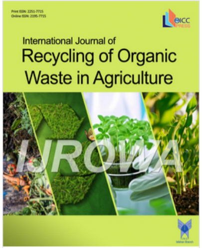

Volume 13, Issue 3, 132430 (1-12)

International Journal of Recycling Organic Waste in Agriculture (IJROWA)

https://dx.doi.org/10.57647/j.ijrowa.2024.1303.30

Swine manure management by bokashi fermentation and composting with biological activators in a Colombian High Mountain Region

Patricia Martínez-Nieto [1*], Carlos Abaunza-González[2], Gustavo García-Goméz [1]

[1]*Tibaitatá Research Center, Corporación Colombiana de Investigación Agropecuaria (Agrosavia), Cundinamarca, Colombia.*
[2]*Nataima Research Center, Corporación Colombiana de Investigación Agropecuaria (Agrosavia), Tolima, Colombia.*

****Corresponding author:** patingli@gmail.com

Original Research

Received:
26 June 2023
Revised:
18 September 2023
Accepted:
20 December 2023
Published online:
15 January 2024

Abstract:

Purpose: Clean and efficient alternatives for sustainable treatment of pig farming wastes are a priority in suburban areas in Forest Reserves of High Andean ecosystems. Among these technologies are Bokashi Fermentation and composting with added microorganisms (bioaugmentation) or nutrients (biostimulation) as biological activators.
Method: In a Colombian rural area located at 3160 m.a.s.l., focused on small-scale swine production, Bokashi fermentation with active dry yeast and in-vessel composting were evaluated using two microbial inoculants and a sterile metabolic stimulant. In addition, these treatments were compared with a non-inoculated composting process used in the study area (control).
Results: The biological additives improved the composting process performance and end-product quality by shortening the degradation cycle ($19.9-45.9\%$), higher germination index ($> 0.8\%$), increasing nutrient content (N, P, S, Fe and Cu) and showing suppressive activity against *Fusarium oxysporum* compared to control. Nevertheless, Bokashi was the only treatment that decreased Enterobacteriaceae concentration below 1E+03 CFU g^{-1}.
Conclusion: Bokashi technology complies with Colombia's environmental regulations for eco-friendly fertilizer production, which allows the sustainable management by-products from swine activities in critical ecological areas such as Forestry Protection Reserves in High Andean ecosystems.

Keywords: Pig manure; Composting; Bokashi fermentation; Biological activators; High Andean ecosystems

1. Introduction

During the last ten years, the Colombian pig sector has increased its competitiveness in the national market and has generated opportunities internationally; Colombia has conducted negotiations and trade agreements with several countries. Currently, Colombia has six slaughterhouses and meat industries authorized to export (Díaz-Rodríguez et al., 2021).

Due to the above, it must be ensured that pig farms are safe for human consumption and the environment. However, pig production can be very polluting and therefore it is one of the most monitored industries by environmental agencies due to the large volume of waste produced, which, if not appropriately managed, causes environmental effects on water sources, soils, and air. The primary pollution sources from swine farms are greenhouse gas emissions from the pig house and the manure management system. Manure management is of greater importance due to its potential environmental impact because of the complex nature of the material, and the volume generated (Abaunza et al., 2008; Díaz-Rodríguez et al., 2021).

In Colombia's intensive pig farming, fresh manure is subjected to one or more treatment processes before its final

disposal; however, small-scale producers need to treat manure in a sustainable way. They use fresh manure directly as fertilizer on soils or carry out inappropriate composting methods, which is the case of pig farming in the high mountain ecosystems located in Bogotá, the second national epicenter of pig processing (Abaunza et al., 2008).
Pig farming developed in the Upper Teusacá River basin, located in the Protective Forest Reserve Area of the Eastern Forest of Bogotá between 3,000 and 3,200 m.a.s.l., impacts environmental quality in two ways; first, pig farmers add directly to the soil the fresh manure without any treatment to fertilize crops, and second, they inappropriately use semi-solid organic leftovers from Bogotá's restaurants to feed their animals, causing the spread of diseases.
Therefore, to avoid an increase in environmental degradation in this area of great biogeographic value, regional and district environmental authorities, seeking "zero discharge" technologies, proposed "dry sweeping" with sawdust (Fresh pig manure on sawdust bedding) and the use of composting or vermiculture to produce organic fertilizers and thus take advantage of its agronomic potential. However, the composting processes developed in the area presented several technical drawbacks, such as pathogens detection and long degradation times that hindered their stability and maturity, affecting the nutritional and biological quality of the compost obtained. Thus, pig manure management was made inefficient, making it difficult to comply with the environmental commitments agreed upon by pig producers and the Regional Autonomous Corporation of Cundinamarca (CAR), resulting in fines and closures of most of these livestock farms.
These closures of farms have generated tension between the community and environmental authorities; however, the current situation for the surviving peasant pig farms at 3,200 meters above sea level that use their work for family sustenance is the commitment to reconversion according to the Reserve's Environmental Management Plan. Nevertheless, the community does not know adequate technologies for improving their production processes and efficiently swine manure manages through composting that allow a correct conversion to sustainable livestock farms (Abaunza et al., 2008; Desarrollo Sostenible, 2016; Guevara, 2021).
The composting quality strongly depends on the processing technology and adequate operational control. One eco-friendly and economically viable strategy for enhancing the composting process is supplementation with biological activators. These activators are additives or adjuvants that use nutrients, selected strains of microorganisms, enzymes, and medicinal plants that, added to fermentative or oxidative waste management processes, seek by different mechanisms to accelerate the organic matter degradation increasing the yield and improving the end-product quality (De-Queiroz et al., 2017; Sutrisno et al., 2020; Wei-Kuang and Chih-Ming, 2021; Greff et al., 2022; Medina-Rastogi et al., 2018).
The external addition of degrading microorganisms or nutrients in bioremediation are known as bioaugmentation and biostimulation, respectively; these methods are being adopted in composting by some researchers, expanding the use of biological activators at industrial level to optimize the degradation cycle and nutritional product quality (Sánchez et al., 2017; Rastogi et al., 2020; Sutrisno et al., 2020; Simarmata et al., 2021; Wei-Kuang and Chih-Ming, 2021; Biyada et al., 2022).
In Colombia, biological additives have been used successfully in biowaste composting (Martínez-Nieto et al., 2011a; Ortiz-Villota et al., 2021) and recently, Matiz-Villamil et al. (2021) added an inoculum with bacteria, fungi, and nematodes to swine mortality composting, finding a decrease in the degradation time and pathogens elimination.
For this reason, in this research, different waste management techniques (composting and Bokashi) were evaluated using biological activators to improve the composting process carried out by small swine farms located at Protective Forest Reserves in the Upper Teusacá River basin with respect to degradation time and the end-product quality.

2. Material and methods

Study site

A pig farm (breeding and fattening) with a working area of 500 m^2 in the rural area of Bogotá DC Km 12 Via Choachí (Eastern Bogotá Protective Forest Reserve, Upper Teusacá River basin) at 3,160 m.a.s.l geographical coordinates Lat 4°34′49.1″ N Long 74°1′20″ W (Fig. 1). Production in breeding and fattening is approximately 154 kg/day of solid excreta on a bed of dry-sweep sawdust.

Raw material

The primary raw materials for the composting process were pig manure collected on a sawdust bed (PMSB), a method known in Colombia as "dry sweeping". The moisture, carbon, nitrogen, and phosphorus of these substrates appeared in Table 1. The microbiological analysis of PMSB showed total mesophilic bacteria (2.3E+08 UFC g^{-1}), Actinomycetes (1.7E+05 UFC g^{-1}) and Fungal (3.2E+05 UFC g^{-1}) counts and the presence of phytopathogen *Fusarium oxysporum*.
In addition to the raw materials, supplements or bulking agents were used for some treatments: molasses, agricultural soil, woodland soil, vegetal coal, vegetal ash, and maize bran.

Inoculant

Two microbial biopreparations were used: a compound of cellulolytic, proteolytic, and amylolytic microorganisms (CPAM) mixed at a concentration of 1E+08 CFU $(mL)^{-1}$ and efficient microorganisms (EM) commercially produced in Colombia by *Fundación para Asesorías del Sector Rural (FUNDASES)* under the supervision of *EM Research Organization (EMRO)* Latin America. In addition, active Dry Yeast (ADY) supplied by *Levapan*® (a Colombian food inputs producer) was also used, and a sterile metabolic stimulant obtained from brown algae with amino acids and B-complex vitamins rich in nitrogen, phosphorus, and potassium (Acty Prad®) distributed in Colombia by *Jorge Triana and Cia. Ltda*.
The bacteria present in CPAM belong to *Comamonas* sp., *Springomonas* sp., *Stenotrophomonas* sp., *Bacillus* spp., *Pseudomonas* sp., *Providencia* sp., *Streptomyces* spp.,

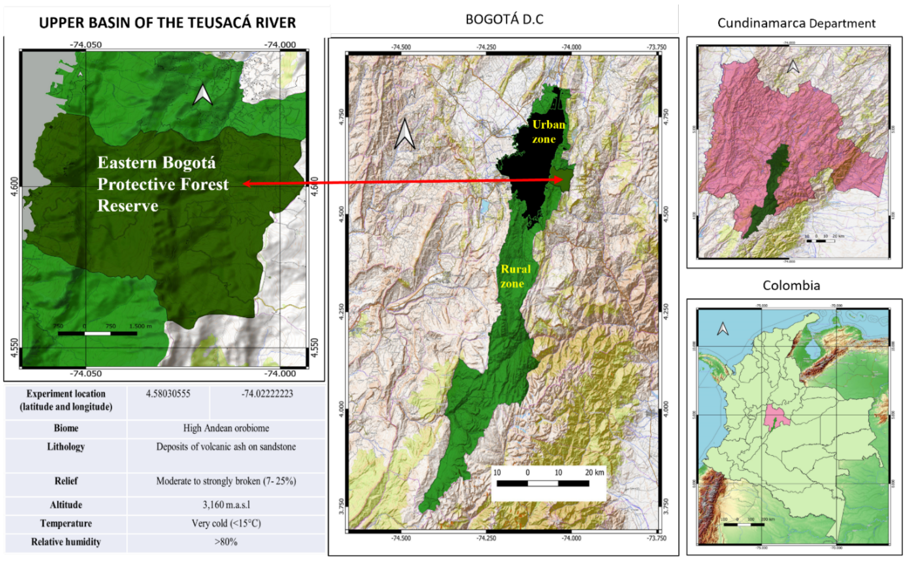

Figure 1. Study area location (Eastern Bogotá Protective Forest Reserve, Upper Teusacá River basin) within the Bogota D.C. (This city is both the capital of the Cundinamarca department and the Republic of Colombia).

Pseudonocardia sp., *Actinobispora* sp. and *Dactylosporangium* sp. The fungi belong to *Syncephalastrum* sp., *Aspergillus* spp., *Rhizophus* sp., and *Absidia* sp. (Martínez-Nieto et al., 2011a). The microorganisms in EM inoculants are yeasts, Phototrophic bacteria, and Lactic bacteria (data sheet FUNDASES).

In the treatments with microorganisms, three CPAM applications a week were applied with 1 mL/kg of residues and four doses of EM initially of 2 mL/kg of residues and the following doses of 1 mL/kg of residues every eight days. For the Bokashi treatment, the initial dose was 20 g of ADY. In addition, the sterile cellular activator Acty Prad was added weekly until four applications of 1 mL/kg of residues were completed.

Experimental design

Under greenhouse conditions (Average ambient temperature 11 °C), five treatments with three repetitions for fifteen experimental units were completely randomized in timber bins with a capacity of 60 kg. The five treatments consisted of three in-vessel composting processes inoculated with biological activators (CPAM, EM, and Acty Prad), a type of Bokashi fermentation with active dry yeast, and in-vessel composting without starter inoculants (Table 2). Twenty days before setting up the experimental design, 300 kg of PMSB was spread over black plastic sheeting. The water content was monitored with the compression test until moisture close to 60% was achieved.

Local producers commonly use treatment without inoculation (control) to manage "dry-sweep manure" by composting. Therefore, the Bokashi fermentation was implemented following the methodology proposed by Abaunza et al. (2008), which consisted of mixing all the substrates described in Table 2 before adding them to the timber bins and once in the containers, the mixtures were compacted. 510 kg of PMSB were used for the experimental design (15 timber bins), distributed according to the treatments described in Table 2.

The microbial inoculants and Acty Prad were incorporated. At the same time, the raw material was added to the timber bins. Once setting-up was completed, the temperature was taken with a compost thermometer, pH with reactive strips, and moisture by the compression method (In each experimental unit, the first two parameters were measured at three points equidistant from the center of the timber bin and approximately 15 g of sample for humidity was taken from each point). Every compost bin was covered with six mil polyethylene sheets to retain heat.

Monitoring of physical-chemical parameters and turnover

The temperature was recorded daily, while pH and moisture were taken weekly. Turnover of composting treatments was carried out by Agrosavia personnel weekly until the compost was mature. At the same time, the Bokashi experimental units were turned twice/per day in the first five days and once/per day after that. Microorganisms (CPAM and EM) or the sterile cellular activator were added to the ap-

Table 1. Feedstocks' composition used in the composting process.

Raw materials	Total Carbon %	Total Nitrogen %	Total Phosphorus %	Moisture %	C/N	C/P
Fresh pig manure on sawdust bedding (PMSB)	54.40	2.15	2.88	75.00	25.30	18.90
Sawdust (S)	54.50	0.19	0.01	31.50	286.80	5,677.10
PMSB (70%) + S (30%)	58.00	1.31	1.62	67.70	44.30	35.80

Table 2. Treatments used in the experimental design under greenhouse conditions in a pig farm at 3,000 m.a.s.l on the Bogotá-Choachí Road.

Materials	Unit	Treatments				
		CPAM	EM	Acty Prad	Bokashi	Not inoculated(NI)
PMS (75% W)	Kg	—	—	—	20	40
PMSB (60% W)	Kg	21	40	40	—	—
70% PMSB +30% S	Kg	9	—	—	—	—
S	Kg	0.5	—	—	—	—
Grass	Kg	—	—	—	1.3	—
Agricultural soil	Kg	10	—	—	6.7	—
Forest soil	Kg	—	—	—	1.7	—
Charcoal	Kg	—	—	—	3.3	—
Vegetable ash	Kg	—	—	—	1.7	—
Corn bran	Kg	—	—	—	0.7	—
Molasses	Kg	0.03	—	—	0.3	—
CPAM	mL/Kg	3	—	—	—	—
EM	mL/Kg	—	5	—	—	—
Acty Prad	mL/Kg	—	—	4	—	—
ADY	g	—	—	—	20	—

propriate experimental unit in the first four weeks by each turnover until the dose for each treatment was complete. When the temperature of each experimental unit did not show increases greater than 8 Celsius in relation to room temperature, they were left for at least 21 days until their maturation.

Physical-chemical and biological assessment to determine the quality of the final product

When the treatments began to smell like wet earth (due to the presence of a volatile microbial compound called geosmin, which indicated a stable state of composting) with a curing time of 21 days and a temperature no higher than room temperature at 8 degrees Celsius, they were sieved, and for each experimental unit (1 kg), a phytotoxicity test was taken (germination percentage and index) in radish (Raphanus sativus L.) to confirm the maturity of the compost produced (Ge et al., 2006; Martínez-Nieto et al., 2011a). The germination index (GI) (Eq. 1) was calculated considering the germination percentage (%G) (Eq. 2) and the radicle length (%L) (Eq. 3).

$$\mathrm{GI} = \frac{\%\mathrm{G} \times \%\mathrm{L}}{10000} \quad (1)$$

$$\%\mathrm{G} = \frac{\mathrm{Gt}\,(\text{Meangermination for treament})}{\mathrm{Gc}\,(\text{Meangermination of control})} \quad (2)$$

$$\%\mathrm{L} = \frac{\mathrm{Lt}\,(\text{Mean radicle length for treament})}{\mathrm{Lc}\,(\text{Mean radicle length of control})} \quad (3)$$

A germination index greater than 0.8 indicates the disappearance of phytotoxicity and compost maturity. Compost enhances germination and radicle growth with values > 1 (Martínez-Nieto et al., 2011b).

With these results, the complete physical-chemical analysis was conducted for organic fertilizers (pH, moisture, density, nutrients, cation exchange capacity, electrical conductivity, carbon to nitrogen ratio, volatilization losses, and ash), heavy metals (Arsenic, cadmium, chromium, mercury, and lead), impurities (Foreign matter), Enterobacteria, *Salmonella* sp., *E. coli*, Human parasites, phytopathogens, and total microorganisms count (mesophilic bacteria, actinomycetes, fungi, and yeasts). The analyses were conducted externally in two laboratories: *Agrosavia and Doctor Calderón Asistencia Técnica Agrícola Ltda*, both certified by *Instituto Colombiano Agropecuario* (ICA), the Colombian agency responsible for the registration of fertilizers, organic manures, and soil amendments.

The results enabled the compost quality to be established based on Colombian Technical Standard NTC5167 issued by the Colombian standards authority, *Instituto Colombiano de Normas Técnicas y Certificación* (ICONTEC) in 2011, and standards of different American, European, and Oceania countries.

3. Results and discussion

Monitoring of physical-chemical parameters and turnover

The Bokashi temperature was kept at ≤ 50 Celsius according to the recommendation for this Japanese method (Abaunza et al., 2008). While in composting treatments, EM recorded the highest temperature peaks during its degradation cycle with an average temperature of ≥ 55 Celsius for 48 hours. In the non-inoculated control, the temperatures did not increase above 34 Celsius (Fig. 2). Some researchers have also observed the increase in temperature due to adding microbial consortia on in-vessel composting systems (Martínez-Nieto et al., 2011a; Awasthi et al., 2018; Brenes-Peralta et al., 2020). The Colombian Technical Standard for organic products used as fertilizers does not require any temperature value as a quality parameter (ICONTEC, 2011). However, in other countries, a quality requirement is an increase of temperature $\geq 55\,^{\circ}$C for three days of in-vessel composting.

One of the factors that influenced the energy balance in composting treatments was the operation scale. In this research, the bins had less than cubic meter (0.08 m^3) volumes, with a ratio of surface area to volume (As / V) of 11.2, commonly used in laboratory-scale exploratory or demonstration studies. However, they presented greater surface heat loss than large-scale composting processes (Martínez-Nieto et al., 2011a; Alkoaik et al., 2019; Wei-Kuang and Chih-Ming, 2021). Furthermore, Arrigoni et al. (2018) expressed that in cold climates, the small-scale composting performance to reach thermophilic temperatures is poor due to biomass's difficulty retaining heat throughout the container, mainly in systems without aeration due to compaction and accumulation of leached in lower layers.

In addition to the bin volumes, another factor that probably influenced the absence of proper thermophilic activity in composting treatments was the initial moisture of the treatments, at $60-75\%$. Although it is recommended that the initial moisture of the waste mixture be between $40-60\%$, for Martínez-Nieto et al. (2011b), it is not advisable to manage moisture around 60% because all composting processes produce carbon dioxide and water, which together with the water of the material itself may cause that the temperature is not increased or maintained within the ranges required to eliminate pathogens. Similar results were observed in a co-composting experiment with food wastes inoculated with EM with initial moisture of $57-58\%$ in 0.03 m^3 bins in which the peak maximum temperature was $50\,^{\circ}$C for 24 hours (Zakarya et al., 2018).

The moisture in the treatments decreased during the composting process to values between 19.7 and 56.6%. Colombian standard NTC5167 requires final moisture contents of $\leq 20\%$ for animal-origin manures and values of $\leq 35\%$ in compost produced by combinations of animal and vegetal residues. Based on these values, only two composts met the requirements, CPAM (30%) and NI (19.7%). The moisture of the other treatments in descending order was Bokashi (56.6%), Acty Prad (46%), and EM (39.3%). Therefore, these treatments were extended to obtain the values required by the Colombian standard.

Changes in pH recorded for all the treatments were those usually expected during typical composting or Bokashi processes. The final pH values were within the range permitted by Colombian Technical Standard, between 4 to 9 (Abaunza et al., 2008; ICONTEC, 2011; Zakarya et al., 2018). The CAPM treatment presented the lowest pH value (7.0), followed by Bokashi (7.8), EM (8.0), Acty Prad (8.3), and the uninoculated control (8.5).

Physical-chemical and biological assessment to determine final product quality

CPAM treatment was the first to reach the curing stage and to complete the composting process, showing significant differences (P 0.031) with other treatments (Fig. 3). According to the treatment, biological inoculation decreased the composting cycle between 19.9% and 45.9%. These results are like other studies where different biological activators were used in the biowastes composting, accelerating the composting time compared to non-inoculated controls (De-Queiroz et al., 2017; Sánchez et al., 2017; Medina-Lara et al., 2018; Rastogi et al., 2020; Ortiz-Villota et al., 2021; Medina-Buelvas et al., 2023).

The control immaturity was observed in the germination test, with an average of 79% (Table 3). Although this parameter is not required in Colombia, most international standards consider a mature compost if the germination test is $> 80\%$ (Ge et al., 2006; Ozores-Hampton, 2017; Pecorini et al., 2020). Also, this treatment severely inhibited radicle growth with a germination index of 0.25, while the other treatments increased germination and growth in radishes with IG > 0.8 (Table 3). The loss of phytotoxicity in compost measures its maturity level and ensures the agronomic quality of the product on vegetal growth (Pecorini et al., 2020). Awasthi et al. (2018) and Rastogi et al. (2020), and Wei-Kuang and Chih-Ming (2021) also observed higher values for indices and percentages of germination in the treatments where microbial inoculation was added in comparison to non-inoculated controls.

As can be seen in Table 3, all treatments complied with Colombian regulations and the international standards consulted about the Carbon/nitrogen ratio and the reduction of organic matter (Ge et al., 2006; Ozores-Hampton, 2017). However, although the control meets these parameters, it is an immature compost according to the phytotoxicity (Table 3). Some researchers have found that the C / N ratio and the reduction of organic matter are not reliable indicators of compost maturity because they depend on the nature of the raw material achieving values ≤ 25 before the compost reaches an adequate level of stability and maturity (Wei-Kuang and Chih-Ming, 2021).

The parameters used in this study to determine stability and maturity (Earthy smell by geosmin, the temperature reached the curing stage, and phytotoxicity tests) were suffi-

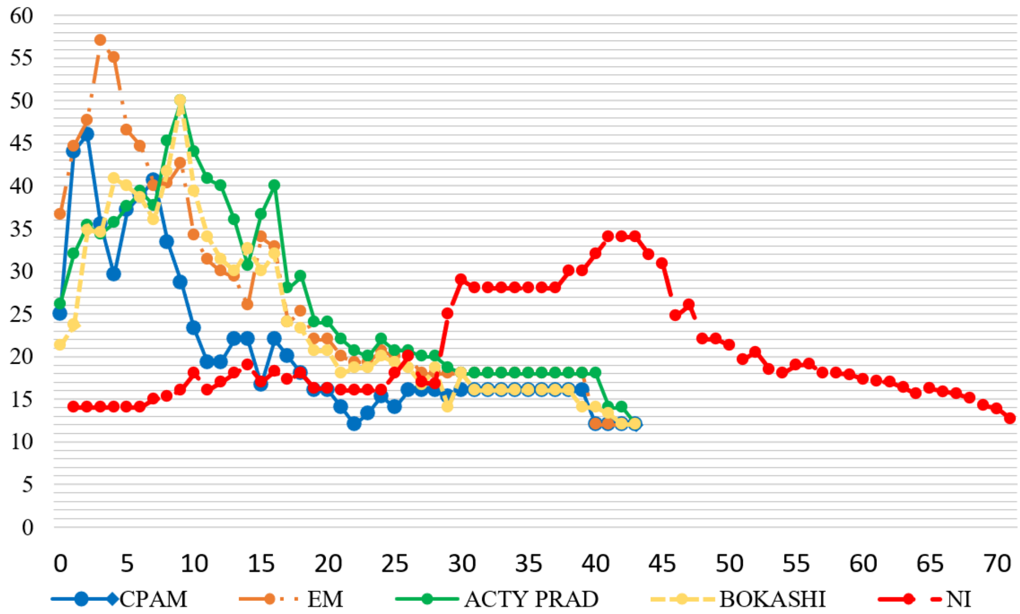

Figure 2. Dynamics of temperature presented by the treatments with "dry sweeping" pig manure in a pig farm on the Bogotá-Choachí Road.

ciently sensitive to assess these attributes, results like those obtained in other research involving different biological wastes (Oviedo-Ocaña et al., 2015; Sutrisno et al., 2020).

The heavy metal and impurities content in all treatments is within permitted limits in Colombian regulations (Table 4) and those of other standards consulted (Ge et al., 2006; Ozores-Hampton, 2017; Pecorini et al., 2020). Except for Bokashi, the other treatments presented Enterobacteria more than the values permitted by the standards consulted, with significant differences between them ($P < 0.05$). However, *Salmonella* spp. and parasites of clinical importance were not detected in any treatment. Regarding phytopathogens, *Fusarium oxysporum* was isolated only in control (Table 4). Additionally, the total microorganisms' counts were higher in the inoculated composts than in control (Table 4). Simarmata et al. (2021) also found stimulation of the native microbiota using microbial inoculants in agricultural waste composting.

The detection of Enterobacteria in composting treatments above typical values was due to a flawed sanitization process with exposures of less than three days to temperatures $\geq$ 55 °C (Fig. 2). However, other factors besides temperature may interact to reduce pathogens, as was observed in this research, where treatments with biological inoculation did not find *F. Oxysporum* (Table 4), but this phytopathogen was isolated in the raw material. This property of suppression of phytopathogens has been widely studied and is mainly due to certain microorganisms present in some composts (native or introduced) with bio-control activity because of different mechanisms such as competition for nutrients or

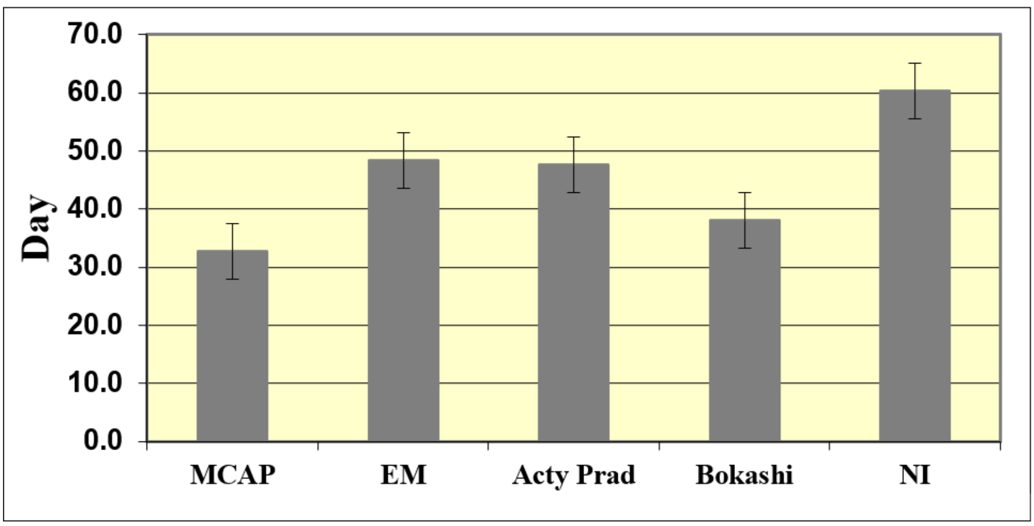

Figure 3. Composting during the inoculated treatments and control. The data represents averages of three replicates. Standard error bars are shown for each mean.

Table 3. Stability and maturity criteria used in this research.

Parameters	Unit	CPAM	EM	Acty Prad	Bokashi	NI	NTC 5167 (ICONTEC, 2011)
End Temperature	°C	12	12	12	12	14	PNR
Reduction of Organic Matter							
Ash (A)	%	40.0	25.2	28.3	39.8	22.4	≤ 60
Volatilization losses (V)	%	60.0	74.8	71.7	60.2	77.6	A+V=100
C / N	14.7	10.8	11.1	8.8	16.8	≤ 25	
Phytotoxicity Bioassay							
Germination of radish seeds P 0,00012	%	119 a	100 b	100 b	120 a	79 c	PNR
Germination Index P 0,021	1.59 a, b	1.61 a, b	1.44 a, b	2.86 a	0.25 c	PNR	

PNR: Parameter not required. The data represents averages of three replicates. Values with different letters show significant differences as determined by Duncan's Multiple Range Test ($P < 0.05$).

space, antagonisms, or the production of lignocellulolytic enzymes or antibiotics (Zaccardelli et al., 2013; Antoniou et al., 2017; Bellini et al., 2020; Hidalgo et al., 2022). Among the microorganisms that were preliminary identified from inoculated treatments, *Penicillium* spp., *Trichoderma* spp., *Pseudomonas* spp., *Streptomyces* spp., *Bacillus* spp. *Enterobacter* spp. y/o *Lactobacillus* spp., have been reported by several researchers as biocontrol agents for phytopathogens of economic importance in the agricultural sector (Zaccardelli et al., 2013; Antoniou et al., 2017; Bellini et al., 2020; Hidalgo et al., 2022).

On the other hand, studies in Colombia using the biological activators MCAP, EM, and Acty Prad in windrow composting with volumes ≥ 1 m^3 observed elimination of *Salmonella* sp. or *E. coli*, decrease in the Enterobacteriaceae counts and/or absence of recolonization of fecal coliforms compared to non-inoculated (Martínez-Nieto et al., 2011b; Panisson et al., 2021). In this research, a decrease in Enterobacteriaceae and *F. oxysporum* elimination during the thermophilic phase and absence of phytopathogen recolonization in the cooling and maturation phases of the composting process were also observed.

About the results obtained in the Bokashi treatment, also observed a decrease in the Enterobacteria concentration, which, according to these authors, was due to the combination between alcoholic fermentation and the increase in temperature between 40 - 50 °C.

Regarding the nutritional quality, this research observed that adding biological activators improved the content of some nutrients in the organic fertilizers produced, in contrast to the unoculated control (Table 4). Acty Prad was the best treatment in relation to phosphorus (P 4.13E-06) and sulfur (P 9.25E-05), while EM and CPAM presented higher concentrations of copper (P 0,000439) and iron (P 1.61E-05), respectively (Table 4). Acty Prad, EM, and Bokashi treatments presented the highest concentration of total nitrogen (P 0.00035). Although the compost inoculated with Acty Prad presented higher average calcium (P 0.02178) and magnesium (P 0.02178), the Duncan multiple range tests did not show significant differences with the control. Potassium, sodium, manganese, and zinc content showed no significant differences between treatments (Table 4).

These results agree with other research findings as it has been found that adding biological activators to composting improves the macronutrient concentrations such as nitrogen, phosphorus, and potassium. The increase in these nutrients depends on the physical and chemical characteristics of the raw materials used, the formulation, the type and concentrations of inoculants used, and operational control (Martínez-Nieto et al., 2011a; De-Queiroz et al., 2017; Sánchez et al., 2017; Medina-Lara et al., 2018; Fan et al., 2018; Xu et al., 2019; Rastogi et al., 2020; Simarmata et al., 2021; Hidalgo et al., 2022).

The biological activators tried in this research have been tested in different composting processes, obtaining the same benefits observed in this research, such as higher peaks of temperature, composting process acceleration, beneficial microorganisms higher count, *Salmonella* sp. elimination, lower phytotoxicity, greater maturity in a shorter time, increment of the nutrient's concentration and phytopathogens elimination. In addition, these activators and other lignocellulosic microbial inoculants showed other benefits such as a longer thermophilic stage, nitrogen loss reduction, higher degradation rate of recalcitrant materials, reduced total coliform content, and the agronomic parameters stimulation (Sánchez et al., 2017; Medina-Lara et al., 2018; Rastogi et al., 2020; Martínez-Nieto et al., 2011b; Xu et al., 2019; Matiz-Villamil et al., 2021; Greff et al., 2022; Hidalgo et al., 2022; Medina-Buelvas et al., 2023).

The effectiveness of the biological additives in stimulating different quality parameters varied between treatments. For example, while CPAM was the best treatment in relation to the duration of the process, and Bokashi significantly stimulated germination; however, CPAM treatment presented the lowest nutrient values, except for magnesium and iron. EM and Acty Prad acted on the same raw materials proportion, stimulating the concentration of most nutrients, and presenting similar patterns in the phytotoxicity tests and the

Table 4. Fertilizers quality assessment of produced by in-vessel composting and Bokashi using as raw material the pig manure produced on a pig farm at 3,000 m.a.s.l. on the Bogotá-Choachí Road.

Parameter	Unit	CPAM	EM	Acty Prad	Bokashi	NI	NTC 5167 (Simarmata et al., 2021)
Density	g/cm^3	0.39	0.28	0.29	0.37	0.28	≤ 0.6
Organic Carbon	%	21.9	29.4	30.7	22.7	31.5	≥ 15
Total Nitrogen (N) P 0.00035	%	1.49 b	2.71 a	2.76 a	2.57 a	1.87 b	Record on the
P2O5 P 4.13E-06	%	1.35 c	3.41 b	4.80 a	3.28 b	3.51 b	product label if
K_2O P 0.779	%	1.08	1.55	1.42	1.47	1.55	its value is > 1
MgO P 0.02178	%	0.49 a	0.43 a, b	0.53 a	0.34 b	0.48 a	-
CaO P 4.4E-06	%	1.05 c	2.59 a, b	3.58 a	2.25 b	3.12 a	-
S P 9.25E-05	%	0.095 d	0.052 e	0.286 a	0.266 b	0.256 c	PNR
Na P 0,372	%	0.56	1.18	1.05	0.84	1.09	PNR
Mn P 0,493	%	0.008	0.011	0.012	0.011	0.011	PNR
Fe P 1.61E-05	%	2.34 a	0.25 c	0.29 c	1.44 b	0.62 c	PNR
Cu P 0,000439	%	0.014 d	0.053 a	0.020 b	0.015 c	0.010 e	PNR
Zn P 0,849	%	0.012	0.014	0.017	0.013	0.014	PNR
Cation Exchange Capacity	$cmol(+)kg^{-1}$	98.6	141.2	149.1	112.3	124.6	≥ 30
Electric conductivity	$dS\ m^{-1}$	19.6	50.2	42.3	34.3	40.2	PNR
Heavy metals							
Arsenic	$mg\ kg^{-1}$	0.27	0.17	0.16	0.29	0.20	≤ 41
Cadmium	$mg\ kg^{-1}$	0.04	0.04	0.04	0.06	0.06	≤ 39
Chromium	$mg\ kg^{-1}$	28.47	8.50	7.99	17.99	6.99	≤ 1200
Mercury	$mg\ kg^{-1}$	2.85	2.20	2.75	3.65	3.30	≤ 17
Lead	$mg\ kg^{-1}$	0.15	0.54	0.55	0.47	0.60	≤ 300
Impurities							
Plastic, metal, rubber < 0,2	%	0	0	0	0	0	< 0.2
Glass > 2 mm	%	0	0	0	0	0	< 0.02
Stones > 5 mm	%	0	0	0	0	0	< 2
Glass > 16 mm	Detection	No	No	No	No	No	No presence
Microorganisms Human	**Pathogenic Bacteria**						
Enterobacteria P 0,0011	$CFU\ g^{-1}$	5.4E+05 b	3.9E+05 b	9.3E+04 b	7.1E+02 a	7.7E+04 b	< 1E+03 UFC g^{-1}
Salmonella sp.	Detection	Absence	Absence	Absence	Absence	Absence	Absence in 25*g*
Human parasites							
Ascaris lumbricoides	Detection	Absence	Absence	Absence	Absence	Absence	< 1 in 4 g
Trichuris trichiura Detection	Absence	Absence	Absence	Absence	Absence	-	
Uncinaria	Detection	Absence	Absence	Absence	Absence	Absence	-
Enterobius vermicularis	Detection	Absence	Absence	Absence	Absence	Absence	-
Strongyloides stercolaris	Detection	Absence	Absence	Absence	Absence	Absence	-
Taenia solium	Detection	Absence	Absence	Absence	Absence	Absence	Absence
Phytopathogens	Detection	Absence	Absence	Absence	Absence	*F. oxysporum*	-
Total count							
Mesophilic bacteria P 1.98E-10	$CFU\ g^{-1}$	7.9E+08 **a**	2.6E+07 **b**	9.1E+06 **b**	3.0E+08 **a**	8.4E+02 **c**	If microbial inoculants
Actinomycetes P 2.38E-07	$CFU\ g^{-1}$	1.6E+05 **b**	1.4E+05 **b**	4.7E+05 **a**	8.1E+05 **a**	1.0E+04 **c**	are added, perform
Fungi P 1.04E-05	$CFU\ g^{-1}$	5.0E+05 **a**	3.2E+05 **a**	1.0E+04 **b**	2.0E+04 **b**	1.0E+04 **b**	the total count of
Yeasts	$CFU\ g^{-1}$	0	0	0	0	0	mesophilic bacteria, fungi, and yeasts.

PNR: Parameter not required. The data represent averages of three replicates. Values with different letters show significant differences as determined by Duncan's Multiple Range Test ($P < 0.05$).

composting duration. Bokashi was the only treatment with Enterobacteria < 1E+03 UFC g^{-1}. Therefore, this treatment meets all parameters required in Colombian quality standards for organic fertilizers used in agricultural activities (ICONTEC, 2011). Although in this research the results were compared with several quality standards from different countries, the NTC 5167 standard (ICONTEC, 2011) is the only one valid in Colombia to establish the organic fertilizers quality from the swine manure composting and compliance of all the required parameters allow us to obtain the production and sale records of these organic inputs.

Moreover, according to the standards of British Columbia in Canada, the Enterobacteria concentrations > 1E+03 and < 2E+06 UFC g^{-1} in other treatments classify them as Class B or restricted use. Nevertheless, its application is recommended in forages, pastures, landscaping, silviculture, and soil recovery (Ge et al., 2006). The differences between treatments may be the result of the interaction between different factors such as the raw materials composition, the biological additives added, the composting system selected, and operational controls that determine the inoculants' effectiveness on end-product quality (Fan et al., 2018; Rastogi et al., 2020; Greff et al., 2022). However, Colombian legislation does not categorize organic fertilizers; if the fertilizer does not meet one or more of the requirements described in Table 4, the product is rejected. Thus the only technique that can be implemented by small pig producers in the Upper Teusacá River basin is Bokashi fermentation.

The Bokashi technique makes it possible to obtain organic fertilizers quickly, at low cost, and with materials available locally and adaptable for small agricultural producers. The cost of producing a 50 kg package in this research was 12.5 dollars and 92.5 dollars for 1 m^3 (unpublished data). Its application, in addition to reducing the risk of contamination of soil, air and water, contributing to soil conservation and the protection of biodiversity, reduces production costs due to the current value of synthetic fertilizers (For example, the value of a 50 kg package of triple 15 chemical fertilizer is 41.44 dollars), therefore improving the profitability of the crops. On the other hand, the development of these proposals can lead to generating a rural development model based on agroecology that would demonstrate the possibilities of communities to use the territory sustainably, guaranteeing and optimizing the conservation, recovery of ecosystem services and their ecological connectivity (ICONTEC, 2011; Ginting, 2019; Pereira et al., 2022).

The results obtained in this research allow pig farmers located in sustainable use areas from the Protective Forest Reserve of the Upper Teusaca River Basin to begin to comply with the environmental authority requirements about improving the swine manure management by composting. Thus, they could continue with pig exploitation and participate in actions aimed at ecological restoration and rehabilitation (Abaunza et al., 2008; Desarrollo Sostenible, 2016; Guevara, 2021). According to Guevara (2021), integrated soil management by the environmental authority must involve the peasant population as co-responsible actors for sustainable development with appropriate technologies that consider the protection, conservation, and rehabilitation of the Forest Reserve and their ecosystem services.

4. Conclusion

Although Bokashi was the only treatment that met all parameters required in Colombian quality standards for organic fertilizers, in all treatments, biological activators improved yield in the composting process undertaken by small pig producers in the Upper Teusacá River basin. However, despite these promising results, a limiting factor is the presence of Enterobacteria in laboratory-scale composting, which could be overcome with future research by using a larger-scale operation with volumes greater than 2 m^3 to secure a true thermophilic phase.

The enhanced agronomic value of the compost produced by the addition of biological inoculants is one of the relevant aspects in this research since the absence the phytotoxicity and phytopathogens elimination are essential criteria in the assessment of the suitability of compounds for agricultural purposes and the avoidance of environmental risks prior to use. Further, the production of suppressors compost is a response to the focus on sustainability required by the Environmental Management Plan for protected areas of the Upper Teusacá River basin since they represent an alternative to the use of chemical fungicides in peasant economy agricultural activities. Thus, Bokashi, by complying with all technical requirements demanded by the environmental authority, allows small pig producers to continue in the reserve area and use this organic fertilizer in their crops and in reforestation programs carried out in the Teusacá River basin for its recovery.

Although work must continue to optimize the operating parameters and to scale processes, the effectiveness observed so far in Bokashi and composting with bioaugmentation, and bio-stimulation methods show that these treatments are viable and sustainable alternatives for the management of byproducts of pig farming activities located in Paramo and high mountain ecosystems from Upper Teusacá River basin, one of the main pillars of the Bogotá DC ecological structure, which generates essential ecosystem goods and services for the local population and inhabitants of this city.

Acknowledgment

The authors express their gratitude to the Santa Fe Local Development Fund (FDLS) and the District Secretary for the Environment SDA (Former Technical Administrative Department of the Environment), which financed the research with public resources, and to the Colombian Agricultural Research Corporation (Agrosavia, the new identity of CORPOICA since 2018).

Author contribution

All authors contributed to the study conception and design. The first draft of the manuscript was written by Patricia Martínez-Nieto and Carlos Abaunza-González, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Patricia Martínez-Nieto participated in the project formulation (conceptual and referential theoretical framework). She also performed the analysis and results interpretation and manuscript preparation. Carlos Abaunza-González participated in experiment methodological design, data collection, results interpretation, and manuscript preparation. Gustavo Octavio García-Gómez participated in the conceptual and referential theoretical framework, data interpretation and preparation manuscript.

Conflict of interest statement

The authors declare that they are no conflict of interest associated with this study.

Open Access

References

Abaunza CA, García G, Martínez-Nieto P, Pinto CO (2008) BOOK: Incorporación de prácticas agroecológicas en los principales sistemas de producción de la localidad de Santa Fe. 125.

Alkoaik FN, Abdel-Ghany AM, Al-Helal IM, Rashwan MA, Fulleros RB, Mansour NI (2019) Effect of insulation on the performance of a rotary bioreactor for composting agricultural residues. *Energies* 12 (5): 315. https://doi.org/10.3390/en12020315

Antoniou A, Tsolakidou MD, Stringlis IA, Pantelides IS (2017) Rhizosphere microbiome recruited from a suppressive compost improves plant fitness and increases pro-tection against vascular wilt pathogens of tomato. *Front Plant Sci* 8:2022. https://doi.org/10.3389/fpls.2017.02022

Arrigoni JP, Paladino G, Garibaldi L, Laos F (2018) Inside the small-scale composting of kitchen and garden wastes: Thermal performance and stratification effect in vertical compost bins. *Waste Manage* 76:284–293. https://doi.org/10.1016/jwasman.201803.010

Awasthi MK, Wang Q, Wang M, Chen H, Ren X, Zhao J, Zhang Z (2018) In-vessel co-composting of food waste employing enriched bacterial consortium. *Food Technol Biotechnol* 56 (1): 83–89. https://doi.org/10.17113/ftb.56.01.18.5439

Bellini A, Ferrocino I, Cucu MA, Pugliese M, Garibaldi A, Gullino ML (2020) A compost treatment acts as a suppressive agent in Phytophthota capsica- Cucurbita pepo path system by modifying the Rhizosphere microbiota. *Front Plant Sci* 11:885. https://doi.org/10.3389/fpls.2020.00885

Biyada S, Imtara H, Elkarrach K, Laidi O, Saleh A, Kamaly O Al, Merzouki M (2022) Bio-augmentation as an emerging strategy to improve the textile compost quality using identified autoch-thonous strains. *Appl Sci* 12:3160. https://doi.org/10.3390/app12063160

Brenes-Peralta L, Jiménez-Morales MF, Campos-Rodríguez R (2020) Valorización de pérdidas de alimentos mediante compostaje y biosecado para pequeñas agroindustrias procesadoras de frutas. *Ingeniería y Competitividad* 23 (1): 1–31. https://doi.org/10.25100/iyc.v23i1.9623

De-Queiroz N, Pereira T, Martínez L, Castro CP De, Souza E (2017) Microbial additives in the composting process. Cienc. *Agrotecnologia.* 41 (2): 159–168. https://doi.org/10.1590/1413-70542017412038216

Desarrollo Sostenible Ministerio de Ambiente y (2016) Thesis: Plan de Manejo de la reserva Forestal Protectora Bosque Oriental de Bogotá. *Resolución 1766 del 27 octubre 2016, Bogotá, Colombia,* 16.

Díaz-Rodríguez G, Jiménez-Ramírez J, Serrano H, López-Arévalo H, Sánchez-Palomino P, Montenegro O (2021) Non-technified management of pigs (Sus scrofa) in the Andean, Amazon, and Orinoquia regions of Co-lombia. *Cienc Tecnol Agropecuaria* 21 (1): e1902. https://doi.org/10.21930/rctavol22_num1_art:1902

Fan YV, Klemeš JJ, Lee TL, Ho CS (2018) Efficiency of microbial inoculation for a cleaner composting technology. *Clean Technol Environ Policy* 20 (3): 517–527. https://doi.org/10.1007/s10098-017-1439-5

Ge B, McCartney D, Zeb J (2006) Compost environmental protection standards in Canada. *Environ Eng Sci* 5:221–234. https://doi.org/10.1139/s05-036

Ginting S (2019) Promoting Bokashi as an organic fertilizer in Indonesia: A Mini Review. *Int J Environ Sci Nat Resour* 21 (4): 556070. https://doi.org/10.119080/IJESNR.2019.21.556070

Greff B, Sxigeti J, Nagy A, Lakatos E, Varga L (2022) Influence of microbial inoculants on co-omposting of lignocellulosic crop residues with far animal ma-nure: A review. *J Environ Manage* 302:114088. https://doi.org/10.1016/j.jenvman.2021.114088

Guevara KC (2021) Thesis: Análisis de los conflictos socioambientales del uso actual del suelo de la ruralidad de la localidad Santafé. *Vereda el Verjón Alto (Bachelor' thesis) Universidad La Salle, Colombia,* 88.

Hidalgo D, Corona F, Martin-Marroquín JM (2022) Manure biostabilization by effective microorganisms as a way to improve its agronomic value. *Biomass Convers Biorefin* 12:4649–4664. https://doi.org/10.1007/s13399-022-02428-x

ICONTEC (2011) NTC 5167- Productos para la industria agrícola. Productos orgánicos usados como abonos o fertilizantes y enmiendas o acondicionadores de suelo. *J Soil Sci. Plant Nutr* Icontec, Bogotá, Colombia:51.

Martínez-Nieto P, Bernal-Castillo J, Calixto-Díaz M, Basto-Riaño MA Del, Chaparro-Rico B (2011a) Biofertilizers and composting accelerators of polluting macrophytes of a Colombian Lake. *J Soil Sci. Plant Nutr* 11 (2): 47-61. https://doi.org/10.4067/S0718-95162011000200005

Martínez-Nieto P, García-González D, Silva-Bonilla PS, Vargas-Chaparro G, Valderrama-Escallón F (2011b) Waste management generated directly or indirectly by onion crop in Aquitania (Boyacá-Colombia). *Revista AIDIS* 4 (2): 23–34.

Matiz-Villamil A, Tobar IC Chamorro, Sáenz-Aponte A, Pulido-Villamarín A, Carrascal-Camacho AK, Rojas I Gutié rrez, Sánchez-Garibello AM, Barrientos-Anzola IA, Zambrano-Moreno DC, Poutou-Piñales RA (2021) Management of swine mortalities through the use of a mixed composting-accelerating bio-inoculant. *Heliyon* 7:e05884. https://doi.org/10.1016/j.heliyon.2020.e05884

Medina-Buelvas A, García-Cuan A, Barraza-Amador B, Espinosa-Fuente E, Castillo-Cabrales M Del, Mendez-Gutiérrez K, Rosales-Hernández N (2023) Production of organic fertilizer using pleurotus sp. as a process Accelerator. *Global J Environ Sci Manage* 9 (1): 59–72. https://doi.org/10.22034/gjesm.2023.01.05

Medina-Lara MS, Quintero R, Espinosa V, Alarcón A, Echevers JD, Trinidad A, Conde FV (2018) Generación de un inoculante acelerador del compostaje. *Rev Argent Microbiol* 50 (2): 206–210. https://doi.org/10.1016/j.ram.2017.03.010

Medina-Rastogi MS, Quintero R, Espinosa V, Alarcón A, Echevers JD, Trinidad A, Conde FV (2018) Generación de un inoculante acelerador del compostaje. *Rev Argent Microbiol* 50 (2): 206–210. https://doi.org/10.1016/j.ram.2017.03.010

Ortiz-Villota MT, Patiño-Casallas CD, Blanco-Ayala DC (2021) Composting of solid waste from the coffee milling process using trench composting and a bioreactor with the help of efficient microorganisms in the Libre University, Socorro Headquarters. *Rev Ing Solidaria* 17:3481. https://doi.org/10.16925/2357-6014.2021.01.05

Oviedo-Ocaña ER, Domínguez I, Torres-Lozada P, Marmolejo-Rebellón LF, Hoyos LV, Gonzales S, Barrera R, Komilis D, Sánchez A (2015) Stability and maturity of biowaste composts derived by small municipalities: Correlation among physical, chemical, and biological indices. *Waste Manage* 44:63–71. https://doi.org/10.1016/j.wasman.2015.07.034

Ozores-Hampton M (2017) Guidelines for assessing compost quality for safe and effective utilization in vegetable production. *Hortitechnology* 27 (2): 162–165. https://doi.org/10.21273/HORTTECH03349-16

Panisson R, Paiva F, Müller C, Treichel H, Pavan E (2021) Increased quality ofsmall-scale organic compost with the addition of efficient microorganisms. *Braz J Environ Sci* 56 (3): 531–540. https://doi.org/10.5327/Z21769478949

Pecorini I, Peruzzi E, Albini E, Doni S, Macci C, Masciandaro G, Iannelli R (2020) Evaluation of MSW compost and digestate mixtures for a circular economy application. *Sustainability* 12:3042. https://doi.org/10.3390/su12073042

Pereira G, Araújo L, Wenneck G, Saath R, Ghuidotti G, Bertolo R (2022) Physicochemical characterization of fermented Bokashi compost produced on-farm in southern Brazil. *Rev Agric Neotrop* 9 (2): e6926. https://doi.org/10.32404/rean.v9i2.6926

Rastogi M, Nandal M, Khosla B (2020) Microbes as vital additives for solid waste composting. *Heliyon* 6:e03343. https://doi.org/10.1016/j.heliyon.2020.e03343

Simarmata R, Widowati T, Nurjanash I, Nuriyanash, Lekatompessy SJR (2021) The role of microbes in organic material decomposition and formation of compost bacterial communities. *IOP Conference Series: Earth and Environmental Science* 762 (3): 012044. https://doi.org/10.1088/1755-1315/762/1/012044

Sutrisno E, Zaman B, Wardhana IW, Simbolon L, Emeline R (2020) Is Bio-activator from vegetables waste are applicable in composting system? *IOP Conference Series: Earth and Environmental Science* 448:012033. https://doi.org/10.1088/1755-1315/448/1/012033

Sánchez OJ, Ospina DA, Montoya S (2017) Compost supplementation with nutrients and microorganisms in composting process. *Waste Manage* 69:136–153. https://doi.org/10.1016/j.wasman.2017.08.012

Wei-Kuang W, Chih-Ming L (2021) Enhancing the compost maturation of swine manure and rice straw by applying bioaugmentation. *Scientific Reports* 11:6103. https://doi.org/10.1038/s41598-021-85615-6

Xu J, Lu Y, Shan G, He X, Huang J, Li Q (2019) Inoculation with compost-born thermophilic complex microbial consortium induced organic matters deg-radation while reduced nitrogen loss during co-composting of dairy manure and sugarcane leaves. *Waste Biomass Valor* 10:2467–2477. https://doi.org/10.1007/s12649-018-0293-y

Zaccardelli M, Nicola F De, Villecco D, Scotti R (2013) The development and suppressive activity of soil microbial communities under compost amendment. *J Soil Sci Plant Nutr* 13 (3): 730–742. https://doi.org/10.4067/S0718-95162013005000058

Zakarya IA, Baya SN, Ramzi NM (2018) Effect of pH, temperature, and moisture content during composting of rice straw burning at different tem-perature with food waste and effective microorganisms. *E3S Web of Conferences* 34:02019. https://doi.org/10.1051/e3sconf/20183402019