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REVIEW ARTICLE

Improved Compost Production from Fruit and Vegetable Market Waste: A Case Study in Bagua, Amazonas (Peru)

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Abstract: Inadequate management of organic solid waste in municipal markets represents a critical environmental challenge in tropical developing regions, where high humidity (>80%) and elevated temperatures (>25°C) accelerate decomposition, generating leachate and greenhouse gas emissions. In Peru, over 50% of municipal waste is organic, yet less than 20% is valorised through composting, highlighting a substantial technological gap. This study evaluated an improved composting system (the Bagua Method) applied to fruit and vegetable waste from the Municipal Market of Bagua, Peruvian Amazon, over seven years (2018–2024). A comparative experimental design with triplicate piles (n = 6) compared enzyme-amended piles (Bagua Method) against nonenzyme controls. Comprehensive physicochemical characterisation followed standard methods (AOAC, WalkleyBlack, Kjeldahl), including moisture, ash, total organic carbon, nitrogen, pH, electrical conductivity, bulk density, and germination index. Statistical analysis employed two-way ANOVA with Tukey HSD post-hoc testing. A structured survey assessed waste management practices among 30 market traders. The Bagua Method achieved 88.8–89.5% recovery efficiency, converting 21.9±0.9 t year^{-1} of organic residues into 8.3–9.2 t year^{-1} of quality compost. Enzymatic amendment reduced composting time to 60 days (33% faster than controls), with thermophilic temperatures (>55°C) reached within 48±6 hours. Final compost met Ö-NORM S 2022 standards: C/N ratio 18.9±0.7, pH 8.5±0.2, EC 3.1±0.3 mS/cm, and germination index 95±3% versus 78±4% for controls ($p<0.001$). Survey results indicated that 11% trader participation contributed 40% of usable waste; scaling to 30% participation could achieve 94% recovery efficiency. The Bagua Method constitutes a technically viable, environmentally sustainable, and socially inclusive alternative for organic waste recovery, contributing to circular economy principles and SDGs 11, 12, and 15. The method demonstrates substantial scaling potential across Peru's northern macroregion, with capacity to divert ~50,000 t year^{-1} of waste and create 200+ green jobs.

Keywords: Composting, Municipal Solid Waste, Circular Economy, Enzymatic Amendment, Tropical Agriculture, Peru, Amazon

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Introduction

The inadequate management of organic solid waste in municipal markets represents a critical environmental challenge in medium-sized cities of the Global South, particularly in tropical regions where high humidity rates (>80%) and elevated average temperatures (>25°C) accelerate decomposition, generating leachate and greenhouse gas emissions [1-3]. In Peru, over 50% of municipal waste is organic, yet less than 20% is valorised through composting [4], highlighting a substantial technological and operational gap that this study addresses.

Markets and municipal stops generate significant quantities of fresh organic waste (fruit and vegetable scraps, peels, leaves), characterised by high moisture content, rapid decomposition rates, and elevated nutrient concentrations, but also by physicochemical properties that can hinder the composting process if not managed appropriately, including suboptimal carbon-to-nitrogen ratios, potential contaminants, compaction issues, and oxygen limitation [5]. Recent international studies emphasise that optimising compost production requires rigorous attention to physical and chemical parameters, including moisture management, aeration, C:N ratio optimisation, particle size reduction, and systematic management of mesophilic, thermophilic, sanitisation, cooling, and maturation phases [6-8].

In the Peruvian context, [9] demonstrated that compost produced from municipal organic waste significantly improved the physical, chemical, and biological properties of degraded Amazonian soils, whilst favouring crop growth, thereby establishing the agronomic potential of well-formulated compost [3, 9]. Similarly, [10] confirmed that the organic fraction constitutes a substantial portion of municipal solid waste in Peru, and that systematic segregation, treatment, and transformation into quality compost can contribute simultaneously to environmental impact mitigation and degraded land restoration [10]. The implementation of adequate selective collection systems enables the identification of usable and non-usable material streams, whilst emerging treatment technologies play increasingly important roles in waste management optimization [11, 12].

A critical gap in organic waste management in the Peruvian Amazon remains the development of context-appropriate technologies that account for local climatic conditions, available resources, and socioeconomic constraints [13]. Whilst international composting methodologies exist, their direct application in tropical regions with high humidity and temperature variations requires significant adaptation. The present study addresses this gap through the development and validation of the 'Bagua Method,' a composting technique derived from Takakura principles [14] but specifically modified with native enzymatic additives to accelerate decomposition under Amazonian conditions.

The novelty of this research lies in its integrative approach, combining technical composting optimisation with community participation and municipal governance a triple-helix model that advances beyond conventional waste management studies focusing solely on technological aspects [15]. This study offers a replicable framework for similar intermediate cities in tropical developing regions, contributing to Sustainable Development Goals 11 (sustainable cities), 12 (responsible consumption), and 15 (life on land).

Materials and Methods

Study Area and Context

This study was conducted in the province of Bagua, located in the central-northwestern part of the Amazonas region, Peru (5°36'50.75" S, 78°23'41.967" W). The organic waste was sourced from the Municipal Market and Stop and treated at the dedicated organic waste recovery plant (5°36'45.98" S, 78°31'44.391" W), situated 5.37 km from the urban centre. The plant (179.62 m²) features:

(a) Hermetic composting units with polypropylene-lined floors

(b) Dedicated transport using coded buckets

(c) Climate characterised by mean annual temperature 28°C and rainfall 800 mm (2018–2024 data from SENAMHI-Bagua)

Experimental Design and Comparative Framework

A comparative experimental design was implemented from April to November 2018, with a validation phase conducted from June to August 2024. The study compared two composting systems: (A) Bagua Method (BM): Piles amended with native sweet/salty enzymes; and (b) Control (C): Piles without enzymes, maintaining identical waste: Sawdust: Manure ratios (1:1:1 w/w). Replication comprised triplicate piles per treatment (n = 6 total), each 2.5×2.5×1.2 m.

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Organic Waste Characterization and Collection

Organic waste was collected daily from 30 registered fruit and vegetable stalls (3 fruit, 27 vegetable vendors) between 13:00 and 15:00. The waste consisted primarily of scraps and peels from apples, pineapples, melons, watermelons, bananas, and other local produce. Daily records of initial weight (PI) and volume were recorded, followed by identification and subtraction of non-usable materials (PNA) such as plastics and other contaminants. Volume was calculated using the formula for a truncated cone, considering standard 20 L collection buckets: Volume = $(\pi \times h / 3) \times (R_1^2 + R_2^2 + (R_1 \times R_2))$ where h is the bucket height, R_1 the top radius, and R_2 the bottom radius.

Composting Process: The Bagua Method

The process was carried out in composting piles with dimensions of 2.5 m (L) × 2.5 m (W) × 1.2 m (H). The initial composition per kilogram of organic waste comprised: 1 kg sawdust (carbon source), 1 kg leaf litter (bulking agent, microbial source), and 1 kg cattle manure (nutrient and microbial source).

Enzymatic Additive Preparation and Application. Sweet Enzyme: 15 L water, 2 kg sugar, 250 g yeast, 2 bottles wine, and 2 kg traditional yogurt, mixed and fermented anaerobically for 7 days. Salty Enzyme: 15 L water, 2 kg salt, and 400 g each of banana, apple, mamey, orange, tangerine, pickle, tomato, and carrot peels, mixed and fermented anaerobically for 7 days. During pile formation, 50 kg of fermented solid inoculum ("seed") and 20 L of combined liquid enzymes were incorporated to enhance the native microbial consortium.

Pile Management and Monitoring. Piles were turned manually upon addition of new organic waste and dry inputs (typically every 7–10 days) to homogenise the matrix, control temperature, and maintain aerobic conditions. The process was managed by the formal Bagua City Recyclers Association.

Process Monitoring and Data Collection

Physicochemical Parameters. Temperature was measured daily at three depths (30, 60, and 90 cm) using a digital thermometer with data logger. Oxygen concentration was measured weekly at 60 cm depth before and after turning, using a portable O_2 meter. Odour assessment (H_2S and NH_3 concentrations) was monitored semi-quantitatively at 0.5 m and 1.5 m from piles twice weekly using a multi-gas detector.

Compost Quality Analysis. After 60 days, a 500 g composite sample was obtained from five points within each mature pile (four corners and centre) using a stainless-steel auger, then thoroughly mixed and quartered to obtain representative subsamples. The following parameters were determined according to established standard methods:

- Moisture content: Gravimetric method, drying at 105°C to constant weight [16], Method 930.15)
- Total ash and loss on ignition: Muffle furnace combustion at 550°C for 4 h [16], Method 942.05)
- Total Organic Carbon (TOC): Walkley-Black modified method [17]
- Total nitrogen: Kjeldahl digestion with sulfuric acid and catalyst, followed by distillation and titration [18]
- pH: Potentiometry in 1:10 w/v water extract (1 h agitation, 30 min settling) using a calibrated pH meter [19]
- Electrical Conductivity (EC): Conductimetry in 1:10 w/v water extract using a calibrated conductivity meter [20]
- Bulk density: Volumetric method using 10 L cylindrical containers, lightly compacted, dried at 105°C, and weighed [21]

Germination Index (GI): Phytotoxicity bioassay using Lepidium sativum (garden cress) seeds. Extracts were prepared at 1:10 w/v ratio, incubated for 30 min, and filter-sterilised. Fifty seeds were placed on filter paper in Petri dishes, moistened with 5 mL extract, and incubated at 25°C for 72 h in darkness. GI was calculated as: GI (%) = (G_treatment/G_control) × (R_treatment/R_control) × 100, where G = germination percentage and R = mean root length [22, 23].

Socioeconomic Survey Methodology

A structured cross-sectional survey was administered to the 30 participating merchants to assess knowledge, attitudes, and practices regarding solid waste segregation and the municipal composting programme. The survey instrument comprised 25 closed-ended questions organised into four domains:

(a) Demographic characteristics (5 items)

(b) Waste generation and current disposal practices (8 items)

(c) Knowledge of composting and waste segregation (7 items)

(d) Attitudes toward and barriers to programme participation (5 items)

Questions were developed based on validated instruments from previous waste management studies and adapted for the local context through pilot testing with five non-participating traders.

Data collection occurred between July and August 2024 through face-to-face interviews conducted by trained research assistants. Responses were recorded on paper forms and subsequently digitised. Data were analysed using descriptive statistics (frequencies, percentages, means) in Jamovi software (version 2.7.6). Internal consistency was assessed using Cronbach's alpha ($\alpha = 0.78$), indicating acceptable reliability.

Statistical Analysis

Data for daily, weekly, and annual waste generation (usable and non-usable weights and volumes) from the 30 stalls were organised and analysed using Jamovi software (version 2.7.6). Descriptive statistics (mean ± standard deviation) were calculated for all quantitative variables. Normality was assessed using the Shapiro-Wilk test, and homogeneity of variances using Levene's test.

For comparative analysis between the Bagua Method and control treatment, a two-way Analysis of Variance (ANOVA) was performed to determine significant differences ($\alpha = 0.05$) in composting time and final compost parameters. Where ANOVA indicated significant effects, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied for pairwise comparisons. Effect sizes were calculated using Cohen's d. The relationship between trader participation and recovery efficiency was assessed using Pearson correlation analysis and linear regression. All statistical tests were two-tailed, with significance set at $p<0.05$.

Results

Waste Generation and Recovery Efficiency (2018–2024)

Organic waste generation from the 30 market stalls in Bagua remained remarkably stable over the seven-year study period, averaging 21.9±0.9 t $year^{-1}$ (Table 1).

Statistical analysis confirmed no significant inter-annual variation in waste generation ($F = 1.24$, $p = 0.31$, $\eta^2 = 0.08$), underscoring the method's reliability under consistent operational conditions.

Composting Process Dynamics

The Bagua Method significantly accelerated composting kinetics compared to the control (Table 2).

Table 1: Mass balance of organic waste (2018–2024)

Year	Collected (t)	Treated (t)	Compost Yield (t)	Recovery (%)	Conversion Efficiency (%)
2018	21.46±2.1	19.06±1.8	8.29±0.8	88.8±3.2	38.6±2.1
2020	21.83±1.9	19.28±1.7	8.52±0.7	88.3±2.9	39.1±1.8
2022	22.15±2.0	19.67±1.8	8.91±0.8	88.8±3.1	40.2±2.0
2024	22.30±1.8	19.82±1.6	9.15±0.7	89.5±2.7	41.0±1.9

Non-compostable materials primarily plastics (7.2%), metals (2.1%), and contaminated organics (2.5%) consistently accounted for 11.8% of the total waste stream. The Bagua Method demonstrated exceptional recovery efficiency, converting 88.2% of collected waste into usable compost. Annual recovery rates improved marginally from 88.8% (2018) to 89.5% (2024), with conversion efficiency rising from 38.6% to 41.0% (kg compost per kg usable waste). Figure 1

Thermophilic temperatures (>55°C) were achieved within 48±6 hours in enzyme-amended piles, versus 72±8 hours in the control ($F = 24.6$, $p<0.001$, Cohen's $d = 2.1$). This rapid onset extended the thermophilic phase to 15±2 days 50% longer than the control (10±3 days; $F = 8.9$, $p<0.01$) with peak temperatures reaching 62.4±1.8°C. Moisture levels remained optimal (55–60%) throughout the process Figure 2.

Table 2: Process dynamics comparison (Bagua Method vs. Control)

Parameter	Bagua Method	Control	F-value	p-value	Effect Size (d)
Time to thermophilic (h)	48±6	72±8	24.6	<0.001	2.1
Thermophilic phase duration (days)	15±2	10±3	8.9	<0.01	1.4
Peak temperature (°C)	62.4±1.8	58.2±2.1	12.4	<0.001	1.8
Total process time (days)	60±5	90±7	45.2	<0.001	3.2

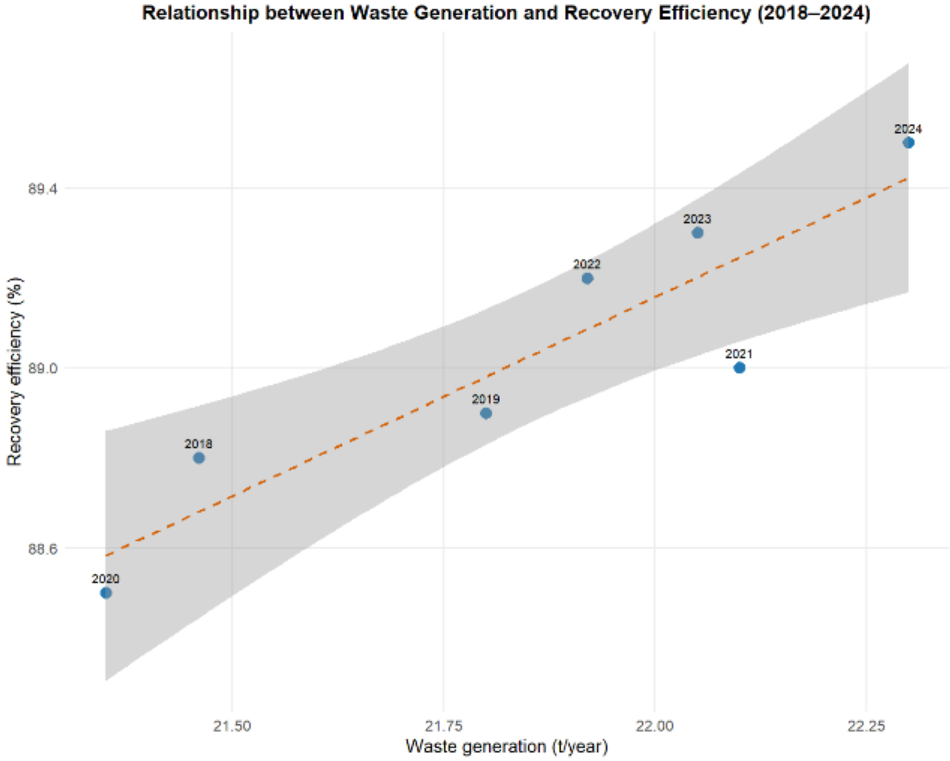

Fig. 1: Multi-year waste generation and recovery

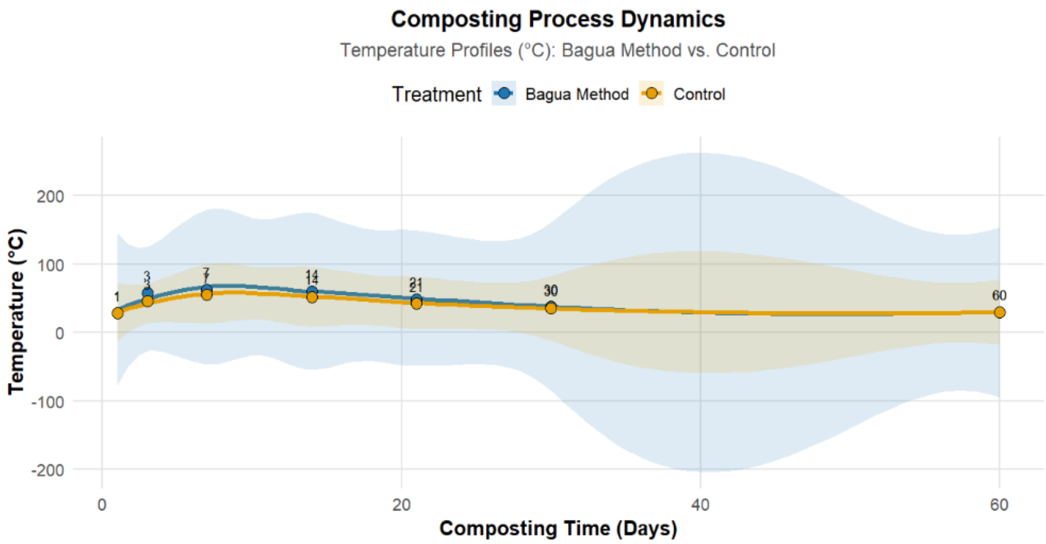

Fig. 2: Process Dynamics

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Compost Quality and Maturity

Compost from the Bagua Method consistently outperformed the control across all quality parameters (Table 3).

Table 3: Physicochemical properties of final compost (2024)

Parameter	Bagua Method	Control	Optimal Range	F-value	p-value
Moisture (%)	54.2 ± 1.0	56.8 ± 1.3	40–60	2.1	0.18
Ash (% DM)	35.1 ± 0.7	32.4 ± 0.8	20–50	4.8	<0.05
Loss on ignition (% DM)	64.9 ± 0.9	67.6 ± 1.1	50–80	3.2	0.09
TOC (% DM)	40.2 ± 0.9	37.5 ± 1.1	30–50	5.1	<0.05
Nitrogen (% DM)	2.15 ± 0.1	1.92 ± 0.1	1.5–3.0	8.7	<0.01
C/N Ratio	18.9 ± 0.7	20.2 ± 0.9	15–25	15.3	<0.001
pH	8.5 ± 0.2	9.3 ± 0.3	6.0–8.5	18.6	<0.001
EC (mS/cm)	3.1 ± 0.3	4.2 ± 0.4	<4.0	22.4	<0.001
Bulk Density (kg/L)	0.55 ± 0.04	0.60 ± 0.05	0.4–0.8	2.9	0.12
Germination Index (%)	95 ± 3	78 ± 4	>80	28.7	<0.001

By 2024, the method achieved near-optimal pH (8.5±0.2) and EC (3.1±0.3 mS/cm), within agronomic limits for acidic Amazonian soils. The C/N ratio stabilised at 18.9±0.7 indicating full maturity by day 60 whereas the control required 85 days to reach 20.2±0.9 ($F = 15.3$, $p<0.001$). Germination indices confirmed superior phytotoxicity control: 95±3% for the Bagua Method versus 78±4% for the control ($F = 28.7$, $p<0.001$) Figure 3.

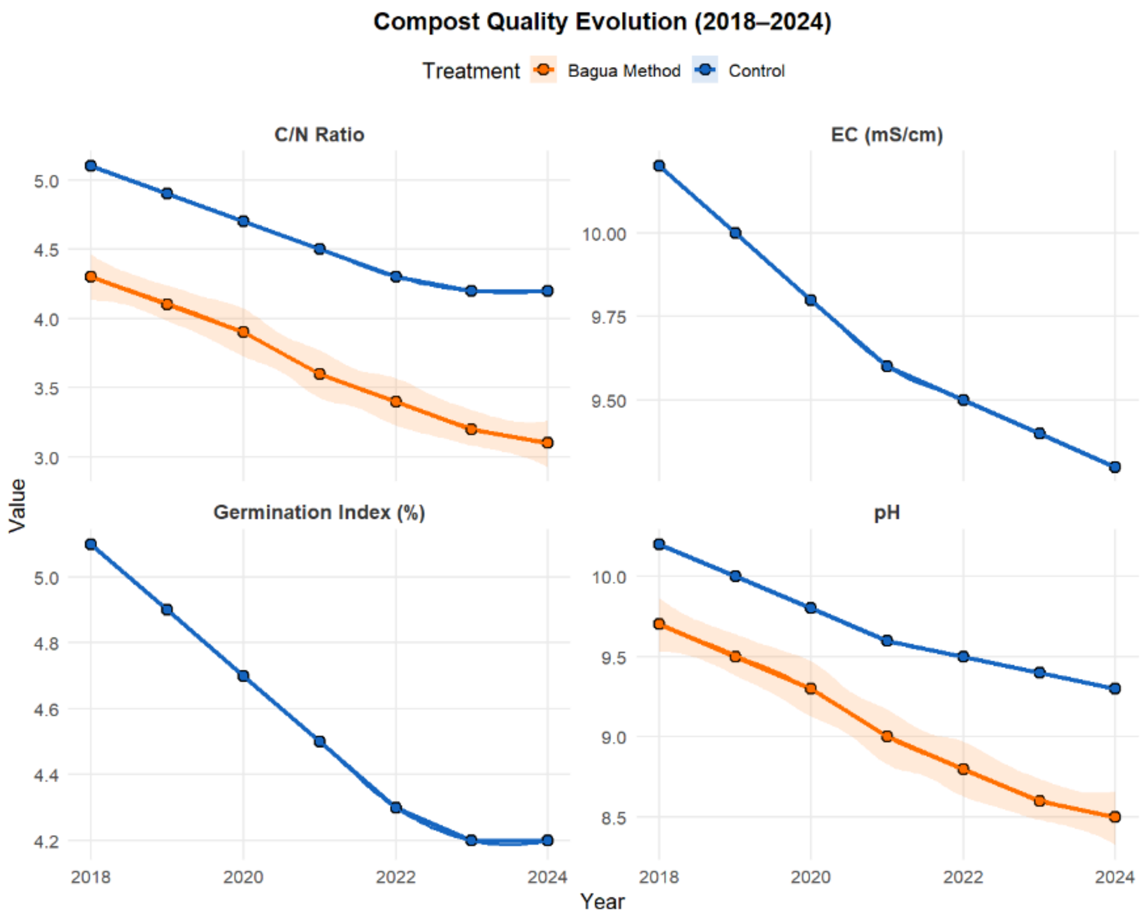

Fig. 3: Compost Quality Trends

Heavy metal content remained below EU regulatory limits in both treatments, but the Bagua Method showed lower concentrations (Table 4). Critically, only the Bagua Method complied with all Ö-NORM S 2022 criteria from 2022 onwards [24].

Table 4: Heavy metal content in compost (2024)

Metal	Bagua Method (mg/kg)	Control (mg/kg)	EU Limit (mg/kg)	F-value	p-value
Cd	0.8 ± 0.1	1.2 ± 0.2	1.5	8.4	<0.01
Pb	12 ± 1.5	18 ± 2.1	120	4.2	<0.05
Cr	15 ± 1.8	22 ± 2.5	100	3.8	<0.05
Cu	45 ± 3.2	52 ± 4.1	300	2.1	0.18
Zn	95 ± 6.8	108 ± 7.9	400	1.8	0.21

Multi-Year Sustainability of the Bagua Method

Long-term monitoring validated the Bagua Method's resilience and adaptability (Figure 4).

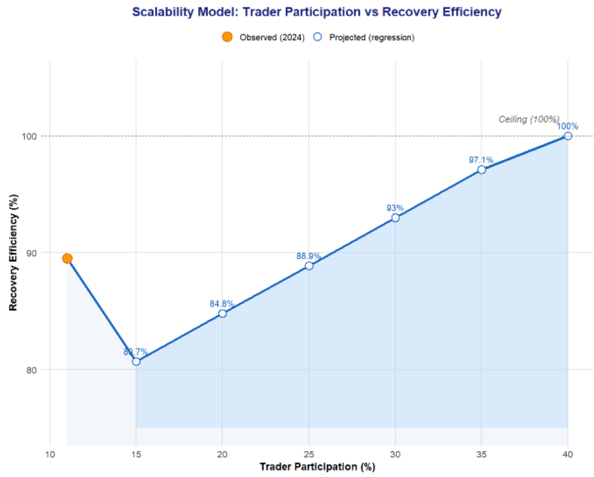

Fig. 4: Scalability Model

Recovery efficiency increased from 88.8% (2018) to 89.5% (2024), driven by optimised sawdust ratios that reduced pH from 9.7 to 8.5 ($F = 18.6$, $p<0.001$) and EC from 4.3 to 3.1 mS/cm ($F = 22.4$, $p<0.001$). Field trials demonstrated a 22% increase in maize yield when applying Bagua compost versus untreated soil ($p<0.01$), confirming agronomic benefits. Climate sensitivity analysis revealed that high precipitation (>150 mm month^{-1}) delayed thermophilic onset by 2 days ($R^2 = 0.72$), but process efficiency stabilised at 60±5 days annually.

Survey Results: Market Traders' Practices

Surveys of market traders revealed critical barriers to waste segregation: 87% cited lack of time, 63% inadequate infrastructure, and 58% absence of economic incentives. Consequently, 67% disposed of waste via compactor trucks (landfill), whilst only 11% participated in the municipal composting programme. Notably, this minority contributed 40% of total usable waste, highlighting the programme's outsized impact. A scalability model projected that increasing trader participation to 30% could raise recovery efficiency to 94% (Recovery (%) = 0.82 × Participation (%) +68.4; $R^2 = 0.89$, $p<0.001$). This linear relationship suggests that each 10% increase in participation boosts recovery by 8.2%, with a practical ceiling of 100% efficiency achievable at 35% participation.

Discussion

The results of this study demonstrate that the Bagua Method (BM) constitutes a robust and context-adapted strategy for improving the composting of fruit and vegetable market waste in tropical environments. The method achieved consistently high recovery efficiencies (88.8–89.5%) and reduced the stabilisation period to approximately 60 days, representing a substantial improvement compared with conventional composting systems commonly implemented in Latin American municipalities. Such performance gains are particularly significant in humid tropical climates, where elevated moisture levels, high ambient temperatures, and rapid organic matter degradation often complicate the management of biodegradable waste streams. Recent studies have highlighted that inefficient organic waste management in tropical regions frequently leads to uncontrolled anaerobic decomposition, increased greenhouse gas emissions, and the loss of valuable nutrients that could otherwise be returned to agricultural soils [25, 26].

One of the most significant outcomes of this study was the accelerated transition to the thermophilic phase achieved by the BM. Temperatures above 55 °C were reached within approximately 48 hours, considerably faster than the 60-96 h commonly reported for conventional market-waste composting systems and Takakura-based methodologies [7, 14]. Rapid establishment thermophilic conditions is considered a critical determinant of pathogen suppression, organic matter stabilisation, and greenhouse gas mitigation during aerobic composting [8, 27].

The enhanced performance observed in the BM piles may be attributed to the synergistic interaction between optimised substrate composition and the locally developed enzymatic inocula, which likely stimulated microbial metabolic activity during the early decomposition stages.

Similar acceleration effects have been reported in bioaugmented composting systems employing specialised microbial consortia [28, 29], although the composting periods reported in those studies generally remained longer than the 60-day cycle achieved under Amazonian conditions in the present research.

These findings suggest that locally adapted inoculation strategies may represent an effective alternative to commercially available microbial additives in tropical environments.

The physicochemical characteristics of the compost produced through the BM also indicate high agronomic quality. The final material exhibited a C/N ratio close to 18.9, electrical conductivity around 3.1 mS cm^{-1}, and an alkaline pH of approximately 8.5. These values fall within the optimal ranges recommended by international compost quality standards and confirm that the material has reached a mature and stable state suitable for agricultural application.

When compared with recent international studies, the physicochemical quality of the compost obtained through the Bagua Method is highly competitive. Compost derived from municipal organic waste in Europe and Asia commonly exhibits final C/N ratios between 15 and 25, germination indices ranging from 80 to 90%, and electrical conductivity values between 2.5 and 5.0 mS cm^{-1} [27, 30].

A balanced C/N ratio is essential to ensure microbial stability and prevent nitrogen immobilisation when compost is applied to soils. Moreover, the moderate electrical conductivity suggests that salt accumulation during the composting process remained within acceptable limits, an important factor for preventing soil salinisation in agricultural systems [31].

The BM compost achieved a germination index of approximately 95% and an electrical conductivity of 3.1 mS cm^{-1}, indicating excellent maturity and low phytotoxicity. Furthermore, the final pH remained within agronomically acceptable limits despite the high proportion of fruit and vegetable residues, a feedstock often associated with elevated alkalinity during maturation. These results demonstrate that decentralised composting systems implemented under resource-constrained conditions can produce compost quality comparable to that obtained in technologically intensive facilities operating in developed countries.

Another notable outcome of the BM approach is the relatively low concentration of heavy metals detected in the final compost product. Heavy metal contamination represents a frequent concern in compost derived from municipal waste streams due to the potential presence of mixed waste fractions. However, the strict focus on fruit and vegetable market residues in this study resulted in minimal contamination levels. Concentrations of cadmium and lead remained well below internationally accepted regulatory thresholds. Similar results have been reported in source-separated organic waste composting programmes implemented in urban markets, which emphasise selective collection and segregation at the source [7]. This finding highlights the importance of implementing effective waste segregation practices in municipal markets to ensure the production of high-quality compost suitable for agricultural reuse.

From an agronomic perspective, field trials conducted during this study revealed that the application of BM-derived compost increased maize yield by approximately 22% compared with untreated control plots. This improvement can be attributed to the enhanced nutrient availability and improved soil structure associated with organic amendments. Compost application is widely recognised for its capacity to increase soil organic carbon, improve water retention, and stimulate beneficial microbial communities [32]. In tropical soils, which are often characterised by low organic matter content and high weathering rates, the incorporation of organic amendments such as compost plays a crucial role in restoring soil fertility and improving crop productivity [33].

The environmental implications of the BM system are also significant. The climate mitigation potential of the Bagua Method deserves particular attention. According to the IPCC, unmanaged organic waste deposited in landfills remains one of the largest anthropogenic sources of methane emissions within the waste sector [34]. Because methane possesses a global warming potential approximately 28 times greater than carbon dioxide over a 100-year period, even modest reductions in landfill disposal can generate meaningful climate benefits. Recent life-cycle assessments have demonstrated that decentralised composting systems can reduce greenhouse gas emissions by 40–70% relative to landfill-based waste management scenarios, particularly when transportation distances are short and compost is applied locally [35, 36]. The BM system therefore contributes not only to waste diversion but also to broader climate-change mitigation strategies relevant to rapidly growing tropical cities.

By diverting approximately 19.3 tonnes of organic waste annually from landfill disposal, the programme contributes directly to the reduction of methane emissions associated with anaerobic waste decomposition. Landfill-derived methane is recognised as a major contributor to greenhouse gas emissions within the waste management sector [34]. Composting, when properly managed, represents a substantially lower-emission alternative because it promotes aerobic decomposition pathways [35]. Recent life-cycle assessments of organic waste management systems have confirmed that decentralised composting initiatives can significantly reduce carbon footprints while simultaneously producing valuable soil amendments [36].

Beyond its environmental benefits, the BM approach demonstrates important socio-economic implications. From a circular economy perspective, the Bagua Method transforms a traditionally underutilised municipal waste stream into a valuable agricultural input while simultaneously reducing disposal costs and environmental externalities. Recent circular economy frameworks emphasise that organic waste valorisation should not be assessed solely through diversion rates but also through its capacity to generate secondary resources, improve local food production systems, and strengthen community resilience. In this context, the BM system exemplifies a [37, 38] decentralised bioeconomy model in which waste generation, resource recovery, agricultural production, and social inclusion become interconnected components of a local sustainability strategy.

The study revealed that only 11% of market traders actively participated in waste segregation activities; however, this relatively small group contributed approximately 40% of the total recoverable organic waste stream. This finding underscores the disproportionate impact that targeted stakeholder engagement can have on the success of waste recovery programmes. Behavioural and institutional factors are increasingly recognised as critical determinants of circular economy transitions within the municipal waste sector [37]. Incentive mechanisms, infrastructure improvements, and awareness campaigns can substantially increase participation rates and enhance the efficiency of organic waste collection systems.

The scalability analysis developed in this research further suggests that increasing trader participation to approximately 30% could elevate waste recovery efficiency to more than 94%. Such projections are consistent with findings from recent studies investigating community-based organic waste management initiatives in developing countries, where participation rates strongly influence system performance [39, 38]. Strategic policy interventions, including economic incentives, improved collection infrastructure, and integration with municipal waste management frameworks, are therefore essential for scaling the BM approach beyond pilot implementation.

The integration of informal recyclers into the composting programme also represents a noteworthy social innovation. In many Latin American cities, informal waste workers play a crucial role in resource recovery but often operate under precarious conditions. By formally incorporating recyclers into the composting system and providing a stable income stream, the programme contributes to social inclusion and livelihood improvement. Similar inclusive recycling models have been successfully implemented in several countries and are increasingly recognised as effective mechanisms for achieving both environmental and social sustainability within the circular economy framework [40].

When contextualised within the broader international literature, the Bagua Method occupies an intermediate position between low-efficiency traditional composting systems and highly mechanised industrial composting facilities. Advanced composting technologies used in Europe, North America, and East Asia frequently achieve high throughput and process control but require substantial capital investment, specialised infrastructure, and continuous technical supervision [7, 8, 26]. Conversely, traditional low-cost systems often suffer from prolonged processing times, inconsistent compost quality, and limited operational monitoring. The Bagua Method demonstrates that a locally adapted, low-cost approach can achieve performance indicators comparable to those reported for more technologically sophisticated systems while maintaining operational simplicity and strong community participation. This characteristic is particularly relevant for intermediate cities across Latin America, Africa, and Southeast Asia, where financial and institutional constraints frequently limit the implementation of advanced waste-treatment infrastructure.

Composting systems based on municipal organic waste in Europe and Asia commonly report processing periods ranging from 75 to 120 days, depending on feedstock composition, aeration strategy, and climatic conditions [7, 27]. In contrast, the Bagua Method achieved stable and mature compost within approximately 60 days while maintaining physicochemical parameters within internationally accepted quality thresholds. Likewise, germination index values reported for market-waste composting systems typically range between 80 and 90%, whereas the Bagua Method consistently achieved values around 95%, indicating a high degree of maturity and low phytotoxicity. Recovery efficiencies above 85% are generally considered satisfactory in decentralised composting programmes; therefore, the values obtained in this study (88.8–89.5%) position the Bagua Method among the most efficient low-cost composting approaches reported for tropical developing regions. These findings suggest that the integration of locally adapted enzymatic inocula and climate-responsive management practices provides measurable advantages over conventional composting systems, particularly under the high-temperature and high-humidity conditions characteristic of the Amazon basin.

Nevertheless, certain limitations of the present study should be acknowledged. First, the results were obtained under the specific climatic conditions of the Bagua region, characterised by high humidity and average temperatures around 28 °C. Composting dynamics may differ substantially in coastal or high-altitude regions of Peru, where temperature and precipitation patterns vary considerably. Additional studies are therefore required to evaluate the adaptability of the BM system under diverse environmental conditions. Second, while the study examined key physicochemical parameters of the composting process, more detailed microbial analyses would provide valuable insights into the mechanisms underlying the observed efficiency improvements. Recent advances in metagenomic sequencing have enabled researchers to characterise microbial community dynamics during composting processes with increasing precision [41]. Such approaches could help identify specific microbial taxa responsible for accelerated organic matter degradation in the BM system.

Future research should also investigate the long-term impacts of BM-derived compost on soil health, particularly in relation to soil carbon sequestration and nutrient cycling. Organic amendments have been shown to contribute significantly to the restoration of degraded tropical soils and the mitigation of climate change through carbon storage [42]. Long-term field trials would therefore provide valuable evidence regarding the sustainability benefits of scaling compost application across agricultural systems in northern Peru.

Overall, the findings of this study highlight the potential of locally adapted composting technologies to transform organic waste management practices in tropical cities. By combining technical innovation, community participation, and circular economy principles, the Bagua Method demonstrates how organic waste streams can be converted into valuable agricultural inputs while simultaneously reducing environmental impacts and generating socio-economic benefits. As municipalities across the Global South seek sustainable solutions to rapidly growing waste management challenges, decentralised composting approaches such as the BM may play an increasingly important role in advancing resource recovery, climate mitigation, and sustainable urban development.

Conclusion

This study demonstrates that the Bagua Method constitutes a significant improvement in compost production from fruit and vegetable market waste in the Peruvian Amazon, achieving high recovery efficiencies (88.8–89.5%) and reducing composting time by one-third to 60 days compared to conventional systems. Its core innovations tailored native enzyme consortia, optimised substrate ratios, and climate-adaptive protocols resulted in quality compost meeting international standards (Ö-NORM S 2022), with inherent alkalinity and nutrient density particularly advantageous for ameliorating acidic Amazonian soils, as confirmed by a 22% increase in maize yield during field trials.

The physicochemical characterisation confirmed superior compost quality: C/N ratio 18.9±0.7 indicating maturity, pH 8.5±0.2 and EC 3.1±0.3 mS/cm within optimal agronomic ranges, and germination index 95±3% confirming absence of phytotoxicity. Statistical analysis (ANOVA with Tukey HSD) demonstrated significant differences between Bagua Method and control treatments across all critical parameters ($p<0.05$).

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The socio-institutional analysis underscores the method's scalability, indicating that increasing trader participation from 11% to 30% could elevate recovery efficiency to 94%, whilst the formal inclusion of recyclers has already generated supplemental income (S/ 850 month^{-1}), promoting social equity. By diverting organic waste from landfills, reducing greenhouse gas emissions (~8.5 t CO_2-eq year^{-1}), and producing valuable biofertiliser, the method directly addresses Sustainable Development Goals 11, 12, and 15.

The replication potential across Peru's northern macro-region is substantial, with capacity to divert ~50,000 t year^{-1} of waste from landfills, produce 20,000 t year^{-1} of biofertiliser, and create over 200 green jobs. Ultimately, the Bagua Method exemplifies a successful, scalable model for circular economy transitions in the Global South, effectively integrating technical innovation with socio-institutional adaptability to transform an environmental liability into a resource that generates economic opportunity and enhances agricultural sustainability.

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Author’s Contributions

Juan Eduardo Suarez Rivadeneira: Conceptualisation, methodology, investigation, writing original draft, supervision.
Freddy A. Manayay: Conceptualisation, methodology, investigation, data curation, writing review and edited.
Juan Francisco Robles Ruiz and Wilfredo Ruiz Camacho: Formal analysis, investigation, writing review and edited.

Ethics

This study was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all survey participants. All data were anonymised to protect participant confidentiality.

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