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Determinants of compost quality across 12 agroecological zones of Peru: the role of regional organic waste and climatic conditions

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Introduction: Composting is a cornerstone of the circular economy in agriculture; however, its efficacy is often undermined by limited knowledge regarding how agroclimatic variability influences compost quality under real-world conditions in megadiverse countries such as Peru.
Methods: We monitored twelve composting processes over a 16-week period, established at agricultural experimental stations across 12 agroecological zones in Peru—spanning the arid coast, the high Andes, and lowland/high-jungle environments. The study utilized locally representative organic residues and employed a multisite observational design analyzed via generalized linear mixed models (GLMM).
Results: High-Andean sites, characterized by low ambient temperatures and quinoa residues, exhibited the highest organic carbon retention and biological stability. In contrast, lowland jungle stations showed accelerated mineralization and suboptimal organic matter content (≈12%), failing to meet national standards. In coastal regions, guinea pig manure helped minimize lead accumulation; however, arsenic concentrations exceeded international safety limits (40 mg kg^{-1}) at certain stations. Furthermore, fixed effects (climate and process parameters) explained more than 67% of the variation in organic matter and nitrogen, while the agroecological context accounted for ≈23% of the variability in yield.
Discussion: These findings indicate that compost quality is driven by non-linear interactions between temperature, humidity, pH, electrical conductivity, and

regional residue composition, demonstrating that "one-size-fits-all" protocols fail to capture these complex dynamics.

KEYWORDS
agroecological zones, carbon stabilization, circular economy, composting, generalized linear mixed models, heavy metals, waste management

1 Introduction

The rapid growth of the global population, projected to reach 9.7 billion by 2050 and 11.2 billion by 2,100, is expected to significantly increase organic waste production, potentially reaching 3.4 billion and 5.1 billion tons per year, respectively (United Nations, Department of Economic and Social Affairs, Population Division, 2017; Saadatlu et al., 2022). This scenario presents significant environmental and economic challenges, as inadequate waste management contributes to greenhouse gas (GHG) emissions, soil and water contamination, and increased pressure on food security due to the intensification of agricultural and livestock systems (Tripathi et al., 2019). In this context, composting has emerged as a sustainable alternative that not only mitigates environmental impacts but also enhances soil fertility and supports the development of more resilient agricultural systems (United Nations, Department of Economic and Social Affairs, Population Division, 2017).

In Peru, agroecological diversity provides a wide range of agricultural and livestock residues, from camelid manure and quinoa residues in the highlands to guinea pig manure and maize stover on the coast. However, 55% of crop residues and 54% of manure are not managed properly (Instituto Nacional de Estadística e Informática (INEI), 2023), contributing to environmental pollution and GHG emissions (Cai et al., 2021; Yousefloo and Babazadeh, 2019). This diversity of organic materials, combined with the country's widely varying climatic conditions, creates a complex and understudied context for understanding the key factors that determine compost quality.

Although some localized composting studies have been conducted in Peru (Shen et al., 2024; Rodrigues et al., 2020), most existing statistical models are limited to homogeneous or controlled conditions and fail to account for the country's pronounced climatic variability, from the arid coast (16 mm of annual precipitation at CELM) to the high Andes (3,835 m.a.s.l. at Illpa, with an average temperature of 8.54 °C), within a unified analytical framework. This gap, which constrains the development of composting protocols tailored to specific agroecological conditions, underscores the need for comprehensive characterization. Such characterization should explicitly relate regional variability in organic waste and climatic conditions to the final quality of compost. This approach is essential for three interrelated reasons: (United Nations, Department of Economic and Social Affairs, Population Division, 2017) economic, to reduce dependence on external feedstocks through the efficient use of locally available materials (Ansar et al., 2025); (Saadatlu et al., 2022) environmental, to mitigate pollutants such as heavy metals (Pinamonti et al., 1997) and GHG emissions (Li et al., 2022); and (Tripathi et al., 2019) technical–methodological, to enable the application of advanced statistical tools such as generalized linear mixed models (GLMMs). These models are particularly well-suited to this context because they allow the hierarchical modelling of the data (compost piles nested within regions) and enable quantification of natural variability among agroecological zones, effectively transforming a logistical constraint into a quantifiable natural experiment.

To address this gap, this study applies, for the first time, a multivariate GLMM approach that integrates regional variability in organic residues and climatic effects, providing a scalable framework that can be applied to geographically diverse contexts. Compost is an organic amendment produced through the controlled aerobic decomposition of organic matter (OM), and its quality depends on both the composition of the waste and environmental factors, including temperature, humidity, pH, C: N ratio, and the presence of contaminants (Lou and Nair, 2009). According to the literature, specific quality indicators are susceptible to these external drivers: for instance, final compost C: N ratio and organic matter retention are primarily affected by ambient temperature and aeration, which regulate the rate of microbial mineralization (Bernal et al., 2009). Similarly, the final concentration of heavy metals is largely determined by the geogenic nature of the feedstocks and the mass loss effect during decomposition (Cerda et al., 2018), while the elimination of pathogens depends strictly on the maintenance of thermophilic temperatures, which can be hindered by extreme cold or excessive moisture in high-altitude or tropical environments (Azim et al., 2018). In countries such as Peru, where these variables vary considerably from one region to another, understanding their interactions is essential for designing region-specific management strategies.

Therefore, this study aims to evaluate, using GLMMs, how regional characteristics of organic waste and local climatic conditions determine the final quality of compost produced across 12 agroecological zones in Peru under real-world management conditions. Our hypothesis is that the specific interaction between waste composition and local environmental conditions exerts a significant and differentiating effect on the physicochemical parameters of the final compost.

2 Materials and methods

2.1 Study area

The study was conducted at 12 Agrarian Experimental Stations (EEA) of the National Institute of Agrarian Innovation (INIA), strategically located across nine regions of Peru: Arequipa, Ayacucho, Cajamarca (Baños del Inca and Jaén), Junín (Huancayo and Pichanaki), Lambayeque, Lima (Lima and Huaral), Puno, San Martín, and Ucayali (Figure 1). These locations encompass a wide range of ecological zones and climatic conditions, from arid coastal environments to high-Andean regions and lowland tropical forests, thereby providing a diverse and representative framework for analyzing composting processes based on locally available agricultural residues.

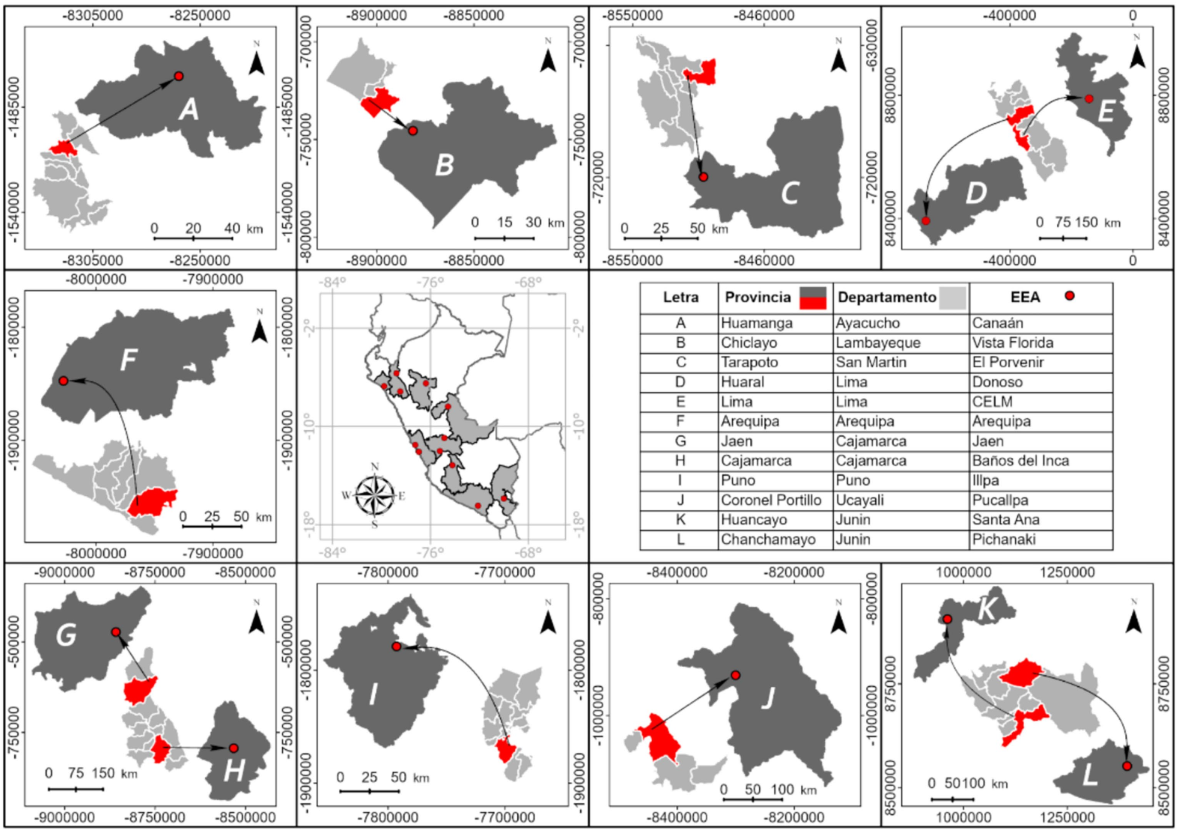

FIGURE 1
Geographic distribution of the twelve study sites across Peru.

These stations were selected for their capacity to capture the country's agroecological heterogeneity, including variation in altitude, climate, land use, and the availability of organic residues. This diversity enabled the evaluation of composting performance under contrasting environmental conditions, thereby providing evidence of the influence of local factors on the quality of the organic amendments produced in each region. To provide environmentally context for each site, data on mean annual temperature, precipitation, and elevation were compiled from updated records of the National Meteorology and Hydrology Service of Peru (Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI), 2024). The values compiled by the EEA can be found in the Supplementary Table S1; additionally, the relative humidity and temperature values were derived from 2024 data provided by WorldClim (Supplementary Figure S1).

2.2 Organic residues utilized as feedstock for composting

The organic residues used in the twelve compost treatments, corresponding to the 12 evaluated regions, were selected based on their representativeness in local agricultural and livestock activities. These materials constitute the predominant and exclusive waste streams generated in each respective region, ensuring the experimental conditions strictly mirror real-world local management. The collection was carried out at respective Agrarian Experimental Stations (EEA) of INIA. The materials included maize stover and guinea pig manure in Lima; avocado leaf litter and cattle manure in Huaral; and sweet potato residues and goat manure in Lambayeque, among others (detailed information on the type, quantity, and C: N ratio of these residues for each EEA is provided in Supplementary Tables S2, S3). The plant material (carbon source) was chopped into fragments measuring 2–5 cm, while the manure (nitrogen source) was air-dried to achieve a moisture content of approximately 60%. Before pile construction, the feedstocks were physicochemical characterized to determine key parameters, particularly the C: N ratio, to formulate balanced mixtures for the composting process. Analyses of the raw materials were conducted at the Soil, Water and Foliar Laboratory (LABSAF) of the National Institute of Agrarian Innovation (INIA). Organic carbon (OC) was determined in accordance with ISO 10694 (International Organization for Standardization (ISO), 1995), and total nitrogen (NT) was measured following ISO 13878 (International Organization for Standardization (ISO), 1998).

2.3 Study design

A multi-site observational design was implemented, leveraging the natural variability across twelve agroecological zones in Peru as a large-scale natural experiment. At each of the twelve Agrarian Experimental Stations (EEA), four compost piles were created using the most representative organic feedstocks of the predominant agricultural and livestock activities in each region.

Each pile was established as an independent experimental unit on an impermeable concrete surface, measuring 2 × 2 m with an initial height of approximately 1.5 m. The base was constructed with a 5%

slope and a central drainage channel to allow controlled leachate evacuation, thereby promoting adequate aeration within the compost mass. The piles were spaced 1 m apart to facilitate operational management and to prevent cross-interference during the composting process.

The selection of an observational design, rather than a controlled experiment with treatments randomly assigned across regions, was dictated by the nature of the research question. In this study, the treatment is intrinsic to each location, comprising the unique combination of locally available biomass and climatic conditions that characterize a given agroecological region. Accordingly, a direct random comparison of waste types across regions with contrasting climates would lack ecological validity. To analyze the data generated by this design, which has a natural hierarchical structure (multiple observations over time nested within piles, which are themselves nested within regions), the generalized linear mixed models (GLMM) framework was employed.

This methodological approach is particularly appropriate for several reasons (Bolker et al., 2009; Zuur et al., 2009). First, GLMMs explicitly account for the lack of independence among the four piles established within the same EEA, which are likely to share unmeasured local influences such as microclimatic conditions, operational management practices, or minor variations in feedstock batches. Second, by incorporating the EEA as a random effect, the model enables the quantification and partitioning of variability in compost quality attributable to latent regional differences (e.g., agroecological context, geology, management traditions) from the variability explained by the measured fixed effects of interest, such as composting process parameters (temperature, moisture, pH) and climatic variables. This decomposition of variance is essential, as it allows us to generalize statistical inferences about fixed effects to the broader population of agroecological conditions represented in the study sample, rather than limiting them solely to the twelve specific stations evaluated. Finally, GLMMs provide the flexibility needed to accommodate the actual distribution of response variables, which often deviate from normality (e.g., proportions such as OM content, metal concentrations, and microbiological counts). This is achieved by specifying alternative distribution families (e.g., Beta, Gamma, and Tweedie) and appropriate link functions.

Accordingly, the four piles established per EEA do not constitute independent statistical replicates in the sense of a completely randomized design. Rather, they function as technical replicates or effectively pseudo-replicated samples within each random grouping unit (the EEA). Their role is to provide a robust estimate of the existing variability within the same regional condition. This analytical strategy transforms an apparent logistical constraint—the impracticality of experimentally replicating all combinations of waste types and climatic conditions at a single location—into a central strength of the study. By leveraging natural variation, the design enables the quantification of the relative effects of process-related factors and regional context on compost quality at the national scale.

2.4 Monitoring of internal composting process parameters

Composting is an aerobic biodegradation process of OM driven by native microorganisms and requires adequate oxygen availability to proceed efficiently (Castro and Chanamé, 2021). The dynamics of this process depend on key internal parameters that directly influence microbial activity, including aeration, moisture, temperature, and pH. In addition, electrical conductivity (EC) provides an estimate of soluble salt accumulation, as elevated concentrations may affect process stability. During the composting period, representative composite samples were collected from each pile at weeks 1, 4, 8, 12, and 16 (Table 1). Moisture content, pH, and EC were determined for each sampling event. The internal temperature of each compost pile was monitored daily over the 16 weeks using a 50-cm metal probe. Three measurements were recorded at depths of 10, 25, and 40 cm from the surface, and their average was calculated to characterize the thermal evolution of the process and the duration and behavior of the thermophilic phase.

2.4.1 Aeration

To maintain aerobic conditions throughout the composting process, the compost was turned manually weekly. This practice ensured adequate aeration of the material, thereby promoting microbial growth and respiration, and facilitating carbon dioxide release, conditions essential for efficient composting (Licea et al., 2023).

2.4.2 Moisture

Moisture control was a key practice during composting, as water regulates the microbial activity responsible for decomposing OM. Efforts were made to maintain moisture levels within the 45–70% range, which is considered optimal for promoting the proliferation of bacteria, fungi, and actinomycetes involved in the mineralization of organic residues (Koul et al., 2021). Moisture levels below this threshold can limit microbial activity, whereas excessive moisture may promote anaerobic conditions and the generation of unpleasant odors (Oshins et al., 2022). The moisture content of the piles was regulated through manual watering, with the frequency adjusted according to local weather conditions.

TABLE 1 Schedule for monitoring parameters during the composting process.

Date	Week	Compost			
		pH	Temperature	Moisture	Electrical conductivity
12/04/2024	1	pH1	T1	M1	EC1
10/05/2024	4	pH2	T2	M2	EC2
05/06/2024	8	pH3	T3	M3	EC3
05/07/2024	12	pH4	T4	M4	EC4
02/08/2024	16	pH5	T5	M5	EC5

2.4.3 Temperature

Temperature monitoring was conducted as a key indicator of the composting process, as this parameter is closely associated with microbial activity (Galecio-Julca et al., 2023). The progressive increase in temperature promotes the development of thermophilic microorganisms, which are responsible for the intensive degradation of OM and the elimination of potential pathogens. During the thermophilic phase, compost piles may reach temperatures between 50 and 71 °C, which can be sustained for several days, thereby ensuring the sanitization of the material. As microbial activity declines, a gradual decrease in temperature was observed, reaching values close to 40 °C, characteristic of the cooling phase, and eventually stabilizing near ambient temperature during the maturation stage (Oshins et al., 2022).

2.4.4 pH and EC

pH and EC were measured at weeks 1, 4, 8, 12, and 16 of the composting process (Table 1) to monitor changes in acidity/alkalinity and the accumulation of soluble salts. For each analysis, composite samples representative of each pile were collected, following the criteria of homogeneity and representativeness.

These analyses recorded the most significant chemical changes during the compost stabilization process, particularly during the maturation phase.

2.5 Analysis of compost quality

Samples for the determination of final compost quality were analyzed within the Soil, Water and Foliar Laboratory network of INIA. The selected parameters serve as key indicators of compost stability, maturity, and safety: pH and EC ensure soil compatibility, while OC and NT (C/N ratio) reflect organic matter humification and biological stability. Additionally, heavy metals and pathogens were quantified to certify chemical and microbiological biosecurity. The final quality of the compost, assessed at 16 weeks based on its physical, chemical, and biological characteristics, was evaluated in accordance with the Peruvian Technical Standards (NTP) 201.207:2020 (2020) and 201.208:2021 (2021). The moisture content was determined by the gravimetric method; OC was measured according to ISO 10694 (International Organization for Standardization (ISO), 1995); and NT was measured according to ISO 13878 (International Organization for Standardization (ISO), 1998). The pH was determined following EPA Method 9,045 (United States Environmental Protection Agency (USEPA), 2004), while EC was measured using the saturation extract method (AS-18) (Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), 2003). Heavy metal concentrations were determined according to EPA Method 3,051.

For microbiological quality assessment, fecal coliforms were determined using the multiple-tube fermentation method in accordance with Standard Methods 9221F.2 (APHA, AWWA, WEF, 2023). Helminth eggs and Salmonella spp. were analyzed following the procedures established in NOM-004-SEMARNAT-2002 (Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), 2003), while nematode larvae were determined according to the validated method MVAL-LAB-32 (Analytical Laboratory E.I.R.L., 2019).

2.6 Climate data collection

Average daily temperature (°C) and daily relative humidity (RH) (%) were used as climatic variables in the model analysis to identify their influence on the compost pile. The daily relative humidity (RH) (%) was calculated from the air temperature and the dew point temperature using the Magnus-type formula shown in Equation 1. For this purpose, data was obtained from the Google Earth Engine (GEE) repository, specifically the ERA5-Land dataset from the Copernicus Climate Data Store (Muñoz-Sabater et al., 2021). The variables temperature_2m and dewpoint_temperature_2m, both expressed in kelvin, were extracted for the period between 12 April and 12 August 2024.

The ERA5-Land dataset includes the variable dewpoint_temperature_2m, representing the dew point temperature at 2 meters above the Earth's surface, which is used as input to estimate RH. Likewise, the variable temperature_2m represents the air temperature at the same height (Supplementary Table S4).

RH is calculated using the formula:

$$RH = 100 * \frac{\exp\left(\frac{aT_d}{b+T_d}\right)}{\exp\left(\frac{aT}{b+T}\right)} \tag{1}$$

where:
a = 17.625—constant.
b = 243.04—constant.
T = Air temperature.
T_d = Dew point temperature.

2.7 Statistical analysis

Statistical analysis was performed using R (version 4.4.1) via the RStudio interface (version 2024). To assess compost quality, one-sided confidence intervals were estimated using non-parametric bootstrapping, applying the percentile method with 5,000 resamples and an initial seed of 230,488. Subsequently, the effects of fixed and random factors on chemical properties, heavy metals, and coliform identification were estimated. These effects were determined using generalized linear mixed models (GLMM). The generalized linear mixed model was specified as in Equation 2, where denotes the expected response for observation *i* at station *j*. The model adopted was as follows:

$$g\left(E\left(Y_{ij}ij\right)\right) = g\left(u_{ij}\right) = \eta_{ij} = \beta 0 + X_{ij}\beta + a_j \tag{2}$$

Where:

$E(Y_{ij})$, Estimated mean for observation *i* in experimental station j; β_0, Overall mean; β, Vector of fixed effects associated with each independent variable X of dimension p × 1; X, Design matrix of dimension n (number of observations) × p (number of variables); a_j, Random effect of experimental station j, where $a_j \sim N(0, \sigma^2_a)$; and g(): Link function. The dependent variables were modelled according to their respective probability distributions. Model parameters were estimated using the glmmTMB function. Given the high number of explanatory variables (n = 27), a two-stage variable selection procedure was performed. First, variables with a collinearity index (VIF) greater than 5 were removed, evaluated using the check_collinearity function from the performance package. In the second stage, automated model selection was applied using the dredge function from the MuMIn package, based on the Corrected Akaike Information Criterion (AICc).

Subsequently, three candidate models were fitted using the selected variables, and the model with the lowest AICc value was chosen as the best-supported model. Model adequacy was then evaluated using the testResiduals function from the DHARMa package. Diagnostic tests confirmed, in most cases, the fulfilment of model assumptions, including residual uniformity, absence of over dispersion and outliers, and homoscedasticity.

3 Results

3.1 Compost quality and regulatory compliance

According to European regulations for organic fertilizers under the Component Material Category for Fertilizing Products (CFP), maximum permissible limits are established for heavy metals, including arsenic (As) < 40 mg kg^{-1}, cadmium (Cd) < 1.5 mg kg^{-1}, chromium (Cr) < 100 mg kg^{-1}, mercury (Hg) < 1 mg kg^{-1}, nickel (Ni) < 50 mg kg^{-1}, and lead (Pb) < 120 mg kg^{-1} (NTP 201.207:2020) (European Commission, 2022). Regarding pathogenic microorganisms, fertilizers must comply with the following microbiological requirements: fecal coliforms < 1,000 MPN g^{-1}, absence of Salmonella spp. in a 25 g sample, absence of helminth eggs in a 1 g sample, and complete absence of nematode larvae. In terms of nutrient content, the CFP establishes minimum thresholds for key macronutrients, requiring TN ≥ 2.50% and phosphorus (P) ≥ 0.87%. Additionally, NTP 201.207:2020 stipulates that OM must be ≥ 20% for the product to be considered as a quality organic fertilizer.

Table 2 presents the estimated lower and upper one-sided confidence intervals for heavy metals, fecal coliforms, and nutrient content across the different experimental stations. Overall, the concentrations of cadmium (0.16–1.11 mg kg^{-1}), chromium (6.34–23.21 mg kg^{-1}), mercury (0–0.78 mg kg^{-1}), nickel (2.70–11.89 mg kg^{-1}), and lead (2.81–39.71 mg kg^{-1}) remained within the regulatory maximum permissible limits, indicating that the produced compost complies with the established safety criteria. However, arsenic (As) concentrations at CELM (41.14 mg kg^{-1}) and Donoso (41.29 mg kg^{-1}) experimental stations slightly exceeded the maximum permissible limit established by current regulations (< 40 mg kg^{-1}), indicating marginal non-compliance with the quality criteria for this element. Regarding the microbiological quality, upper one-sided confidence intervals were estimated exclusively for fecal coliforms, which remained within the established regulatory limits. In addition, helminth eggs and nematode larvae were detected at concentrations below 1 per 2 g of substrate, while the presence of Salmonella spp. was below 3 MPN g^{-1} of total solids (TS). These results indicate that the composting process was adequately conducted and that the evaluated microbiological parameters met the sanitary criteria required for high-quality compost.

For nutrients, lower one-sided confidence intervals were estimated and compared with the minimum permissible limits. The OM content ranged from 12.21 to 56.50%, falling below the minimum value required by the regulations at the Canaán, El Porvenir, Pucallpa, and Vista Florida stations. TN content ranged from 0.68 to 2.89%, meeting the regulatory threshold (≥ 2.50%) only at the Baños del Inca, CELM, and Santa Ana stations. Phosphorus (P) concentrations ranged from 0.86 to 3.51%, with the Pucallpa station being the only location where the value was below the minimum level established by the regulations. Overall, these results indicate that the compost produced in Pucallpa did not meet the regulatory quality standards for the three evaluated nutrients.

3.2 Determinants of compost quality

3.2.1 Physicochemical properties of compost

The GLMMs enabled the identification of the key factors regulating the final composition of the compost by distinguishing between the general effects of the process (fixed factors) and the

TABLE 2 Compost quality across experimental stations is based on heavy metal concentration, microorganisms, and nutrient content.

EEA	UCI $_{95\%}$ of heavy metals (mg kg^{-1})						UCI $_{95\%}$ of FC (MPN g^{-1})	LCI $_{95\%}$ of nutrients (%)		
	As	Cd	Cr	Hg	Ni	Pb		OM	TN	*p*
Arequipa	37.44	0.44	11.10	0.00	9.17	6.95	0.70	20.57	1.81	1.32
Baños del Inca	27.14	0.42	7.85	0.00	4.75	2.81	< 0.18	40.79	2.85	3.31
Canaán	36.61	0.16	11.81	0.78	10.48	8.62	< 0.18	17.29	1.31	1.52
CELM	41.14	1.11	23.21	0.23	9.08	39.71	40.85	56.50	2.89	3.51
Donoso	41.29	0.36	6.34	0.00	3.57	15.74	127.61	31.26	1.87	1.41
El Porvenir	30.75	0.66	10.32	0.00	7.91	5.91	0.20	19.22	1.36	1.73
Illpa	36.04	0.86	10.34	0.00	8.13	8.05	1.05	29.75	2.14	1.79
Jaén	27.97	0.39	7.36	0.00	5.34	5.85	5.25	35.85	2.09	1.67
Pichanaki	36.16	0.34	11.83	0.00	11.89	6.34	8.73	28.15	2.05	0.97
Pucallpa	39.58	0.35	6.98	0.00	2.70	4.48	8.30	12.21	0.68	0.86
Santa Ana	29.88	0.43	6.92	0.00	6.40	15.32	< 0.18	37.36	2.85	1.68
Vista Florida	34.65	0.50	7.13	0.00	5.62	7.57	< 0.18	19.98	1.75	1.20

UCI and LCI, Upper and lower one-sided confidence intervals, respectively. As, Arsenic; Cd, Cadmium; Cr, Chromium; Hg, Mercury; Ni, Nickel; Pb, Lead; FC, Fecal coliforms; OM, Organic matter; TN, Total nitrogen; P, Phosphorus.

influence of the regional context (random factors). In addition, these models allowed the estimation of the explained variance at both marginal and conditional levels, as well as the selection of the model that best fitted the data. The results of this analysis are presented in Table 3.

In general, fixed factors explained most of the variability associated with compost quality, acting through different internal and environmental parameters depending on the variable evaluated. OM and carbon fractions (TC and OC) showed dynamics mainly regulated by temperature and moisture. The OM content increased with higher moisture during the thermophilic phase (M2, week 4) and maturation phase (M5, week 16). However, its relationship with ambient temperature (AT) and pile temperature during the thermophilic phase (T2, week 4) exhibited a quadratic pattern (Figures 2A,B). The higher initial temperature had a positive effect on total carbon (TC) and organic carbon (OC) (T1, week 1) and moisture during the thermophilic phase (M2). In contrast, pH during the thermophilic phase (pH2) showed a quadratic effect on both parameters (TC: Figure 2C; OC: Figure 2D). Additionally, EC during the active maturation phase (EC3, week 8) exhibited a quadratic behavior specifically over OC (Figure 2E).

The thermophilic phase (M2) was sensitive to stress-related factors. High EC during the thermophilic phase (EC2, week 4) reduced TN content. Like carbon fractions, TN exhibited a quadratic relationship with pH during the maturation phase (pH5, week 16) and with EC at week 8 (EC3), as shown in Figure 2G.

TABLE 3 Physicochemical properties of compost based on its internal and environmental parameters: fixed effects, distribution selection, and variance of random effects.

Predictors	OM (%)	TC (g kg^{-1})	OC (g kg^{-1})	TN (mg g^{-1})	P (mg kg^{-1})	Final C: N ratio
Fixed effects ($\hat{\beta}$)						
Intercept	−1.50***	5.35***	5.11***	2.93***	5.25***	2.16***
M1					0.16**	
AT	−0.40***					
AT^2	0.24***					
T1		0.16***	0.15***	0.11***	0.30***	
T2	0.10°					
T2^2	0.51***					
T5						0.01
T5^2						0.07***
M2	0.23***		0.16***	0.26***	−0.17*	
M3		0.10*				
M5	0.51***					0.05**
pH1						−0.05*
pH2		−0.23***	−0.23***			
pH2^2		−0.09**	−0.07*			
pH5				−0.22***		0.05*
pH5^2				−0.04*		
EC2				−0.08**		
EC3		0.22***	0.16**	0.17***	0.29***	
EC3^2			0.10*	0.33***		
Initial C: N ratio					−0.32***	
Distribution selection						
Distribution	Beta	Tweede	Tweede	Gamma	Gamma	Gamma
AICc	−149.36	496.14	485.50	239.97	519.81	120.48
Variance of random effects ($\hat{\sigma}$)						
EEA	0.10	0.09	0.09	0.00	0.12	0.07
Nakagawa's R^2 coefficient						
Marginal	0.9269	0.7281	0.7859	0.9277	0.6964	0.6502
Conditional	0.0317	0.0686	0.0584	0.0000	0.0728	0.2074

OM, Organic matter; TC, Total carbon; OC, Organic carbon; TN, Total nitrogen; P, Phosphorus; TC/TN, Total carbon to total nitrogen ratio. M1, Ambient humidity in week 1 of compost maturation; AT, Average ambient temperature; T1, T2, T5, Compost temperature during maturation stage (weeks 1, 4, and 16); M2, M3, M5, Compost moisture content during maturation stage (weeks 4, 8, and 16); pH1, pH2, pH5: Compost pH during maturation stage (weeks 1, 4, and 16); EC2, EC3: Electrical conductivity of the compost during maturation stage (weeks 4 and 8); Initial and final C: N ratio: Compost carbon-to-nitrogen ratio at weeks 1 and 16 of maturation, respectively. AICc, Corrected Akaike information criterion.

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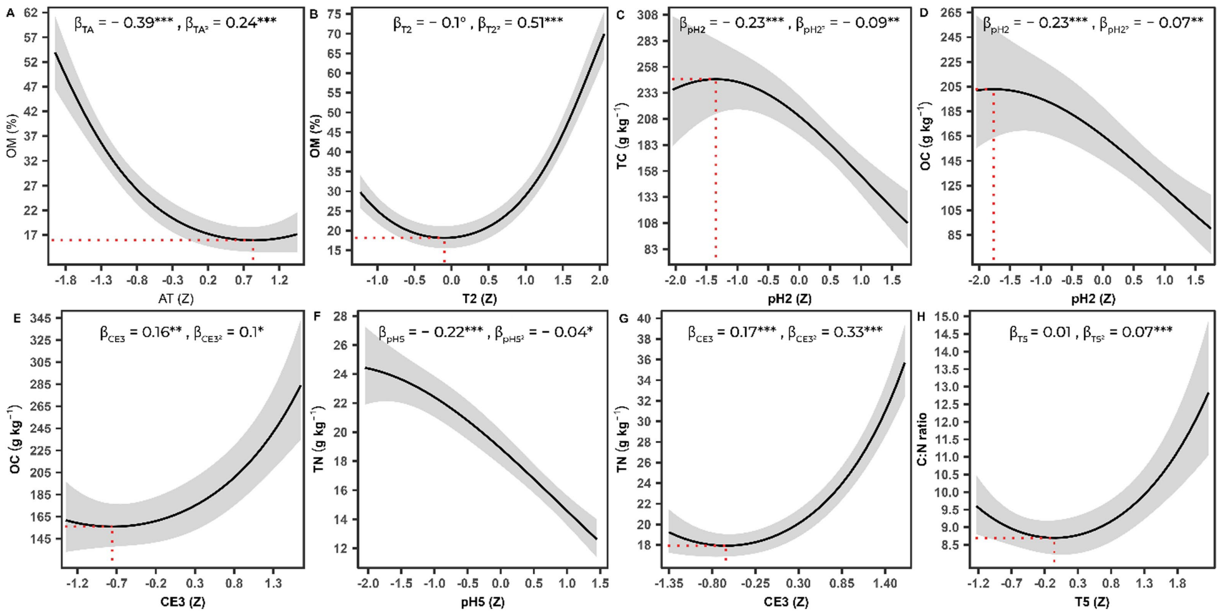

FIGURE 2
Quadratic fixed effects of internal and environmental parameters on the chemical properties of compost. **(A)** Effect of average ambient temperature (optimum at $Z = 0.833$) on OM; **(B)** Effect of compost temperature at week 4 (optimum at $Z = -0.097$) on OM; **(C)** Effect of compost pH at week 4 (optimum at $Z = -1.347$) on TC; **(D)** and **(E)** Effects of compost pH at week 4 (optimum at $Z = -1.768$) and compost EC at week 8 (optimum at $Z = -0.755$), respectively, on OC; **(F)** Total nitrogen (TN) vs. compost pH in week 16 (pH5) and **(G)** Effects of compost pH at week 16 (optimum at $Z = -2.05$) and compost CE at week 8 (optimum at $Z = -0.622$), respectively, on TN; **(H)** Effect of compost temperature at week 16 (optimum at $Z = -0.056$) on the final C: N ratio. Z: Standardized values.

In contrast, phosphorus (P) accumulation showed a different regulatory pattern. Although it increased with higher initial environmental humidity (M1), initial temperature (T1), and EC (EC3), it was negatively affected by a high initial C: N ratio and greater moisture content during the thermophilic phase (M2). This pattern suggests the presence of microbial competition or a phosphorus immobilization mechanism distinct from that observed for nitrogen.

Finally, the final C: N ratio, an indicator of compost maturity and stability, decreased with lower initial pH (pH1), whereas higher pH at the maturation stage (pH5) and greater final moisture content (H5) increased this ratio. Likewise, temperature during the maturation phase (T5, week 16) exhibited a quadratic effect on the final C: N ratio.

The random effects associated with the experimental stations showed different levels of heterogeneity across the physicochemical properties of the compost. The greatest heterogeneity was observed for P ($\sigma = 0.12$), whereas TN showed no variability attributable to the stations ($\sigma^2 = 0$). Likewise, the proportion of variance explained by the random effects was higher for the final C: N ratio, indicating that approximately 20% of its variability can be attributed to characteristics specific to each experimental station. In contrast, the absence of heterogeneity for TN suggests that the observed variability was explained almost entirely by fixed factors (99.77%).

In this context, the analysis by each experimental station revealed differential patterns among regions. For OM (Figure 3A), CELM showed a greater effect compared with Vista Florida and Pichanaki. For TC (Figure 3B), Donoso recorded higher values than Arequipa, Canaán, and Illpa. Similarly, for OC (Figure 3C), Donoso also reported higher levels than those in Arequipa and Canaán. Regarding phosphorus (Figure 3D), Baños del Inca exhibited higher concentrations compared with Pichanaki and Santa Ana. Finally, for the final C: N ratio (Figure 3E), the Illpa station showed higher values than those at Arequipa and Santa Ana.

3.2.2 Fecal coliforms in compost quality

The presence of fecal coliforms was modelled using a GLMM with a binomial distribution and a logit link function, selected based on the AICc criterion, given the dichotomous nature of the response variable. The fixed factor EC explained approximately 67.10% of the variability observed in the presence of fecal coliforms. Specifically, a one-standard-deviation increase in EC reduced the odds of detecting fecal coliforms by 94.04% (Figure 4).

3.2.3 Heavy metal content in compost

Heavy metals were modelled using GLMMs, with probability distributions selected based on the AICc criterion. The variance explained by fixed effects (marginal R^2) predominated for Cr, As, Ni, and Pb, whereas for Cd, the contribution of the random effect associated with the experimental stations was relatively higher. The low R^2 values observed, particularly for As, mainly reflect the characteristics of the lognormal model used (Table 4).

The fixed factors exerted different effects on heavy metal concentrations. For example, As decreased by an average of 7.69% with a one-standard-deviation increase in pH5; in contrast, M5 (Figure 5A) and EC2 (Figure 5B) showed quadratic effects. For Cd, the concentrations increased by an average of 34.98 and 7.25% as T2 and M3 increased by one standard deviation, respectively. In the case of Cr, its concentration increased by an average of 32.31% when pH1 increased by one standard deviation. However, increases of one standard deviation in T4, M4, pH5, EC3, and the initial C: N ratio led to average decreases in Cr concentration of 18.12, 14.79, 15.63, 22.89, and 15.63%, respectively. Regarding Ni, quadratic effects of M1 (Figure 5C) and the initial C: N ratio (Figure 5D) were observed.

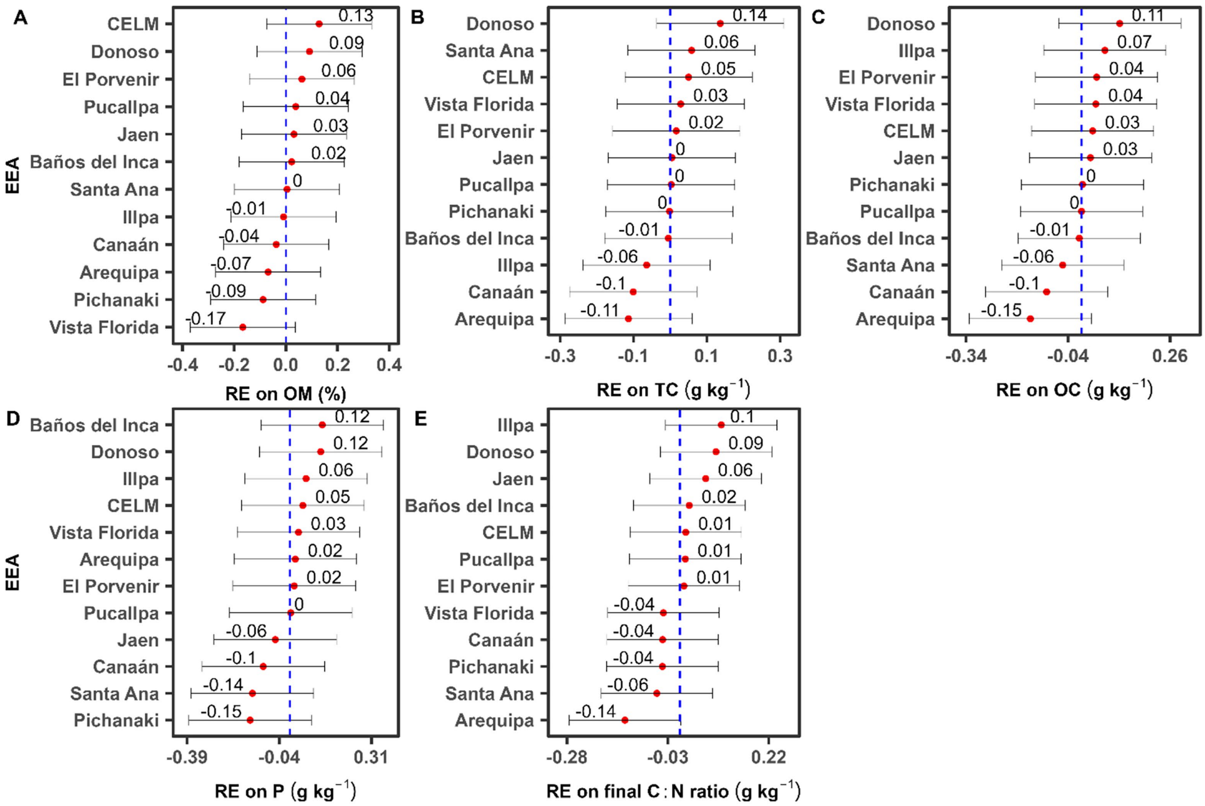

FIGURE 3
Random effects of the experimental stations on the chemical properties of compost. **(A)** Random effects of the EEA on OM; **(B)** random effects of EEA on TC; **(C)** random effects of EEA on OC; **(D)** random effects of EEA on P; and **(E)** random effects of EEA on the final C: N ratio. RE: Random effects.

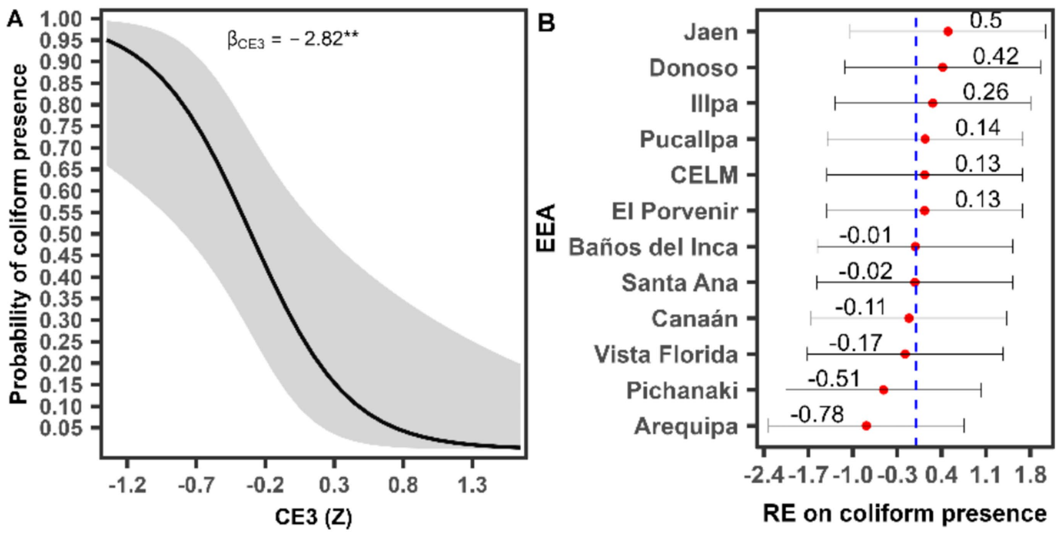

FIGURE 4
Fixed and random effects on the presence of fecal coliforms in compost. **(A)** Effect of EC at week 8 (CE3) on the probability of detecting fecal coliforms; **(B)** random effects of the EEA on the presence of fecal coliforms.

Finally, Pb concentrations increased by an average of 33.64% with one-standard-deviation increase in T4 and decreased by an average of 24.20% with a one-standard-deviation decrease in EC5.

Regarding the variance of the random effects, Cd ($\hat{\sigma}$ = 0.45) showed greater heterogeneity, suggesting that 60.52% of the observed variability was explained by characteristics specific to each experimental station. In contrast, Cr ($\hat{\sigma}$ = 0) exhibited no heterogeneity, indicating that 72.45% of the observed differences were explained exclusively by fixed factors.

Regarding the random effects, the experimental stations exhibited heterogeneous additional contributions to the concentration of heavy metals in the compost (Figure 6), suggesting that

TABLE 4 Heavy metals in compost based on their internal parameters: fixed effects, distribution selection, and variance of random effects.

Predictors	As (mg kg^{-1})	Cd (mg kg^{-1})	Cr (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})
Fixed effects ($\hat{\beta}$)					
Intercept	3.46***	−0.95***	2.13***	2.22***	1.94***
T2		0.30*			0.29*
T4			−0.20***		
M1				−0.17***	
M1^2				−0.05*	
M3		0.07			
M4			−0.16***		
M5	−0.06**				
M5^2	0.03**				
pH1	−0.08***		0.28***		
pH5			−0.17***		
EC2	−0.04°				
EC2^2	0.02*				
EC3			−0.26***		
EC5					−0.28**
Initial C: N ratio			−0.17***	0.28	
Initial C: N ratio^2				−0.43**	
Distribution selection					
Distribution	Lognormal	Tweede	Gamma	Gamma	Gamma
AICc	230.36	−137.48	203.35	184.28	231.37
Variance of random effects ($\hat{\sigma}$)					
EEA	0.09	0.45	0.00	0.31	0.43
Nakagawa's R^2 coefficient					
Marginal	0.006	0.2676	0.7245	0.5076	0.4649
Conditional	0.0039	0.6052	0.000	0.3695	0.3907

As, Arsenic; Cd, Cadmium; Cr, Chromium; Ni, Nickel; Pb, Lead. T2, T4: Compost temperature during the maturation stage (weeks 4 and 12); M1, M3, M4, M5: Compost moisture content during the maturation (weeks 1, 8, 12, and 16); pH1, pH5: Compost pH during the maturation stage (weeks 1 and 16); EC2, EC3, EC5: Electrical conductivity of the compost during maturation (weeks 4, 8, and 16); Initial C: N ratio: Carbon-to-nitrogen ratio of the compost at the beginning of the maturation stage. AICc, corrected akaike information criterion.

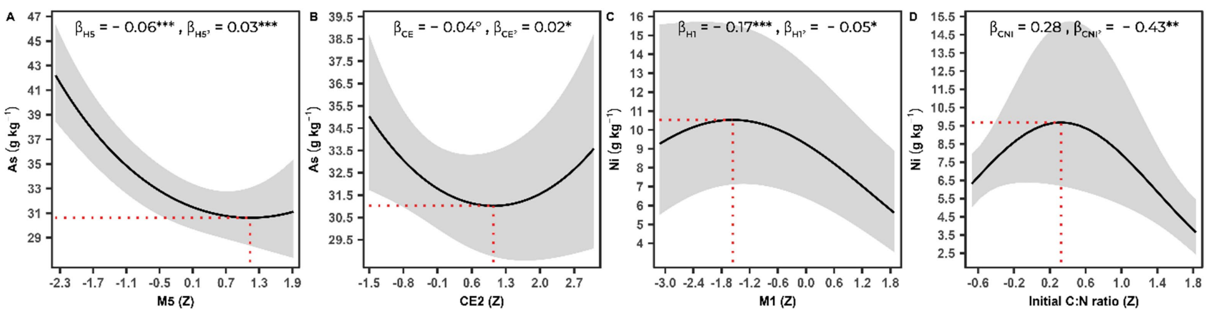

FIGURE 5
Quadratic fixed effects of internal and environmental parameters on heavy metals in compost. **(A)** and **(B)** Effects of compost moisture content at week 16 (optimum at Z = 1.134) and compost CE at week 4 (optimum at Z = 1.045), respectively, on As concentration. **(C)** and **(D)** Effects of compost moisture content at week 1 (optimum at Z = −1.563) and the initial C: N ratio of the compost.

these concentrations varied with the specific conditions of each station. Specifically, As concentrations were higher in Canaán than in Illpa, Santa Ana, Baños del Inca, CELM, and Jaén (Figure 6A). For Cd, Illpa showed the highest values compared with Jaén, Donoso, Vista Florida, and Canaán (Figure 6B). In the case of Ni, concentrations were higher in Pichanaki than in

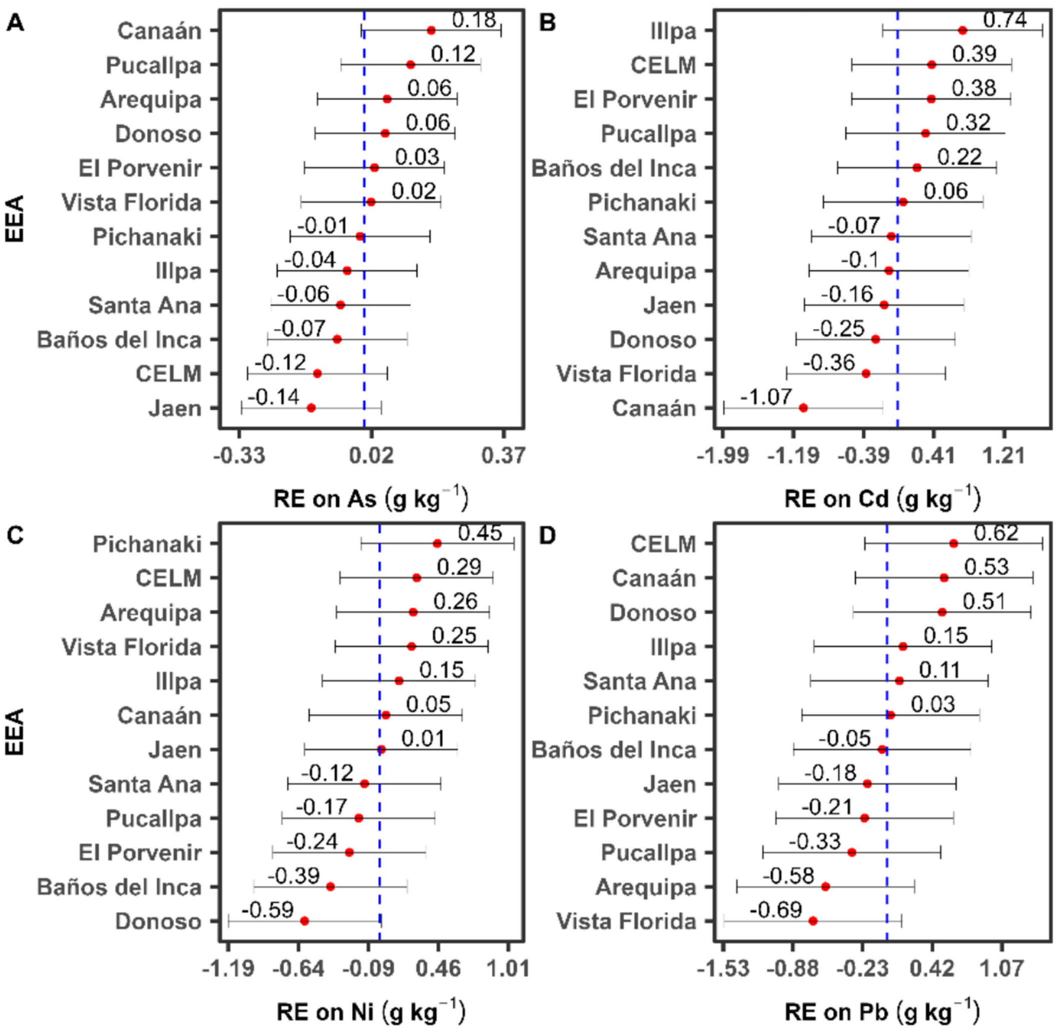

FIGURE 6
Random effects of the experimental stations on heavy metal concentrations in compost. **(A)** Random effects of the EEA on As; **(B)** random effects of the EEA on Cd; **(C)** random effects of the EEA on Ni; and **(D)** random effects of the EEA on Pb.

Pucallpa, El Porvenir, Baños del Inca, and Donoso (Figure 6C). Finally, Pb reached its highest levels in CELM, exceeding those observed in Illpa, Pucallpa, Baños del Inca, Vista Florida, and Arequipa (Figure 6D).

3.3 Determinants of compost yield

Compost yield was modelled using a GLMM with a beta distribution, selected because it provided the best fit according to the AICc criterion and because the response variable is proportional. The results indicate that the fixed factors (EC1, M1, M4, and T4) explained approximately 75.26% of the variability in yield. Increases of one standard deviation in T4 and M4 increased the average yield by 64.87 and 37.71%, respectively, whereas an equivalent increase in EC1 reduced yield by 17.30%. In addition, Figure 7A shows a quadratic effect of M1 on yield.

Regarding the variability associated with random effects on yield ($\sigma = 0.41$), heterogeneity was observed among experimental stations, suggesting that approximately 22.61% of the yield variability is attributable to station-specific differences. Jaén, El Porvenir, Santa Ana, Pucallpa, Baños del Inca, and Donoso showed higher baseline yields compared with Canaán and Vista Florida (Figure 7B). These differences among stations may be associated with local factors not explicitly included in the model, such as management practices or characteristics of the used feedstocks. Among these, the proportions of nitrogen-rich feedstocks applied in Vista Florida, Canaán, CELM, and Arequipa (91.74, 80, 62.12, and 73.91%, respectively) may be relevant, as high nitrogen proportions have previously been associated with nitrogen losses through volatilization.

4 Discussion

4.1 Carbon and nitrogen dynamics: synergy between thermal drivers and chemical equilibrium

The results indicate that ambient temperature (AT) and initial temperature (T1) act as primary drivers of carbon stabilization, regulating the kinetics of biomass degradation across regions. The

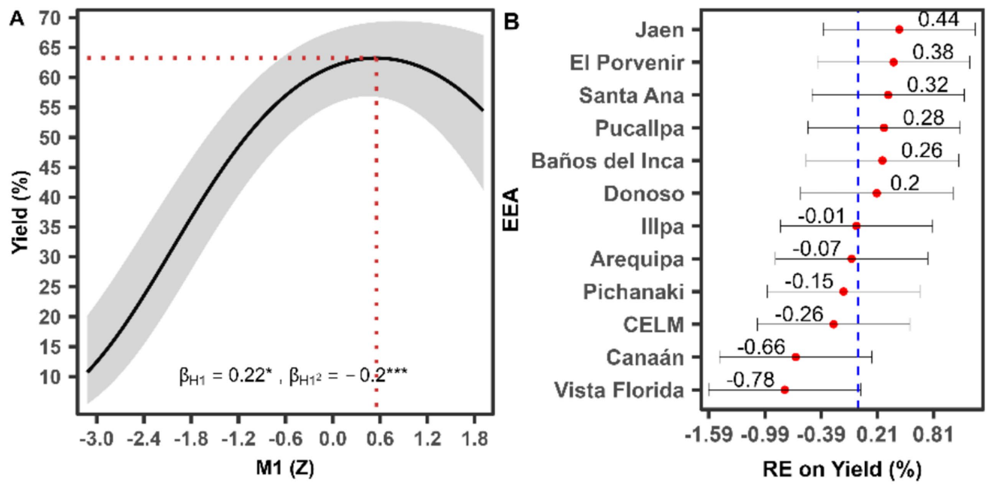

FIGURE 7
Quadratic fixed effects and random effects on compost yield. **(A)** Effect of compost moisture content at week 1 (optimum at $Z = 0.55$) on yield; **(B)** random effects of the EEA on yield.

positive effect of AT on OM content is consistent with the findings of Noor et al. Noor et al. (2024), who reported that higher temperatures enhance microbial enzymatic activity responsible for the degradation of carbon compounds. However, it is important to ensure that temperatures do not excessively exceed 55–60 °C, as prolonged exposure to such levels may reduce the diversity of essential mesophilic microorganisms during the later stages of composting, thereby decreasing overall degradation efficiency (Cai et al., 2023; Miyatake and Iwabuchi, 2005). This phenomenon is particularly relevant in lowland rainforest regions such as Pucallpa, where elevated ambient temperatures can intensify mineralization processes, reducing OM to suboptimal levels, as observed with OM values of 12.21%.

Regarding TC, the initial thermal rise showed a highly significant effect, promoting the transformation of easily biodegradable compounds into more stable fractions (Jusoh et al., 2013). This finding is associated with the succession of carbohydrate-active enzymes (CAZymes): the initial stages are dominated by cellulolytic microorganisms, whereas the later stages involve the degradation of more complex polysaccharides and lignin-derived compounds (Wang et al., 2025). In high Andean regions such as Illpa, the chemical recalcitrance of quinoa (*Chenopodium quinoa*) stubble, which is rich in phenolic compounds, favored a slower but more robust humification process, allowing greater retention of OC compared with lignocellulosic residues commonly found in coastal regions.

This process requires strict water balance; moisture content in weeks 4 and 16 showed a positive effect on OM and OC, suggesting that water acts as a stabilizing agent for humic and fulvic fractions when maintained between 50%–60% (Gajalakshmi and Abbasi, 2008), thereby preventing carbon losses through oxidation. Conversely, moisture levels above 60% can inhibit O_2 diffusion, inducing anaerobic conditions (Das and Keener, 1997; Bernal et al., 2017). In addition, pH in week 4 (pH2) was identified as a key factor for nitrogen balance within the range of 6.5–7.5, intensifying mineralization and reducing TC and OC reserves through both linear and quadratic effects, likely due to the volatilization of NH_3 or the release of CO_2 (Ye et al., 2023). Finally, optimization of the final C: N ratio occurred at 26.83 °C during the maturation phase, confirming that lower temperatures delay the decomposition of recalcitrant materials such as lignin (Zhang et al., 2022).

4.2 Chemical safety: the role of humic acids in metal passivation and the arsenic challenge

Our results indicate that the composting process does not eliminate heavy metals; rather, it functions as a biogeochemical transformation system in which the measurable fraction fluctuates according to the mineralization of OM and the biosynthesis of humic substances. According to Reyes et al. (Pinto et al., 2020), humic acids act as organic ligands that immobilize metals in the solid fraction through chelation and surface adsorption processes, thereby reducing their systemic mobility toward plants (Ortiz-Dongo et al., 2024). In this context, the use of guinea pig (*Cavia porcellus*) manure on the central coast proved to be a strategic alternative, maintaining Pb levels in CELM below the limit recommended by the German standard RAL-GZ 251 (Gottschall et al., 2023). The digestive physiology of guinea pigs may act as a biological filter, preventing the excessive accumulation of metals in their excreta compared with cattle raised on pastures exposed to industrial contamination (Chirinos-Peinado et al., 2025).

However, arsenic (As) was a critical exception, linked to both geological conditions and anthropogenic activity. Concentrations in CELM and Donoso exceeded the 20 mg kg^{-1} threshold established in European standards applied in Belgium, Germany, and Ireland (Prasad and Foster, 2023), posing a potential carcinogenic risk if the compost is used indiscriminately in agriculture (Speer et al., 2023; Yang et al., 2017).

The GLMM captured uncontrolled variability through random effects associated with the EEA, with variances ranging from 0.09 to 0.12, revealing station-specific biases despite the multi-site observational design. Random variance in Lima was approximately twice as high as in the highland regions, supporting the interpretation that geological conditions act as a dominant factor over common physicochemical driver such as EC3 and pH2.

Composting can partially immobilize arsenic through the formation of stable organometallic complexes; however, high levels of available P may act as a driver of mobilization. Phosphates, due to their chemical similarity to arsenates, compete for the same adsorption sites in soil colloids, potentially displacing immobilized arsenic into the soil solution and increasing its uptake by crops (Stazi et al., 2022). These findings suggest that in coastal ecoregions of Peru, compost management should priorities not only the total concentration of metals but also the P: As ratio to mitigate potential carcinogenic risks in the food chain.

4.3 Sanitary efficacy and osmotic stress: pathogen inactivation under regional variability

Sanitary quality was optimal across all Agrarian Experimental Stations (EEA), with fecal coliform (FC) levels below 1,000 CFU g^{-1}, confirming the effectiveness of the composting process in eliminating pathogens (Mengistu et al., 2018; Siles-Castellano et al., 2020). This sanitary success is based on a multitarget inactivation mechanism that goes beyond simple thermal exposure. Although sustained temperatures above 55 °C induce enzymatic denaturation and disrupt cell membranes (Germer et al., 2009; Bernal et al., 2017), our model revealed an additional decisive factor.

The central finding is the inhibitory effect of accumulated salinity on pathogen persistence. The negative coefficient of EC at week 8 (EC3) indicates that osmotic stress acts as a secondary disinfecting agent. According to Bremer and Krämer (Bremer and Krämer, 2019), high external osmotic pressure limits intracellular hydration, disrupting microbial homeostasis and leading to persistent cellular viability even under suboptimal temperature conditions. This synergy is particularly relevant in decentralized systems such as those evaluated in this study, where salt accumulation, resulting from water evaporation and the degradation of OM, complements the overall thermal inactivation (Siles-Castellano et al., 2020).

Nevertheless, the analysis of random effects revealed regional variability that should be considered in management protocols. Stations such as Jaén and Illpa showed higher model residuals for FC survival, which may be associated with more humid microclimates or greater amounts fresh OM content that can temporarily protect bacteria through mechanical shielding. In contrast, Arequipa and Pichanaki exhibited better sanitation performance, likely due to lower RH, which enhances aeration and facilitates thermal regulation (Gurtler et al., 2018). However, excessive moisture content (>60%) during the composting process can promote the persistence of FC by reducing oxygen availability and creating anaerobic zones that not only prevent achieving sustained thermophilic temperatures but also promote the survival of enterobacteria (Das and Keener, 1997; Bernal et al., 2017; Richard et al., 2002). Furthermore, moisture levels between 50–60% have been reported to maintain optimal microbial activity while reducing carbon losses through oxidation (Gajalakshmi and Abbasi, 2008; Céspedes et al., 2018; Morocho et al., 2025).

4.4 Compost yield optimization and regionalized water balance under climatic drivers

The final biomass yield was strongly influenced by an optimal moisture content of 60%. According to Weerasinghe et al. (Vpa et al., 2017) and Peña et al. (Peña et al., 2020; Bai and Wang, 2010; Vpa et al., 2017), maintaining this threshold is essential for microbial respiration; excessive moisture reduces oxygen availability and can halt the composting process (Wang et al., 2025; Germer et al., 2009). In addition, we observed that an average temperature of 31 °C in week 12 positively influenced yield by preventing the excessive volatilization of nitrogen in the form of ammonia (NH_3), a phenomenon commonly observed under prolonged high-temperature regimes (Liu et al., 2021; Nigussie et al., 2016). In this context, temperature also acts as an indirect indicator of overall microbial activity and process efficiency (Wang et al., 2024).

Regarding nutrients, the variability observed in OM (12–40%), TN (1.3–2.9%), and P (0.9–3.5%) reflects climatic pressures in regions such as Pucallpa, El Porvenir, and Vista Florida. High temperatures and intense rainfall in these areas can stimulate microbial activity and accelerate mineralization processes, thereby promoting nitrate leaching (Woo and Seo, 2022). This trend is consistent with findings from Palestine, where temperature variations were identified as a key factor determining the final OM content of compost (Al-Khatib et al., 2023). The average values of TN (1.91%) and P (2.4%) obtained in this study are consistent with international reports on agro-industrial compost produced under tropical conditions (Shim et al., 2022). These results highlight the importance of evaluating the applicability of regional standards, such as NTP 201.207:2020, and international guidelines, including those of the European Commission (Miyatake and Iwabuchi, 2005), within diverse ecoregional contexts.

The lowest yields were observed at nitrogen-rich sites, such as Vista Florida and Canaán (Supplementary Table S3). This pattern can be attributed to the volatilization of ammonia (NH_3) during the thermophilic phase, resulting from the transformation of ammonium (NH_4^+) at high temperatures.

4.5 Methodological robustness: the value of GLMMs in complex territorial research

From a statistical perspective, the use of generalized linear mixed models (GLMMs) represents a significant methodological advance, as it enables the capture of sources of variability that traditional analysis of variance (ANOVA) often overlooks in large-scale field experiments lacking perfect replication. According to Madden and Ojiambo Madden and Ojiambo (2024), the GLMM framework allows models to be fitted to the data rather than forcing the data to conform to restrictive assumptions, thereby effectively addressing issues of non-independence and the non-Gaussian distribution commonly observed in biological indicators.

The inclusion of Agrarian Experimental Stations (EEA) as a random effect captures unobserved variability (latent heterogeneity) within each province, enabling inferences about compost quality to extend beyond individual cases and be generalized at a national scale. This approach is particularly important when analyzing socio-ecological systems, where factors such as the native microbial load of soil or local microclimatic conditions introduce spatial correlations that must be explicitly accounted for in the model. Furthermore, the assignment of specific probability distributions (Beta for OM, Tweedie for carbon-related variables, and Gamma for nutrients) avoided the distortions often associated with conventional logarithmic transformations, which can underestimate standard errors. This flexibility in handling asymmetric and positively skewed distributions ensures more reliable results in biomass studies. Finally, the use of simulation-based validation (DHARMa) enabled the detection of potential overdispersion or under dispersion, which are critical aspects in validating multilevel models.

This approach not only strengthens the scientific validity of the results but also provides a methodological framework for future research in countries with high geographical diversity, where controlled laboratory experiments alone are insufficient to capture the complexity of real-field conditions.

5 Conclusion

Research conducted across the 12 agroecological zones in Peru demonstrates that there is no single formula for composting; rather, compost quality emerges from adapting biotechnological practices to local environmental conditions. This finding implies that in other megadiverse regions with similar altitudinal and climatic gradients, composting protocols must be dynamically adjusted based on local abiotic drivers to ensure consistent end-product quality. The abundance of OC in high-Andean regions, driven by quinoa residues and cold climatic conditions, presents a strategic opportunity to transform these areas into centers for producing highly stable soil amendments for soil restoration. By prioritizing high-altitude environments for carbon stabilization, carbon sequestration efforts can be optimized by targeting regions where low temperatures naturally favor organic matter retention, directly influencing the long-term agronomic value of the compost. Furthermore, the validation of guinea pig manure as a high-quality raw material with a low risk of heavy metal contamination in coastal regions offers a practical solution for improving food security in areas exposed to geogenic or industrial pollution. This identification of regional low-risk feedstocks allows for the intentional selection of inputs that minimize chemical hazards, thereby ensuring that the final compost quality meets stringent international biosafety standards.

From a methodological perspective, the application of generalized linear mixed models (GLMMs) has proven an indispensable tool for studies of this nature, where logistical constraints hinder the implementation of traditional experimental designs with multiple replicates. Crucially, this approach allows for the extrapolation of results to broader geographical contexts by isolating the systematic effects of climate and feedstock from site-specific variability, providing a scalable model for organic waste management in similar global ecosystems.

From a practical perspective, these results provide a scientific basis for developing region-specific composting protocols that incorporate the monitoring of critical parameters during the first 4 weeks of the process, thereby simplifying technical management for smallholder farmers without compromising international sanitary standards. The results indicate that in coastal regions, farmers could prioritize mixtures containing guinea pig manure to produce safe and nutrient-rich compost, whereas those in highland areas could utilize locally available Andean residues to enhance the OC content of the final product. The minimum (or ideal) percentages of each material might be determined in additional individualized studies for each region based on the recommendations proposed in this research. These differentiated management strategies directly influence the chemical and biological stability of the compost, allowing for the customization of the final product to meet the specific nutritional needs of local soils.

This study demonstrates that GLMMs are a suitable tool for analyzing complex and heterogeneous agronomic systems, such as the composting processes evaluated at a regional scale using local feedstocks. This approach made it possible to distinguish the effects of fixed variables from the combined influence of other factors characterizing each area, while explicitly incorporating the hierarchical structure of the data. By integrating inter-area variability into the modelling framework, GLMMs enable quantification of the heterogeneity inherent in the system and strengthen statistical inference in contexts where the implementation of controlled experiments is limited. In this regard, the proposed methodological approach represents a transferable analytical framework for optimizing organic waste management in countries with high agroclimatic diversity.

These recommendations, tailored to local resources, promote more sustainable agriculture that is less dependent on external input. Finally, the study highlights the importance of taking regional characteristics into account in agricultural waste management policies. Ultimately, understanding the interplay between regional climatic constraints and biomass availability serves as a predictive framework for determining final compost quality in diverse agroecological settings. A single set of regulations for the whole country could fail to capitalize on the specific advantages offered by each type of waste depending on its origin, whereas differentiated approaches, based on evidence such as that generated here, could maximize both the agronomic and environmental benefits of composting at a national level.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

NH: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. UA: Formal analysis, Methodology, Software, Visualization, Writing – review & editing. LO: Conceptualization, Resources, Writing – original draft. CP: Resources, Writing – original draft. SA: Resources, Writing – original draft. UC: Resources, Visualization, Writing – original draft. RO: Writing – review & editing. LR: Data curation, Methodology, Writing – original draft. NC: Resources, Writing – original draft. YP: Conceptualization, Resources, Writing – original draft. GA: Conceptualization, Resources, Writing – original draft. AS: Methodology, Resources, Writing – original draft. JC: Methodology, Resources, Writing – original draft. RS: Supervision, 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.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1837350/full#supplementary-material

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