmann J. Maize yield and nutrition during four years after biochar application to a Colombian savanna Oxisol. Plant Soil. 2010;333:117–28. https://doi.org/10.1007/s11104-010-0327-0.
34. Martín-García J, Gómez-Limón JA, Arriaza M. Conventional versus organic olive farming: which has a better economic performance? Agric Food Econ. 2023;11:51. https://doi.org/10.1186/s40100-023-00292-5.
35. Menegat S, Ledo A, Tirado R. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Sci Rep. 2022;12(1):14490. https://doi.org/10.1038/s41598-022-18773-w.
36. Ministerio de Desarrollo Agrario y Riego (Midagri). Boletín estadístico mensual: El agro en cifras. 2022; https://www.gob.pe/institucion/midagri/informes-publicaciones/2826318-boletin-estadistico-mensual-el-agro-en-cifras-2022
37. Mie A, Andersen HR, Gunnarsson S, Kahl J, Kesse-Guyot E, Rembiałkowska E, et al. Human health implications of organic food and organic agriculture: a comprehensive review. Environ Health. 2017;16(1):111. https://doi.org/10.1186/s12940-017-0315-4.
38. Morton J. The impact of climate change on smallholder and subsistence agriculture. Proc Natl Acad Sci U S A. 2007;104(50):19680–5. https://doi.org/10.1073/pnas.0701855104.
39. Namaswa T, Burslem D, Smith J. Emerging trends in appropriate kiln designs for small-scale biochar production in low to middle income countries. Bio Technol Repor. 2023. https://doi.org/10.1016/j.biteb.2023.101641.
40. Okebalama CB, Safo EY, Yeboah E, Abaidoo RC, Logah V. Fertilizer microdosing in the humid forest zone of Ghana: an efficient strategy for increasing maize yield and income in smallholder farming. Soil Sci Soc Am J. 2016;80(5):1254–61. https://doi.org/10.2136/sssaj2016.03.0065.
41. Pardo G, Perea F, Martínez Y, Urbano JM. Economic profitability analysis of rainfed organic farming in SW Spain. Outlook Agric. 2014;43(2):115–22. https://doi.org/10.5367/oa.2014.0161.
42. Quesada J, Elena M. Costos de producción en la agricultura orgánica: Un análisis comparativo. Centro de Investigaciones Agronómicas; 2020.
43. Rijks JM, et al. Global emergence of HPAI H5N1 in seabirds: implications for conservation. Science. 2022;376(6595):1201–2. https://doi.org/10.1038/s41467-023-41182-0.
44. Roy RN, Finck A, Blair GJ, Tandon HLS Plant nutrition for food security: A guide for integrated nutrient management (Fertilizer and Plant Nutrition Bulletin 16). FAO. 2006; https://www.fao.org/fileadmin/templates/soilbiodiversity/Downloadable_files/fpnb16.pdf
45. Schnug E, Jacobs F, Stöven K. Guano: the white gold of the seabirds. In: Seabirds. IntechOpen; 2018. p. 79–100. https://doi.org/10.5772/intechopen.79501.
46. Servicio Nacional de Meteorología e Hidrología (SENAMHI). Informe técnico: Comportamiento de las precipitaciones en la cuenca de los ríos Chillón, Rímac y Lurín "CHIRILU", Lima, durante el período septiembre 2023-abril 2024. 2024; https://www.gob.pe/institucion/senamhi/informes-publicaciones/6390134-informe-tecnico-comportamiento-de-las-precipitaciones-en-la-cuenca-de-los-rios-chillon-rimac-y-lurin-chirilu-lima-durante-el-periodo-septiembre-2023-abril-2024
47. Sharma P, Abrol V, Nazir J, Samnotra RK, Gupta SK, Anand S, et al. Optimizing soil properties, water use efficiency, and crop yield through biochar and organic manure integration in organic soil. J Environ Manage. 2025;373:123673. https://doi.org/10.1016/j.jenvman.2024.123673.
48. Solano SVV, Arancibia MEC. Fertilizantes en la producción agrícola: un análisis de la percepción de uso. Apunt Cenes. 2024;43(78):143–70. https://doi.org/10.19053/uptc.01203053.v43.n78.2024.17532.
49. Thomas E, Borchard N, Sarmiento C, Atkinson R, Ladd B. Key factors determining biochar sorption capacity for metal contaminants: a literature synthesis. Biochar. 2020;2:151–63. https://doi.org/10.1007/s42773-020-00053-3.

50. Venuste N, Nsenganeza J, Hagenimana T, Dekoninck W. Impact of chemical fertilizers on diversity and abundance of soil-litter arthropod communities in coffee and banana plantations in southern Rwanda. Curr Res Environ Sustain. 2023;5:100215. https://doi.org/10.1016/j.crsust.2023.100215.
51. Waheed A, Xu H, Qiao X, Aili A, Yiremaikebayi Y, Haitao D, et al. Biochar in sustainable agriculture and climate mitigation: mechanisms, challenges, and applications in the circular bioeconomy. Biomass Bioenergy. 2025;193:107531. https://doi.org/10.1016/j.biombioe.2024.107531.
52. World Bank. Fertilizer prices expected to remain higher for longer. World Bank Blogs. 2022; https://blogs.worldbank.org/opendata/fertilizer-prices-expected-remain-higher-longer
53. Zavalaga C Índices para el inicio y cierre de las campañas de extracción de guano en la RNSIIPG (Especial atención a los aspectos reproductivos de las tres especies de aves guaneras y considerando como caso de estudio a la Isla Guañape Sur) [Tesis de licenciatura, Universidad Científica del Sur]. 2015; https://www.researchgate.net/publication/305720207_INDICES_PARA_EL_INICIO_Y_CIERRE_DE_LAS_CAMPANAS_DE_EXTRACCION_DE_GUANO_EN_LA_RNSIIPG
54. Zeleke T, Beyene F, Deressa T, Yousuf J, Kebede T. Vulnerability of smallholder farmers to climate change-induced shocks in East Hararghe Zone, Ethiopia. Sustainability. 2021;13(4):Article 4. https://doi.org/10.3390/su13042162.
55. Zhao Y, Wang X, Yao G, Lin Z, Xu L, Jiang Y, et al. Advances in the effects of biochar on microbial ecological function in soil and crop quality. Sustainability. 2022;14(16):10411. https://doi.org/10.3390/su141610411.

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