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Physicochemical evaluation of humus and compost as a strategy to strengthen sustainable agriculture

Evaluación fisicoquímica de humus y compost como estrategia para fortalecer la agricultura sostenible

Avaliação físico-química do húmus e composto como estratégia para fortalecer a agricultura sustentável

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Abstract

Soil degradation due to unsustainable anthropogenic management has generated the deterioration of its quality and health, for this reason alternatives such as the use of organic fertilizers are sought for the rehabilitation of its ecological functions. Therefore, the present study evaluated the physical-chemical properties of humus and compost produced at the Tunshi experimental station, Chimborazo, Ecuador, in order to validate their suitability for sustainable agriculture. Formulations based on local inputs were used, including guinea pig manure, plant residues, green manure, and rice husks. The analyses included parameters such as pH, electrical conductivity (EC), organic matter (OM) and macronutrients, following the Ecuadorian standard NTE INEN 211:1998 and the INIAP technical manual. The results revealed that the compost and humus formulations comply with quality standards, highlighting the F2 compost formulation and the H2 formulation for humus with their high total nitrogen and OM content. The compost (F3) and humus (H3) formulations showed higher levels of phosphorus and potassium, although with lower nitrogen content, where F2 (35 % guinea pig manure, 25 % green manure) and H2 (50 % guinea pig manure, 50 % plant residues) showed higher nitrogen and OM content, while in F3 (25 % guinea pig manure, 30 % green manure) and H3 (40 % guinea pig manure, 60 % plant residues), there were no significant differences in the parameters of the humus formulations. These fertilizers represent a viable and sustainable agroecological alternative for the rehabilitation of degraded soils.

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Resumen

La degradación del suelo por la gestión antropogénica insostenible ha generado el deterioro de la calidad y salud del mismo, por éste motivo se buscan alternativas como el uso de abonos orgánicos para la rehabilitación de sus funciones ecológicas. Por ello, el presente estudio evaluó las propiedades físico-químicas del humus y del compost producidos en la estación experimental Tunshi, Chimborazo, Ecuador, con el fin de validar su idoneidad para la agricultura sostenible. Se emplearon formulaciones basadas en insumos locales, incluyendo estiércol de cuy, restos vegetales, abono verde y cascarilla de arroz. Los análisis incluyeron parámetros como pH, conductividad eléctrica (CE), materia orgánica (MO) y macronutrientes, siguiendo la normativa ecuatoriana NTE INEN 211:1998 y el manual técnico del INIAP. Los resultados revelaron que las formulaciones de compost y humus cumplen con los estándares de calidad, destacándose la formulación F2 de compost y la formulación H2 para humus con su alto contenido de nitrógeno total y MO. Las formulaciones de compost (F3) y humus (H3) mostraron niveles superiores de fósforo y potasio, aunque con menor contenido de nitrógeno, donde F2 (35 % estiércol de cuy, 25 % abono verde) y H2 (50 % estiércol de cuy, 50 % restos vegetales) mostraron mayor contenido de nitrógeno y MO, mientras que en F3 (25 % estiércol de cuy, 30 % abono verde) y H3 (40 % estiércol de cuy, 60 % restos vegetales), no existieron diferencias significativas en los parámetros de las formulaciones de humus. Estos abonos representan una alternativa agroecológica viable y sostenible para la rehabilitación de suelos degradados.

Palabras clave: abonos orgánicos, compostaje, restauración de suelos.

Resumo

A degradação do solo pela gestão antropogênica insustentável tem gerado a deterioração da qualidade e saúde do mesmo, por este motivo se buscam alternativas como o uso de adubos orgânicos para a reabilitação de suas funções ecológicas. Por isso, o presente estudo avaliou as propriedades físico-químicas do húmus e do composto produzidos na estação experimental Tunshi, Chimborazo, Equador, com o fim de validar sua idoneidade para a agricultura sustentável. Foram empregadas formulações baseadas em insumos locais, incluindo esterco de cobaia, restos vegetais, adubo verde e casca de arroz. As análises incluíram parâmetros como pH, condutividade elétrica (CE), matéria orgânica (MO) e macronutrientes, seguindo a normativa equatoriana NTE INEN 211:1998 e o manual técnico do INIAP. Os resultados revelaram que as formulações de composto e húmus cumprem com os padrões de qualidade, destacando-se a formulação F2 de composto e a formulação H2 para húmus com seu alto conteúdo de nitrogênio total e MO. As formulações de composto (F3) e húmus (H3) mostraram níveis superiores de fósforo e potássio, embora com menor conteúdo de nitrogênio, onde F2 (35 % esterco de cobaia, 25 % adubo verde) e H2 (50 % esterco de cobaia, 50 % restos vegetais) mostraram maior conteúdo de nitrogênio e MO, enquanto que em F3 (25 % esterco de cobaia, 30 % adubo verde) e H3 (40 % esterco de cobaia, 60 % restos vegetais), não existiram diferenças significativas nos parâmetros das formulações de húmus. Estes adubos representam uma alternativa agroecológica viável e sustentável para a reabilitação de solos degradados.

Palavras-chave: Fertilizantes orgânicos, compostagem, restauração do solo.

Introduction

Soil quality and health is a crucial factor for agricultural sustainability, as it not only supports food production but also plays a fundamental role in the balance of ecosystems and agroecosystems (Hameed Ologunde *et al*., 2024). Fertile soils allow optimal plant development, which is essential for ensuring global food security (Kuria *et al*., 2019). However, in recent decades, the increase in the indiscriminate use of agrochemicals has generated significant negative impacts on soil health, currently one-third of the world's soils are in some process of degradation, and in Ecuador it is considered 50 % (Potthast *et al*., 2010; Sánchez-Cortez, 2019). This phenomenon includes the progressive decrease in fertility, loss of organic matter, increased salinity, and deterioration of its physicochemical properties (Jiménez *et al*., 2024; Manzano Vela, *et al*., 2024a). These effects not only affect agricultural productivity but also soil biodiversity and surrounding water resources (Kleemann *et al*., 2022). Faced with this problem, the need for sustainable alternatives that minimize environmental impact and promote rational management of natural resources has been raised (Dengiz *et al*., 2024; Manzano Vela *et al*., 2024b). Among these alternatives, the use of organic fertilizers, such as humus and compost, has emerged as an agroecological solution with great potential for soil regeneration and promotion of sustainable agricultural practices (Awoonor *et al*., 2025).

Various studies have documented the broad benefits of organic fertilizers in soil management (Ziajahromi & Leusch, 2022). These amendments improve soil structure, increase its water retention capacity, enhance microbial activity, and facilitate carbon sequestration, key factors for maintaining a healthy agroecosystem (Wen *et al*., 2025). They also provide essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, fundamental for plant development (Bonilla-Bedoya *et al*., 2023). Unlike chemical fertilizers, which can cause contamination problems in soils, groundwater, and rivers, organic fertilizers represent an environmentally responsible alternative (Amoah-Antwi *et al*., 2020). This approach contributes to the mitigation of pollution and rehabilitation of degraded soils while supporting the production of healthy food (Adetunji *et al*., 2020). According to recent research, the preparation of humus and compost using local inputs such as plant residues and manure is not only an economical option for farmers but also constitutes an effective strategy to strengthen food security and sovereignty, reduce waste, and conserve ecosystems and agroecosystems (Bünemann *et al*., 2018).

In this context, the Bio-Knowledge Centre of the Tunshi Experiment Station presents an ideal environment to evaluate the potential of organic fertilizers in sustainable agriculture (Bhattacharya *et al*., 2024). However, despite local initiatives oriented towards agroecology, there is insufficient information about the physicochemical properties of fertilizers produced in the region or their adequacy to national and international technical standards (Rani *et al*., 2023). Therefore, scientifically evaluating these fertilizers will not only validate their suitability but also identify necessary improvements to optimize their production and promote their replicability in other areas of the country and region (Eijsackers & Maboeta, 2023).

Based on the above, the present study aims to analyze the physical-chemical composition of humus and compost produced in Tunshi, in order to demonstrate that replicable formulations at field scale constitute a viable resource for sustainable soil management

Materials and methods

Location of the study

The study, conducted in the rainy and dry seasons of 2023 at the Bio-Knowledge Centre of the Tunshi Experimental Station, belonging to the Escuela Superior Politécnica de Chimborazo (ESPOCH), located in the Licto parish, Riobamba canton, Chimborazo province (1°45'01.7" S 78°37'35.4" W, 2,840 m.a.s.l). The climate is temperate-cold with an average annual precipitation of 738 mm, average temperature of 12.9 °C and relative humidity close to 82 %. The area is part of the Chambo river sub-basin, whose water network defines the hydroedaphological dynamics of the environment.

At the same time, the physicochemical determinations of humus and compost were carried out in the Soil and Chemistry Laboratories of the Faculty of Natural Resources (ESPOCH), equipped with reference instruments and standardized procedures for the analyses.

Preparation of humus and compost

The production of both organic fertilizers was carried out in accordance with the Ecuadorian Technical Standard NTE INEN 211:1998 and the technical manual of the National Institute of Agricultural Research (INIAP) (Feicán Mejía, 2011), using guinea pig manure, green manure, horticultural residues and rice hulls as structuring material. The inputs were shredded (< 5 cm), homogenized and arranged in piles of 1.5 × 1.0 × 1.0 m. The piles were turned weekly during the first month and biweekly afterwards, maintaining humidity with light irrigation; the thermophilic phase culminated at 30 days and maturation at 90 days, when the internal temperature stabilized ≤ 5 °C above ambient and the pH approached neutrality.

For the humus, the pre-composted mixture was transferred to vermicomposting beds (0.8 × 3 m) inoculated with 1 $kg.m^{-2}$ of *Eisenia foetida*. The beds were covered with agricultural mesh and maintained at 70 - 80 % humidity and 18 - 25 °C. After 60 days, the vermicompost was sieved at 2 mm to separate the earthworm and obtain the humus, subsequently stabilizing it for 10 days in permeable sacks before its physicochemical characterization.

Physicochemical analyses

The analyses for the determination of physicochemical parameters were carried out according to the following protocols; pH was determined in a 1:2.5 fertilizer-water suspension following NTE INEN 221:1997, using an potentiometer (Orion 720A+, Thermo Electron Corp., USA); electrical conductivity was measured in the same suspension with a conductivity meter (YSI 30, YSI Inc., USA). Organic carbon was quantified by the Walkley-Black method (ISO 14235:1998) (International Organization for Standardization [ISO], 1998) using a digester-titrator (VELP DK 6, VELP Scientifica, Italy), while total nitrogen was obtained by Kjeldahl (ISO 11261:1995) (ISO, 1995) with a distiller (Kjeltec 2100, Foss Tecator, Sweden); from these values the C:N ratio was calculated as an indicator of stability and maturity. Available phosphorus was determined by UV-Visible spectrophotometry (ISO 11263:1994) (ISO, 1994) in a spectrophotometer (Shimadzu UV-1601, Japan), and calcium and magnesium contents were analyzed by atomic absorption spectrophotometry (AOAC 978.02) (Association of Official Analytical Chemists [AOAC], 1984) (PerkinElmer AAnalyst 200, USA). All instruments were calibrated with certified reference materials and the tests were performed in triplicate in the Soil and Chemistry Laboratories of the Faculty of Natural Resources of the Escuela Superior Politécnica de Chimborazo.

Statistical design and analysis

The experimental design included six treatments: three of compost (F1, F2, and F3) and three of humus (H1, H2, and H3). Each treatment underwent three repetitions, forming a total of 18 experimental units (9 for compost and 9 for humus), seeking to guarantee the consistency and reproducibility of the data (table 1).

Table 1. Combinations of inputs in the elaboration of compost (F) and humus (H) for the formulation of treatments. Chimborazo, Ecuador.

Ingredient / Input	F1	F2	F3	H1	H2	H3
	Proportion (%)					
Rice husk	40	30	35	–	–	–
Guinea-pig manure	30	35	25	60	50	40
Green manure*	20	25	30	–	–	–
Vegetable scraps	10	10	10	–	–	–
Plant remains	–	–	–	40	50	60

All formulations present their values as percentage values on a wet basis, and all humus formulations were processed with a constant density of 500 worms (*Eisenia foetida*) per kilogram of material. These proportions were designed prioritizing inputs available within the study locality, the relevance to their utilization, and the reproducibility of the production process in communities and regions with similar conditions. The statistical analysis was performed using one-way ANOVA to compare the six treatments, each with three repetitions. After confirming normality and homogeneity of variances (Shapiro-Wilk and Levene tests, respectively), The Tukey test (α= 0.05) was applied exclusively to the parameters whose ANOVA was significant; for the humus variables, no significance was detected, so no post-hoc comparison was performed

Results and discussion

Physical analysis of the compost and humus formulations revealed numerical differences in pH, electrical conductivity (EC), and organic matter (OM) content as shown in table 2. Nevertheless, one-way ANOVA followed by Tukey's post-hoc test ($p<0.05$) showed that none of these three physicochemical parameters differed significantly among either the composts or the humus treatments. Regarding chemical composition, the formulations displayed distinct profiles of essential macronutrients; statistical analysis ($p\leq0.05$) detected specific variation patterns, particularly for phosphorus (P) and potassium (K). The F2 recorded pH the numerically highest value (8.01±0.05), attributable to the 35 % guinea pig manure in its mixture. All treatments remain within the optimal range for most crops (6.5-8.5) (Wang *et al*., 2019).

The EC values of the evaluated composts ranged between 5.28 ± 0.05 and 5.40 ± 0.04 $mS.cm^{-1}$, well below the salinity threshold of 8 $mS.cm^{-1}$ recommended for organic amendments intended for agricultural use (Yang *et al*., 2024). Consequently, treatments F1, F2 and F3 can be considered suitable even for application in agroecosystems with a tendency to salinization, without risk of ionic toxicity for crops.

Table 2. Mean values of physical and chemical analysis of humus and compost simples, Chimborazo, Ecuador.

Parameter	Unit	Compost			Humus		
		F1	F2	F3	H1	H2	H3
		(Mean ± SD)					
pH	–	7.96±0.04	8.01±0.05	7.92±0.03	7.35±0.05	7.40±0.04	7.30±0.03
EC	mS.cm⁻¹	5.32±0.06	5.28±0.05	5.40±0.04	2.26±0.05	2.31±0.06	2.20±0.05
MO	%	11.46±0.05	11.50±0.06	11.40±0.04	10.53±0.05	10.60±0.05	10.50±0.04
N total	%	0.57±0.01	0.58±0.01	0.56±0.01	0.53±0.01	0.54±0.01	0.52±0.01
P	%	0.60±0.02	0.62±0.02	0.58±0.02	0.09±0.01	0.10±0.01	0.08±0.01
K	%	1.20±0.02	1.22±0.02	1.18±0.02	1.35±0.02	1.37±0.02	1.33±0.02
Ca	%	2.40±0.02	2.42±0.02	2.38±0.02	0.64±0.01	0.65±0.01	0.63±0.01
Mg	%	0.99±0.02	1.01±0.02	0.97±0.02	0.11±0.01	0.12±0.01	0.10±0.01

n: 3, EC: electric conductivity, SD: standard deviation.

For OM, F2 (11.50 ± 0.06 %) significantly exceeded (p≤0.05) F3 (11.40 ± 0.04 %), while F1 (11.46 ± 0.05 %) showed an intermediate value that did not differ significantly from either F2 or F3, a result explained by the higher combined proportion of guinea pig manure (35 %) and green manure (25 %) which provides easily degradable compounds (Naderi-Boldaji & Keller, 2016). The 5 % difference in manure fraction between formulations was not sufficient to alter OM in a statistically relevant manner between F1 and F3, confirming the greater incidence of green manure as a determining factor.

In humus the pH values remained stable (7.30 ± 0.03 - 7.40 ± 0.04) suggesting that the regulatory activity of worms buffers alkalinization (AL-Kayssi, 2021).

EC was significantly lower than in composts and also showed no internal differences (2.20 ± 0.05 - 2.31 ± 0.06 mS.cm⁻¹), partly due to salt excretion via calciferous glands during vermicomposting (Serri *et al*., 2022).

OM varied between 10.50 ± 0.04 % (H3) and 10.60 ± 0.05 % (H2) without significant differences (p>0.05), consistent with the high efficiency of stabilization and humification characteristic of the process (Vasu *et al*., 2024). Although composts presented slightly higher OM and moderately higher EC than humus, inter-process differences were statistically significant only for EC and OM (p≤0.05), while pH remained comparable (p>0.05). This evidence shows that vermicomposting reduces final salinity without compromising organic carbon stability, thus offering a bioproduct for sensitive crops (Satriani *et al*., 2024).

For compost the concentrations of N, P, and K ranged, respectively, between 0.56 ± 0.01 % - 0.58 ± 0.01 %, 0.60 ± 0.02 % - 0.62 ± 0.02 %, and 1.20 ± 0.02 % - 1.22 ± 0.02 %, coincident ranges reported in the literature (Yin *et al*., 2021; Kong *et al*., 2024; Reyes-Torres *et al*., 2018).

Although F2 showed numerically higher values, ANOVA indicated absence of significant differences among the three formulations (p>0.05). This confirms that the 5 % increase in guinea pig manure and green manure was not sufficient to modify the availability of macronutrients in a statistically relevant manner, coinciding with reports where variations ≤ 10 % in the animal fraction generate minor changes in NPK (Faverial *et al*., 2016; Wang *et al*., 2025). Nevertheless, the slight upward trend suggests that the combination of nitrogen-rich manure and leguminous green manure favors nutrient stabilization during composting, an aspect that could acquire greater importance in mixtures with a higher proportion of lignocellulosic residues (Chen *et al*., 2024).

In humus, the contents of P (0.09 ± 0.01 % - 0.10 ± 0.01 %) and K (1.33 ± 0.02 % - 1.37 ± 0.02 %) were lower than in composts (p≤0.05 inter-group), due to the partial loss of soluble salts during the vermicomposting process (Antonangelo *et al*., 2021). The ANOVA indicated that the concentrations of N, P, K, Ca and Mg did not differ significantly between the humus treatments H1, H2 and H3 (p>0.05, in all cases); therefore, none can be considered statistically “superior” in the contribution of macronutrients. However, descriptively, the formulation with 50 % plant residues (H2) presented slightly higher values of P and K, a trend consistent with studies that report faster mineralization when the plant fraction approaches a 1:1 ratio with manure (Ebrahimi *et al*., 2024; Niedrite *et al*., 2024; Wang *et al*., 2025; Feng *et al*., 2024; Wang *et al*., 2019). Although these differences do not reach statistical significance, they suggest that a higher content of plant matter could favor the initial availability of certain macronutrients.

However, such a trend should be confirmed with larger batches or a factorial design that modifies the proportion of inputs more broadly. Despite numerical variations, all formulations met the optimal ranges of N (> 0.5 %), P (> 0.08 %), and K (> 1.2 %) for organic amendments for agricultural use (Vaz-Moreira *et al*., 2025; Tao *et al*., 2024).

In humus, the lower EC and higher microbial stability offer advantages for crops sensitive to salinity, while compost, with slightly higher NPK, may be preferred in low-fertility loam soils (García-Rández *et al*., 2025). The Tukey test (table 3) revealed significant differences (p<0.05) among compost formulations for total N, P, K, and OM, while no significant differences were found for pH and EC.

Table 3. Tukey’s multiple comparisons for physicochemical parameters of compost formulations, Chimborazo, Ecuador.

Parameter	F1	F2	F3
	(Mean ± SD)		
pH	7.96 ± 0.04 a	8.01 ± 0.05 a	7.92 ± 0.03 a
EC (ms.cm⁻¹)	5.32 ± 0.06 a	5.28 ± 0.05 a	5.40 ± 0.04 a
N total (%)	0.57 ± 0.01 ab	0.58 ± 0.01 a	0.56 ± 0.01 b
P (%)	0.60 ± 0.02 ab	0.62 ± 0.02 a	0.58 ± 0.02 b
K (%)	1.20 ± 0.02 ab	1.22 ± 0.02 a	1.18 ± 0.02 b
OM (%)	11.46 ± 0.05 ab	11.50 ± 0.06 a	11.40 ± 0.04 b

Note: Values with different letters in the same row indicate statistically significant differences (p<0.05) according to Tukey’s test,n: 3, EC: electric conductivity, SD: standard deviation.

F2 had the highest pH, P, and K, attributed to a balanced mix of plant and animal residues that enhances mineralization and nutrient availability. Meanwhile, F3 exhibited the highest EC. A slightly alkaline pH, as in F2, is known to improve phosphorus and potassium solubilization (Sánchez *et al*., 2017).

F2 stood out in its total nitrogen content and OM, slightly surpassing F1 and F3. This advantage is attributed to the higher proportion of guinea pig manure and green manure, which promote a more balanced C/N ratio during the composting process. Meanwhile, the estimated average C/N ratios were 21:1 in F1, 19:1 in F2, and 22:1 in F3. The higher organic matter content in F2 demonstrates its potential to improve soil structure and promote moisture retention (Li *et al*., 2024).

From an agronomic perspective, it would be important to consider whether these differences, although statistically significant, have practical relevance under field conditions. Future studies could evaluate whether these slight variations in physicochemical parameters translate into measurable differences in plant growth or soil quality.For humus, one-way ANOVA revealed no statistically significant differences ($p>0.05$) among formulations for any of the physicochemical parameters evaluated consequently, a Tukey post-hoc test was not applied.

Regarding humus, there is a nutrient dynamic in vermicomposting, as the worms decompose the organic matter and homogenize the nutrients (Domínguez & Gómez-Brandón, 2013).

These results confirm that, despite minor numerical variations, the three vermicomposts provide comparable nutrient availability and do not present organic-matter limitations.

Conclusions

Physicochemical evaluations of compost and humus formulations confirm their usefulness as organic amendments for sustainable agriculture. The observed variations in pH, EC, organic matter, and macronutrients are related to the type of input in the formulation, considering the easy acquisition and replicability for the generation of these fertilizers. In the compost, formulation F2, enriched with 35 % guinea pig manure and 25 % green manure, stood out for its higher content of total N (0.58 ± 0.01 %), P (0.62 ± 0.02 %), K (1.22 ± 0.02 %), pH (8.01 ± 0.05) and organic matter (11.50 ± 0.06 %), making it an ideal option for nutrient-deficient soils. In contrast, F3 registered the highest electrical conductivity (5.40 ± 0.04 $mS.cm^{-1}$), which could be beneficial for crops tolerant to salinity.

Regarding humus, H2, with a balance between guinea pig manure (50 %) and plant residues (50 %), showed the highest concentrations of total N (0.54 ± 0.01 %), P (0.10 ± 0.01 %), K (1.37 ± 0.02 %) and organic matter (10.60 ± 0.05 %), positioning itself as the most suitable alternative to increase soil fertility and plant development. These formulations comply with Ecuadorian regulations and INIAP standards, validating their potential for sustainable soil management. Local replication, taking advantage of available inputs and appropriate methodologies, favors the adoption of agroecological practices. However, strict control of production parameters and variability in inputs is recommended to ensure consistent quality of the fertilizers.

Literature cited

Adetunji, A.T., Ncube, B., Mulidzi, R., & Lewu, F.B. (2020). Management impact and benefit of cover crops on soil quality: A review. *Soil and Tillage Research*, *204*, 104717. https://doi.org/10.1016/J.STILL.2020.104717

AL-Kayssi, A.W. (2021). Use of water retention data and soil physical quality index S to quantify hard-setting and degree of soil compactness indices of gypsiferous soils. *Soil and Tillage Research*, *206*, 104805. https://doi.org/10.1016/J.STILL.2020.104805

Amoah-Antwi, C., Kwiatkowska-Malina, J., Thornton, S.F., Fenton, O., Malina, G., & Szara, E. (2020). Restoration of soil quality using biochar and brown coal waste: A review. *Science of the Total Environment*, *722*, 137852. https://doi.org/10.1016/J.SCITOTENV.2020.137852

Antonangelo, J.A., Sun, X., & Zhang, H. (2021). The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. *Journal of Environmental Management*, *277*, 111443. https://doi.org/10.1016/J.JENVMAN.2020.111443

Association of Official Analytical Chemists. (1984). *Nitrogen (Total) in fertilizers. Modified combustion method (AOAC Official Method 978.02-1984).* http://www.aoacofficialmethod.org/index.php?main_page=product_info&cPath=1&products_id=471

Awoonor, J.K., Amoakwah, E., Buri, M.M., Dogbey, B.F., & Gyamfi, J.K. (2025). Impact of land use on soil quality: Insights from the forest-savannah transition zone of Ghana. *Heliyon*, *11*(1), e41183. https://doi.org/10.1016/J.HELIYON.2024.E41183

Bhattacharya, D., Tripathy, S., Swain, D.K., & Mitra, A. (2024). Can organic farming improve the soil properties, food quality and human health?. *Food and Humanity*, *3*, 100398. https://doi.org/10.1016/J.FOOHUM.2024.100398

Bonilla-Bedoya, S., Valencia, K., Herrera, M.., López-Ulloa, M., Donoso, D.A., & Macedo Pezzopane, J.E. (2023). Mapping 50 years of contribution to the development of soil quality biological indicators. *Ecological Indicators*, *148*, 110091. https://doi.org/10.1016/J.ECOLIND.2023.110091

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., & Brussaard, L. (2018). Soil quality - A critical review. *Soil Biology and Biochemistry*, *120*, 105-125. https://doi.org/10.1016/J.SOILBIO.2018.01.030

Chen, K., Li, J., Lin, L., Qin, W., Gao, Y., Hu, E., & Jiang, J. (2024). Occurrence, fate and control strategies of heavy metals and antibiotics in livestock manure compost land application: A review. *Science of the Total Environment*, *957*, 177381. https://doi.org/10.1016/J.SCITOTENV.2024.177381

Dengiz, O., Alaboz, P., Saygın, F., Adem, K., & Yüksek, E. (2024). Evaluation of soil quality of cultivated lands with classification and regression-based machine learning algorithms optimization under humid environmental condition. *Advances in Space Research*, *74*(11), 5514-5529. https://doi.org/10.1016/J.ASR.2024.08.048

Domínguez, J., & Gómez-Brandón, M. (2013). *The influence of earthworms on nutrient dynamics during the process of vermicomposting. Waste Management & Research, 31*(8), 859–868. https://doi.org/10.1177/0734242X13497079

Ebrahimi, M., Gholipour, S., Mostafaii, G., & Yousefian, F. (2024). Biochar-amended food waste compost: A review of properties. *Results in Engineering*, *24*, 103118. https://doi.org/10.1016/J.RINENG.2024.103118

Eijsackers, H., & Maboeta, M. (2023). Pesticide impacts on soil life in southern Africa: Consequences for soil quality and food security. *Environmental Advances*, *13*, 100397. https://doi.org/10.1016/J.ENVADV.2023.100397

Faverial, J., Boval, M., Sierra, J., & Sauvant, D. (2016). End-product quality of composts produced under tropical and temperate climates using different raw materials: A meta-analysis. *Journal of Environmental Management*, *183*, 909-916. https://doi.org/10.1016/J.JENVMAN.2016.09.057

Feicán Mejía, C. (2011). *Manual de producción de abonos orgánicos*. Estación Experimental del Austro-INIAP. http://repositorio.iniap.gob.ec/handle/41000/2396

Feng, D., Cui, Y., Zeng, Y., Wang, D., Zhang, H., Zhang, Y., & Song, W. (2024). Enhancing compost quality through biochar and oyster shell amendments in the co-composting of seaweed and sugar residue. *Chemosphere*, *366*, 143500. https://doi.org/10.1016/J.CHEMOSPHERE.2024.143500

García-Rández, A., Orden, L., Marks, E.A.N., Andreu-Rodríguez, J., Franco-Luesma, S., Martínez-Sabater, E., Saéz-Tovar, J.A., Pérez-Murcia, M.D., Agulló, E., Bustamante, M.A., Cháfer, M., & Moral, R. (2025). Monitoring of greenhouse gas emissions and compost quality during olive mill waste co-composting at industrial scale: The effect of N and C sources. *Waste Management*, *193*, 33-43. https://doi.org/10.1016/J.WASMAN.2024.11.039

Hameed Ologunde, O., Kehinde Bello, S., & Abolanle Busari, M. (2024). Integrated agricultural system: A dynamic concept for improving soil quality. *Journal of the Saudi Society of Agricultural Sciences*, *23*(5), 352-360. https://doi.org/10.1016/J.JSSAS.2024.03.002

Instituto Ecuatoriano de Normalización. (1997). *Fertilizantes o abonos. Etiquetado. Requisitos (NTE INEN 221:1997, 1.ª revisión).* https://www.agrocalidad.gob.ec/wp-content/uploads/2013/11/inen-0221-1997.pdf

Instituto Ecuatoriano de Normalización. (1998). *Fertilizantes o Abonos. Tolerancias (NTE INEN 211:98).* bit.ly/4mWmsJ9

International Organization for Standardization. (1994). *Soil quality - Determination of phosphorus - Spectrometric determination of phosphorus soluble in sodium hydrogen carbonate solution (ISO 11263:1994).* https://www.iso.org/standard/19241.html

International Organization for Standardization. (1995). *Soil quality - Determination of total nitrogen - Modified Kjeldahl method (ISO 11261:1995).* https://www.iso.org/standard/19239.html

International Organization for Standardization. (1998). *Soil quality - Determination of organic carbon by sulfochromic oxidation (ISO 14235:1998).* https://www.iso.org/standard/23140.html

Jiménez, L., Jiménez, W., González, L., Quichimbo, P., Fierro, N., & Capa-Mora, D. (2024). Rescuing local knowledge with regards to soil management and fertility in the Amazon region of Ecuador. *Environmental Development*, *50*, 100984. https://doi.org/10.1016/J.ENVDEV.2024.100984

Kleemann, J., Koo, H., Hensen, I., Mendieta-Leiva, G., Kahnt, B., Kurze, C., Inclan, D.J., Cuenca, P., Noh, J.K., Hoffmann, M.H., Factos, A., Lehnert, M., Lozano, P., & Fürst, C. (2022). Priorities of action and research for the protection of biodiversity and ecosystem services in continental Ecuador. *Biological Conservation*, *265*, 109404. https://doi.org/10.1016/J.BIOCON.2021.109404

Kong, Y., Zhang, J., Zhang, X., Gao, X., Yin, J., Wang, G., Li, J., Li, G., Cui, Z., & Yuan, J. (2024). Applicability and limitation of compost maturity evaluation indicators: A review. *Chemical Engineering Journal*, *489*, 151386. https://doi.org/10.1016/J.CEJ.2024.151386

Kuria, A.W., Barrios, E., Pagella, T., Muthuri, C.W., Mukuralinda, A., & Sinclair, F.L. (2019). Farmers' knowledge of soil quality indicators along a land degradation gradient in Rwanda. *Geoderma Regional*, *16*, e00199. https://doi.org/10.1016/J.GEODRS.2018.E00199

Li, Y., Herbst, M., Chen, Z., Chen, X., Xu, X., Xiong, Y., Huang, Q., & Huang, G. (2024). Long term response and adaptation of farmland water, carbon and nitrogen balances to climate change in arid to semi-arid regions. *Agriculture, Ecosystems & Environment*, *364*, 108882. https://doi.org/10.1016/J.AGEE.2023.108882

Manzano Vela, D.R., Ortega Castro, J.O., & Moya, A.E. (2024a). Caracterización fisicoquímica del biol en varias mezclas generadas por biodigestión. *Recursos Naturales Producción y Sostenibilidad*, *3*(1), 35-51. https://doi.org/10.61236/renpys.v3i1.596

Manzano Vela, D.R., Villegas Freire, C.N., Zabala Vizuete, R.F., & Flores Mancheno, A.C. (2024b). Utilization of forest residues for cellulose extraction from timber species in the high montane forest of Chimborazo, Ecuador. *Polymers, 16*(19), 2713. https://doi.org/10.3390/POLYM16192713

Naderi-Boldaji, M., & Keller, T. (2016). Degree of soil compactness is highly correlated with the soil physical quality index S. *Soil and Tillage Research*, *159*, 41-46. https://doi.org/10.1016/J.STILL.2016.01.010

Niedrite, E., Klavins, L., Dobkevica, L., Purmalis, O., Ievinsh, G., & Klavins, M. (2024). Sustainable control of invasive plants: Compost production, quality and effects on wheat germination. *Journal of Environmental Management*, *371*, 123149. https://doi.org/10.1016/J.JENVMAN.2024.123149

Potthast, K., Hamer, U., & Makeschin, F. (2010). Impact of litter quality on mineralization processes in managed and abandoned pasture soils in Southern Ecuador. *Soil Biology and Biochemistry*, *42*(1), 56-64. https://doi.org/10.1016/J.SOILBIO.2009.09.025

Rani, M., Kaushik, P., Bhayana, S., & Kapoor, S. (2023). Impact of organic farming on soil health and nutritional quality of crops. *Journal of the Saudi Society of Agricultural Sciences*, *22*(8), 560-569. https://doi.org/10.1016/J.JSSAS.2023.07.002

Reyes-Torres, M., Oviedo-Ocaña, E.R., Domínguez, I., Komilis, D., & Sánchez, A. (2018). A systematic review on the composting of green waste: Feedstock quality and optimization strategies. *Waste Management*, *77*, 486-499. https://doi.org/10.1016/J.WASMAN.2018.04.037

Sánchez-Cortez, J.L. (2019). Conservation of geoheritage in Ecuador: Situation and perspectives. *International Journal of Geoheritage and Parks*, *7*(2), 91-101. https://doi.org/10.1016/J.IJGEOP.2019.06.002

Sánchez, Ó.J., Ospina, D.A., & Montoya, S. (2017). *Compost supplementation with nutrients and microorganisms in composting process. Waste Management, 69*, 136-153. https://doi.org/10.1016/j.wasman.2017.08.012

Satriani, A., Belviso, C., Lovelli, S., di Prima, S., Coppola, A., Hassan, S.B.M., Rivelli, A.R., & Comegna, A. (2024). Impact of a synthetic zeolite mixed with soils of different pedological characteristics on soil physical quality indices. *Geoderma*, *451*, 117084. https://doi.org/10.1016/J.GEODERMA.2024.117084

Serri, D.L., Pérez-Brandan, C., Meriles, J.M., Salvagiotti, F., Bacigaluppo, S., Malmantile, A., & Vargas-Gil, S. (2022). Development of a soil quality index for sequences with different levels of land occupation using soil chemical, physical and microbiological properties. *Applied Soil Ecology*, *180*, 104621. https://doi.org/10.1016/J.APSOIL.2022.104621

Tao, R., Cui, M., Li, Y., Wang, J., He, W., Zhao, Y., Xie, W., Shen, Y., Feng, Y., & White, J.C. (2024). Nanoscale biochar for fertilizer quality optimization in waste composting: Microbial community regulation. *Bioresource Technology*, *414*, 131571. https://doi.org/10.1016/J.BIORTECH.2024.131571

Vasu, D., Tiwary, P., & Chandran, P. (2024). A novel and comprehensive soil quality index integrating soil morphological, physical, chemical, and biological properties. *Soil and Tillage Research*, *244*, 106246. https://doi.org/10.1016/J.STILL.2024.106246

Vaz-Moreira, I., D'Arnese, A., Knoll, M., Teixeira, A.M., Barbosa, J.B., Teixeira, P., & Manaia, C.M. (2025). Bacteriological safety and quality of composted products from animal, urban or sewage sludge wastes. *Environmental Pollution*, *364*, 125329. https://doi.org/10.1016/J.ENVPOL.2024.125329

Wang, S., Chen, D., Zhang, X., Xu, J., Lei, W., Zhou, C., Chen, C., Li, F., & Wang, N. (2019). Humus composition of mineral–microbial residue from microbial utilization of lignin involving different mineral types. *Canadian Journal of Soil Science*, *99*(2), 208-216. https://doi.org/10.1139/CJSS-2018-0135

Wang, X., You, G., Liu, C., & Sun, Y. (2025). Bioaugmentation strategies in co-composting anaerobically digested food waste with agricultural by-products: Enhancing fertilizer quality and microbial communities. *Ecotoxicology and Environmental Safety*, *290*, 117539. https://doi.org/10.1016/J.ECOENV.2024.117539

Wen, Y., Yao, W., Yu, T., Cheng, L., Zhang, Q., Yang, J., Lin, F., Zhu, H., Gunina, A., Yang, Y., Mganga, K.Z., Zeng, Z., & Zang, H. (2025). Long-term organic farming improves the red soil quality and microbial diversity in subtropics. *Agriculture, Ecosystems & Environment*, *381*, 109410. https://doi.org/10.1016/J.AGEE.2024.109410

Yang, X., Yan, R., Li, S., Li, F., Yang, C., Zhang, H., Lyu, H., Liu, T., Zhou, L., Li, W., Duo, J., Li, R., & Yao, Y. (2024). Soil drives humus formation during composition of wheat straw and cattle manure. *Journal of Environmental Chemical Engineering*, *12*(4), 113271. https://doi.org/10.1016/J.JECE.2024.113271

Yin, Z., Zhang, L., & Li, R. (2021). Effects of additives on physical, chemical, and microbiological properties during green waste composting. *Bioresource Technology*, *340*, 125719. https://doi.org/10.1016/J.BIORTECH.2021.125719

Ziajahromi, S., & Leusch, F.D.L. (2022). Systematic assessment of data quality and quality assurance/quality control (QA/QC) of current research on microplastics in biosolids and agricultural soils. *Environmental Pollution*, *294*, 118629. https://doi.org/10.1016/J.ENVPOL.2021.118629