




Assessment of organic agricultural waste and efficient native microorganisms in obtaining compost

Valoración de residuos orgánicos agropecuarios y microorganismos eficientes autóctonos en la obtención de compost

Authors

¹Jesús Eduardo Vázquez Quirumbay 
✉ jesus.vasquez.41@espam.edu.ec

²Ángel Monserrate Guzmán Cedeño 
✉ aguzman@espam.edu.ec

¹Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López. 10 de agosto N°82 y Granda Centeno. Calceta, Manabí.

²Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López. 10 de agosto N°82 y Granada Centeno. Calceta, Manabí, Ecuador. Universidad Laica Eloy Alfaro de Manabí, carrera Ingeniería Agropecuaria. Ciudadela Universitaria vía San Mateo. Manta, Manabí, Ecuador.

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Abstract

The poor management of organic waste generates pollution and impacts the environment; therefore, the production of organic fertilizers, such as compost, is an alternative to consider. The objective of this research was to assess agricultural organic waste and microorganisms efficient in obtaining compost. To this end, three phases were executed: Phase 1 consisted of generating information on agricultural waste to be used in compost production. A survey was conducted among technicians and/or administrators of the relevant production units. In Phase 2, information on efficient microorganisms generated in previous studies at universities in Manabí was systematized. In Phase 3, the microorganisms efficient in composting agricultural waste defined in the first phase were inoculated. The process was carried out using the INDORE system. Environmental, microbiological, chemical, and phytotoxic indicators of compost were evaluated. The results showed that the main agricultural waste generated in the study area are cocoa hulls, rice hulls, pig manure, and cattle manure. The mixture of these wastes allows for a good carbon/nitrogen ratio, which was a requirement for compost production. Regarding efficient microorganisms, it was established that their main function was as degraders of organic materials, plant growth promoters, antagonists, and bioremediators, with the genera *Trichoderma* and *Bacillus* standing out. Finally, after 120 days of composting, a Class "A" compost was obtained according to international standards.

Keywords: composting, biodegradation, biofertilizer, sustainability, organic farming.

Resumen

El mal manejo de residuos orgánicos genera contaminación e impactos en el ambiente; ante ello, la producción de abonos orgánicos, como el compost, son alternativas para tener en cuenta. El objetivo de esta investigación consistió en valorar los residuos orgánicos agropecuarios y microorganismos eficientes en la obtención de compost; para lo cual, se ejecutaron tres fases: la fase 1 consistió en generar información de los residuos agropecuarios a emplear en la producción de compost, se realizó una encuesta dirigida a los técnicos y/o administradores de las unidades de producción pertinentes; en la fase 2 se sistematizó información sobre microorganismos eficientes, generada, en estudios previos, en universidades de Manabí; en la fase 3 se realizó la inoculación de los microorganismos eficientes en el compostaje de residuos agropecuarios definidos en la primera fase, el proceso se llevó a cabo mediante el sistema INDORE, se evaluaron indicadores ambientales, microbiológicos, químicos y fitotóxicos del compost. Como resultado se obtuvo que los principales residuos agropecuarios generados en la zona de estudio fueron: cáscara de cacao, cascarilla de arroz, porquinaza y bovinaza, la mezcla de estos residuos permitió una buena relación carbono/nitrógeno que es un requisito para la elaboración del compost. En cuanto a los microorganismos eficientes se estableció que la función principal de estudio fue como degradadores de materiales orgánicos, promotores de crecimiento vegetal, antagonistas y biorremediadores, sobresalieron los géneros *Trichoderma* y *Bacillus*; por último, después de 120 días de compostaje se consiguió un compost de clase "A" según normas internacionales.

Palabras clave: residuos orgánicos, compostaje, compost, microorganismos eficientes.



Introduction

At the global level, large amounts of agricultural and livestock waste are generated and discarded, acting as sources of environmental pollution; in very few places are they given a productive use and assigned an added value that can become a source of energy within the production system to which they belong (Castro et al., 2020). Reports and evidence frequently indicate that the inadequate management of agricultural and livestock residues, solid waste, and other by-products of agri-food companies directly affect environmental balance; a clear example is solid waste, which leads to accumulation and dispersion not only in agricultural fields but also in aquatic environments (Muñoz et al., 2022).

Within this range of problems, agroindustrial residues arising from the different stages of agricultural production processes have also been added, generating high CO₂ emissions, particulates from uncontrolled burning, contamination of water bodies by leachates, the generation of foul odors, and the proliferation of rodents and insects (Romero, 2022). In this regard, Aguilar et al. (2022) reported the existence of research aimed at recovering and making use of agroindustrial residues according to their origin; among these studies are those dedicated to obtaining renewable energies, such as the production of bioplastics, glycerol, edible fungi, compost, among others.

According to Alvarado and Rangel (2020), the reuse of organic waste (OW) seeks to implement sustainable strategies for its utilization in organizations engaged in food production within alternative systems, through the application of different techniques and the results obtained from various feasibility studies for the production and commercialization of organic fertilizer.

Aguñaga et al. (2020) maintained that modern agriculture has incorporated the use of organic products, given the scientific evidence that they have increased crop growth and yield, harvest quality, and that they have also had physiological effects including cell elongation, vascular differentiation, and the development of production. Undoubtedly, the use of these organic residues is gaining increasing interest as an efficient means of rational nutrient recycling, since they promote plant growth and return to the soil many of the elements extracted during the productive process (Aguñaga et al., 2020; Intriago and Plaza, 2020; Huapaya, 2024).

Agricultural and livestock organic residues used in compost production naturally contain a microbial load; however, it is desirable to inoculate specific microorganisms that contribute to the composting of fibrous materials that are difficult to decompose.

Paredes et al. (2021) emphasized that the use of native efficient microorganisms (NEM) accelerated the transformation of organic residues into fertilizers, such as compost, where microorganisms participated in the decomposition of organic matter (Cruz et al., 2023). Likewise, when compost is used agronomically, mixed cultures of beneficial microorganisms can be inoculated to enhance energy conservation in the soil, maintain microbial balance, suppress pathogenic agents, and promote biological nitrogen fixation (Noboa, 2021; Vega et al., 2021; Han et al., 2022).

In compliance with the initiative of the Biological Input Production Research Group (GI-PROINBIO), faculty researchers and students of the Escuela Superior Politécnica Agropecuaria de Manabí “Manuel Félix López” (ESPAM MFL) have developed several studies, and thus important information has been generated related to the isolation, selection, and identification of native efficient microorganisms (NEM), as well as their validation according to the specific enzymatic activity of the isolated strains.

In this regard, Guzmán et al. (2014) isolated strains of microorganisms with cellulolytic capacity, and *Trichoderma longibrachiatum* and *Bacillus cereus* were molecularly identified as promising for the composting of fibrous peanut shell residues. Intriago and Plaza (2020) characterized endophytic bacteria obtained from tomatillo plants (*Lycopersicon pimpinellifolium* L.), which were evaluated as plant growth promoters. For their part, Andrade and Avellán (2020) assessed the cellulolytic capacity of *B. subtilis*, *B. licheniformis*, and *T. longibrachiatum* in the composting of cellulolytic agricultural residues.

Based on the aforementioned background, this research carried out an assessment of agricultural and livestock organic residues and native efficient microorganisms (NEM) in the production of compost. For this purpose, the following specific objectives were proposed: to characterize the main agricultural and/or agroindustrial organic residues generated in the area of influence of ESPAM-MFL; to determine the eco-functional activity of locally isolated NEM; to validate the NEM in the composting process of the selected organic residues; and to evaluate the nutritional value of the compost obtained.

Materials and methods

The work was carried out at ESPAM-MFL and was developed in three phases: in phase one, a survey was conducted within the area of influence of ESPAM-MFL (Junín, Canuto, Calceta, and Tosagua), where information was collected on the organic residues (OR) generated in the different agricultural or agroindustrial production units; phase two had the purpose of

systematizing information related to the use of native efficient microorganisms within and outside ESPAM (Molecular Biology Laboratory), especially those that are inoculated in soil or composting processes; finally, in phase three, the composting process was implemented to validate the NEM in the organic residues selected in phase one, and composted organic fertilizer was obtained as a result. This activity was carried out in the recycling area of the ESPAM MFL Polytechnic Campus. The main actions carried out within each phase are detailed below:

Phase 1. Assessment of agricultural and agroindustrial organic residues for composting

The following activities were carried out: a) Identification of agricultural and agroindustrial production units generating OR. Exploratory field visits, surveys using standardized forms, and semi-structured interviews were conducted in accordance with the objectives of the study and validated by experts; observations and measurements were also performed to classify the agricultural and/or agroindustrial production units generating OR that can be used as raw materials in valorization processes either through direct use or after being transformed into organic fertilizers by means of various biotechnological applications.

The scope considered was the ESPAM MFL Polytechnic Campus and its area of influence; in total, information was collected from 14 production units; b) Quantification and characterization of OR. To determine the amount of OR generated in the selected production units, historical data from 2019 to 2024 provided by the technical managers were analyzed; this information was contrasted with bibliographic references in order to estimate the averages per establishment and the periods of highest OR generation, and c) Diagnosis of OR management.

Based on the information provided by representatives of the agricultural, livestock, and agroindustrial companies of ESPAM MFL and its area of influence, the following were identified: 1) level of participation of the members of the production unit in the OR management process; 2) type and level of adoption of technologies for OR treatment, which was evaluated depending on the destination of the residues in the production areas (municipal dumps, natural channels such as ravines and rivers, OR treatment plant, and others such as sale, septic tank, livestock feed, research, and direct application in the plantation); 3) effectiveness of the technologies used; 4) environmental education processes on OR management; and 5) levels of impact caused by OR management. The responses were of a binomial nature (yes-no).

Phase 2. Determination of the eco-functional activity of locally isolated NEM

In this phase, a review was conducted of research works on the isolation, selection, and identification of native efficient microorganisms (NEM) that have been carried out at ESPAM

MFL and other universities in Manabí (UTM - Universidad Técnica de Manabí; ULEAM - Universidad Laica Eloy Alfaro de Manabí; Universidad Estatal del Sur de Manabí). For this purpose, it was necessary to access the institutional repositories of the universities of Manabí, search for degree projects within this field, and extract information such as: year of publication, project title, and enzymatic/antagonistic function of the NEM. Based on the published results, the state of the art of promising NEM by specific function was expanded, such as: decomposers of organic matter (cellulolytic), plant growth promoters, and biological control agents.

Phase 3. Validation of NEM in the composting process of OR and production of eco-functional compost

The information generated in the first two phases was essential for developing the composting process. The following actions were established consecutively: a) The most suitable raw material (OR) for the composting process was defined; that is, it met the particle size requirement with fragments of 3 to 5 cm, and a C/N ratio of around 25:1; b) Reactivation of the NEM decomposers of organic matter (OM) that were inoculated during the composting process; c) Establishment of the composting process through the following experimental design:

Formation of the piles. The OR were obtained from the agricultural and/or agroindustrial production units identified in Phase 1. For the composting process, the INDORE method was used on a concrete platform, with shade regulated by dense timber trees of laurel and mahogany established around the site; during pile formation, successive layers of the residues were added until forming a compost pile measuring 3 m in length × 1 m in width × 1 m in height.

Control of environmental indicators during composting.

The initial moisture of the organic residues was approximately 60%; thereafter, rehumidification was carried out according to the requirements of each phase of the process: mesophilic phase (20-40 °C, moisture 40-60%), thermophilic phase (45-70 °C, moisture 40-60%), where moisture was crucial for microbial activity, and maturation (ambient temperature, moisture 40-60%), in accordance with that suggested by Delgado et al. (2019) and Córdova et al. (2022). The pile was covered with plastic to prevent the entry of rainwater and to control the temperature inside the pile. During the first 15 days, the composting piles were monitored; temperature was recorded daily with a digital industrial thermometer (30 cm Tp101), moisture was measured using a Kalstein laboratory oven and a high-temperature-resistant watch glass, and pH was measured with an Oakton pH meter, model pH 700; turning was carried out to regulate temperature and homogenize the decomposition of the OR. Data collection was performed at 30 cm depth, at four edges and at the center of each compost pile. Subsequently, these parameters were monitored every 15 days until evidence of stabilization and compost maturity was obtained.



Inoculation of the NEM. Once the thermophilic stage had been completed in each of the piles, inoculation with the NEM that fulfilled the function of decomposers was carried out; for this purpose, a combined biopreparation with 1% molasses was prepared, with a concentration of 10^4 for fungi and 10^8 for bacteria. In each pile, 1000 mL of the biopreparation diluted in 20 L of H₂O was applied and sprayed over the entire pile with a CP3 backpack sprayer.

Compost evaluation. This was carried out every 30 days from the formation of the pile. Five compost samples were taken at a depth of 30 cm, from four edges and the center of each pile. The samples from each pile were mixed and homogenized to obtain a composite sample, which was sent to the laboratory for physical analysis: temperature was measured directly with a digital thermometer in °C at 30 cm depth at five points (four edges and the center); hydrogen potential (pH) was determined by the electrometric method at a 1:5 dilution (Garrido et al., 2023); for moisture determination, 50 g of sample were placed on a 5 cm diameter watch glass and introduced into an oven at 108 °C for 24 hours, after which they were weighed and the data were processed by the gravimetric method; electrical conductivity (EC) was measured using a compost/water suspension at a 1:5 ratio with a conductivity meter (Delgado et al., 2019); phytotoxicity (% and germination index of indicator seeds).

The evaluation of the phytotoxicity of the compost-optimizing agents was carried out through a germination and growth assay using 10 radish seeds that were placed in Petri dishes with a mixture of 67% sieved soil volume and 33% compost. Each dish received 5 mL of water, after which it was sealed and wrapped with kraft paper for 7 days. The germination data were entered into an Excel matrix and organized according to the type of treatment, from which the germination index (GI%) was calculated using the method adapted from the study conducted by Camacho et al. (2019).

The results were compared with the values established by national quality standards (Ministry of Environment and Water of Ecuador, 2020) and international standards (Chilean Compost Standard 2880, 2004; Mexican Standard AA-180-SCFI-2018, 2018; Colombian Technical Standard, 2011); the nutritional analysis of the compost was carried out at the Water and Soil Laboratory of the Santa Catalina Experimental Station of INIAP, where macro- and micronutrients were determined through acid digestion methods of the sample, followed by analysis by ICP (inductively coupled plasma atomic emission spectrometry).

Six treatments were established (T1: cocoa husk + cattle manure + NEM; T2: cocoa husk + cattle manure without NEM; T3: rice husk + cocoa husk + cattle manure + NEM; T4: rice husk +

cocoa husk + cattle manure without NEM; T5: rice husk + cattle manure + NEM; T6: rice husk + cattle manure without NEM), with five replications under a completely randomized design (CRD). The response variables in the compost assessment are presented descriptively, since subsamples were obtained from the replications to form one composite sample per treatment, which was sent to the laboratory for the corresponding physicochemical analysis. The results were then compared with the values established in the respective standards.

Results and discussion

Phase 1. Assessment of agricultural and agroindustrial organic residues for composting

Types of OR-generating companies

Figure 1 shows that the main enterprises visited in the study area corresponded to the agricultural sector; 50% were dedicated to animal production and 21% belonged to the crop farming sector, while the remaining 29% were agroindustrial. The surveyed enterprises reported that they work in the production of agricultural commodities such as rice, cocoa, coffee, plantain, mango, maize, citrus fruits, and sugarcane; livestock (swine, poultry, and cattle); and in the processing of these raw materials for the production of alcoholic beverages and other food products. In all of them, organic residues were generated that can be used as raw material for the production of organic fertilizers.

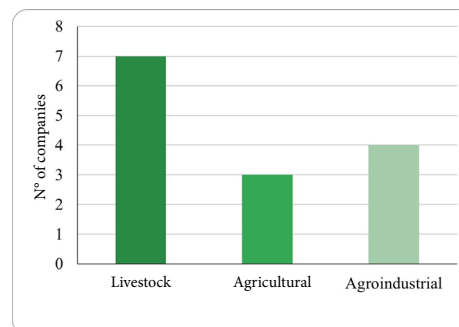


Figure 1. Typology of OR-generating enterprises.

Of the 14 companies surveyed, it was determined that 36% of the establishments were public and 64% belonged to private businesses. This indicates that agricultural and agroindustrial productive activity in the area of influence of ESPAM MFL corresponds mainly to family-based enterprises. The establishments surveyed comprised small and medium-sized companies, with areas ranging from 1 to 14 ha. The OR generated in the surveyed companies corresponded to the productive activities carried out. The main organic materials of plant origin were: husks, bagasse, stems, and other crop residues; in the

livestock sector these included poultry litter, cattle manure, and pig manure. Meanwhile, in the agroindustrial sector, waste was generated from the plant- and animal-origin raw materials that were processed.

This typology of enterprises was consistent with what was reported by Ojeda et al. (2021), who highlighted the performance of companies in Ecuador. Riera et al. (2024) detailed that in Manabí the products that generated residues included maize due to the residues from its ears, husks, and stover; rice due to the straw and husk produced in large quantities; and cocoa husk due to the post-harvest residues of its pods. For Ormaza et al. (2025) the variety, quantity, and seasonality of the residues generated depended on the production areas to which they corresponded.

The results showed that the generation of organic residues in the area of influence of ESPAM-MFL reached 431 t·year⁻¹ (table 1). The volume of organic residues evidenced the potential of the study area for the use and valorization of these materials. The largest proportion of residues came from the livestock sector (40.4% of the total), which indicated the importance of livestock production in local productive dynamics, since Manabí has the largest livestock area in Ecuador and approximately 339,819 head of cattle (Mena, 2022; Taipe et al., 2022).

Table 1. Quantity and type of OR generated in the different production areas.

Areas of production	Generated residue per year (t·year ⁻¹)	Type of residue
Agricultural	89	Crop residues (stems, leaves, stubble, harvest residues)
Livestock	174	Manure and slurry, forage residues (straw, stems, husks), and bedding from breeding and fattening operations.
Agroindustrial	168	Processing by-products (bagasse, bran, molasses, whey, fruit peels, vegetable scraps, among others).
Total	431	

The contributions from agriculture (20.6%) and agroindustry (39.0%) complemented this scenario, in which different sources of residual biomass converged that are susceptible to being transformed into value-added inputs, such as organic fertilizers, biogas, or biocomposites. These results reflected the need to design sustainable management strategies that integrate primary production and agroindustrial processing, in order to reduce environmental impacts and generate economic alternatives for agroproductive enterprises.

The findings were consistent with previous studies conducted in the province of Manabí, where agricultural and agroindustrial

activity has constituted one of the main sources of organic residues. For example, Cedeño et al. (2020) reported that in agricultural areas of Portoviejo and Rocafuerte, plant residues reached volumes close to 90 t·year⁻¹, figures similar to those recorded in this study. Likewise, Zambrano et al. (2019) identified that livestock production in Chone and Tosagua generated bovine and poultry manures with a utilization potential exceeding 150 t·year⁻¹, which coincided with the 174 t·year⁻¹ observed in the area of influence of ESPAM-MFL.

In the agroindustrial sector, studies by Loor and Delgado (2021) highlighted that the processing of dairy products, sugarcane, and fruit derivatives in Bolívar canton generated organic residue volumes exceeding 160 t·year⁻¹, data that were consistent with the 168 t·year⁻¹ reported in this study. At the national level, studies by Mendoza and Herrera (2018) have emphasized that the inadequate management of agroindustrial residues has represented one of the main environmental challenges of the Ecuadorian productive sector, which reinforces the relevance of promoting circular economy strategies and residue valorization in the region.

OR quantity generated by companies

As shown in figure 2, the volume of OR generated in agricultural and agroindustrial production units was highly variable. Based on the data collected, three OR generation volume intervals were established; from this, it was deduced that 86% of the companies generated OR between 0–10 tons or more than 20 tons annually. The highest volume of OR was generated in livestock production companies, which was related to the excreta and bedding from poultry and pig rearing operations.

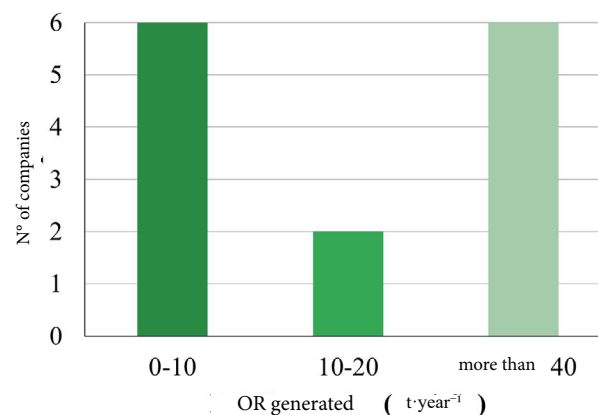


Figure 2. OR quantity generated by companies.

Compared with livestock production, agricultural and agroindustrial activities must be taken into account as generators of large amounts of solid waste such as crop residues and animal excreta, among others (Cartay et al., 2023). Another example is bovine manure, since each adult bovine unit (ABU) produces 5.6 kg·day⁻¹, as reported by Lozano et al. (2020). It should be considered that the lack of treatment or proper management of these residues could generate pollution, greenhouse gas emissions, and changes in the landscape (Cartay et al., 2023).

Season of OR production

From the baseline survey, it became evident that OR are available throughout the entire year, especially in those companies that generate large volumes, such as livestock production units (bovine and porcine manure), distilleries (sugarcane bagasse), and chocolate producers (cocoa husk). There were also companies that generated the highest amounts of OR seasonally during the second four-month period of the year (figure 3).

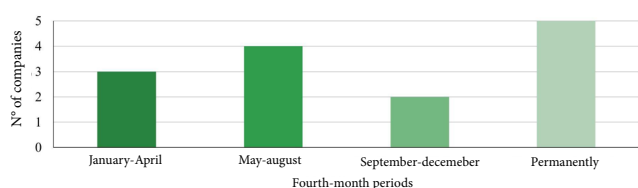


Figure 3. Season of the year when OR are generated.

The periods of organic residue production varied according to the productive activities carried out (Romero, 2022; Gutiérrez et al., 2024). The seasonality observed in the generation of organic residues was consistent with studies conducted in other areas of Ecuador. Albiño (2020) and Barona et al. (2020) agreed in reporting that agricultural residues showed generation peaks during the rainy season, mainly in short-cycle crops such as maize and rice; whereas during the dry season, vegetable residues were produced (Riera, 2024). In the Coastal region, residues derived from cocoa and sugarcane increased during the first and second four-month periods of the year, which coincided with the main harvest seasons (Ordoñez et al., 2021). In contrast, livestock residues maintained constant production throughout the year; for example, bovine manure was produced daily (Lozano et al., 2020), which supported the results of this study. These consistencies underscored the importance of considering seasonal variability when planning residue utilization programs, especially in agricultural and agroindustrial areas dependent on rainfall.

Knowledge of OR management and treatment

Twenty-nine percent of the respondents stated that they were aware of the chemical composition of the residues generated at the establishment, while 71% were unaware of the composition and chemical characterization of the OR. Sixty-four percent of the respondents did not know that OR are an important raw material for the production of organic fertilizers (Table 2). Seven percent of the respondents indicated that the OR were destined for the municipal dump, 21% reported that they were sent to an internal OR treatment plant, and 72% stated that they had other

destinations; that is, they attempted to use them in different activities specific to the production unit.

With regard to OR management, it was observed that 71% of the respondents were aware of the impact generated by OR; of these, 64% had basic knowledge about the production of organic fertilizers from these materials. Thirty-six percent had received training on the management of organic residues; however, 71% of the respondents were interested in developing a plan for the utilization of OR (table 2).

Tabla 2. OR management diagnosis.

Survey responses in %						
Options	Chemical composition and characterization of OR	Perceived value of OR for the production of organic fertilizers	Impact of OR on public health and the environment	Knowledge about the production of organic fertilizer	Has received training on OR management	Interest in developing a plan for the utilization of OR
Yes (%)	29	36	29	36	36	71
No (%)	71	64	71	64	64	29

Based on the survey results, it is possible to point out the need to seek alternatives that promote the reuse of residues and, at the same time, generate a source of economic income for those who engage in this activity. Solid waste destined for the municipal dump generates an excessive and diffuse amount of greenhouse gases (GHG), especially methane (CH₄), accounting for 50 to 70% of all the biogas produced (Herrera et al., 2023; Gavilánez et al., 2024). In view of this, Barros and Tovar (2023) pointed out that it is necessary to raise awareness of the severity of cultural and ecological demand-driven crises; therefore, it was suggested that the community should adopt new life habits in all the spheres that shape its reality.

Phase 2. Determination of the eco-functional activity of locally isolated NEM

Analysis of research studies conducted at ESPAM MFL

In the ESPAM-MFL degree project repository, a total of 24 documents addressing the use of microorganisms in different areas of study were identified (50% environmental, 42% agricultural, and 8% agroindustrial). The studies were focused on processes related to the production of organic fertilizers and nursery management (42%), inhibition of phytopathogens (biological control agents, 27%), recovery and conservation

of NEM (19%), and reduction of organic load and wastewater treatment (12%) (figure 4).

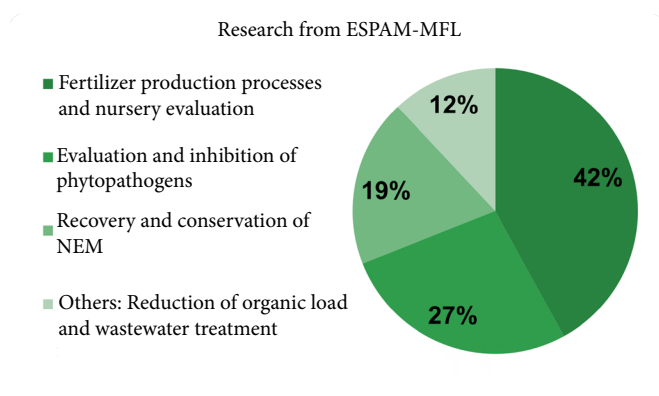


Figure 4. Uses of NEM in degree projects at ESPAM MFL.

It is of utmost importance to carry out the molecular identification of promising NEM; however, this field is still incipient. Morphological or biochemical characterization has predominated, which in many cases has only allowed identification at the genus level, as occurred with *Trichoderma*. In some studies, species-level identification has been achieved for the following NEM: *T. longibrachiatum*, *T. harzianum*, *B. subtilis*, and *B. cereus*. For the third phase of the study, bacterial strains (*B. subtilis*) and strains of the genus *Trichoderma* (EM-150, EM-72, EM-49) were selected.

Microbial communities in soils drive between 80 and 90% of the biological processes that occur in the soil, due to their multiple ecological niches, among which the mitigation of exogenous disturbances, promotion of plant growth, biocontrol activity, nutrient recycling, production of plant biomass, soil structure and fertility, and the degradation of toxic compounds stand out, among others (Cruz et al., 2022). For this reason, the information collected on efficient microorganisms is of utmost importance, since it makes it possible to clearly identify the type of cell that will provide the best response in the treatments evaluated during the composting process and thus replicate them in future studies.

Rosado et al. (2020) emphasized that without a biochemical analysis of the strains, it would not be possible to know which species of a given genus is being used, since species with identical genotypes may exhibit different responses depending on the type of treatments in which they are applied. Paredes et al. (2021) stated that knowledge of the species of efficient microorganisms is essential, as they are responsible for enhancing decomposition within the composting process; in this way, it is possible to differentiate the NEM that are specifically involved in decomposition from those that contribute to production and better development of seedlings after the composting process.

Analysis of studies using NEM in other universities in Manabí

In the studies conducted at UTM, ULEAM, and UNESUM, it was observed that most of the use of NEM (90%) was concentrated in the agroindustrial area, while only 10% corresponded to the medical field. Within these applications, degree projects accounted for 30%, followed by the validation of microorganisms in livestock production (30%). The production of organic fertilizers reached 10%, and biofertilizers constituted 20%. Finally, the remaining 10% was applied in different areas of medicine (figure 5).

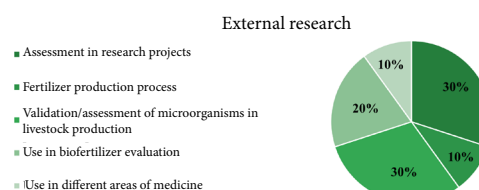


Figure 5. Use of NEM in research studies at UTM, ULEAM, and UNESUM.

The results showed that the use of NEM in the universities studied was mainly oriented toward agroindustry, which reflected the strong linkage of research with the productive needs and the valorization of organic residues in the region. The significant participation in degree projects and in the validation of microorganisms in livestock production evidenced a growing interest in applied research and in sustainable production strategies. The smaller proportion of studies in biology and medicine indicated that, although there were applications in other fields, priority was focused on optimizing productive processes and generating inputs such as organic fertilizers and biofertilizers. This was consistent with previous findings in Ecuador, where the use of NEM in agroindustry has shown a relevant impact on improving soil fertility and reducing residues. For Borjas (2021), it was imperative to deepen the study of NEM, given the evidence of their beneficial contributions in different anthropogenic activities.

Phase 3. Validation of NEM in the composting process of OR and production of eco-functional compost

Analysis of the behavior of environmental indicators (temperature, pH, moisture, and electrical conductivity)

Within the environmental parameters (table 3), the composting piles began at ambient temperature (around 20 °C). During the first week, an increase was observed in treatments T1 and T2, which reached 40 °C, indicating the onset of natural and inoculated microbial activity; in this context, Jara et al. (2020) stated that the increase in temperature was a real-time indicator of composting efficiency and was related to the rate of the biological reactions involved. The behavior of pH in the composting process was conditioned by the source materials and

varied among phases; according to Bailón and Florida (2021), this indicator was essential for determining compost quality, and its values were influenced by the composition of the residues used in the composting process.

In the present investigation, during the first four weeks, the pH in treatments T3, T4, T5, and T6 ranged between 5.01 and 6.96; in the third and fourth months of the composting process, an increase in pH values was observed, which ranged between 6.07 and 8.31 in treatments T1 and T2, which recorded the highest pH values; in contrast, treatments T5 and T6 registered low pH values. At the end of the process, pH values ranged between 6.0 and 7.5 in all treatments (table 3). The Chilean standard NCh 2880 defined pH values according to product quality, with class “A” compost ranging from 5.0 to 7.5 and class “B” compost from 7.51 to 8.5; these results were very close to those reported by Aguirre et al. (2022), which ranged between 6.47 and 8.89.

Table 3. Environmental parameters in the piles during the composting process.

Parameters	Treatment	Month 1				Month 2	Month 3	Month 4
		7 days	14 days	21 days	30 days			
Temperature (°C)	T1	40.22	41.09	36.30	37.50	37.17	38.86	32.16
	T2	40.30	40.00	36.48	36.40	35.00	38.00	32.60
	T3	33.18	34.46	35.06	35.80	39.26	34.80	37.00
	T4	33.58	33.31	35.78	35.80	36.10	33.90	35.90
	T5	34.76	34.46	35.88	36.10	37.17	35.50	35.70
	T6	36.07	34.50	34.70	34.50	37.18	36.00	36.00
pH	T1	6.43	5.78	6.10	6.07	8.31	8.00	7.00
	T2	6.12	6.78	6.50	6.14	8.31	8.31	7.50
	T3	6.07	6.24	5.01	5.01	7.10	7.18	6.72
	T4	6.12	6.23	5.40	5.40	7.87	7.90	6.54
	T5	6.32	6.80	6.90	6.96	6.70	6.07	6.00
	T6	6.35	6.88	6.81	6.90	6.60	6.08	6.09
Humidity (%)	T1	83.16	84.00	89.00	90.00	83.00	76.00	76.10
	T2	79.52	76.10	85.00	85.00	84.90	78.00	78.10
	T3	76.40	84.50	81.50	80.00	64.90	51.30	51.40
	T4	81.50	61.50	73.30	71.00	62.70	50.00	50.10
	T5	72.31	63.50	77.70	72.00	74.80	74.00	74.10
	T6	77.90	78.40	79.80	74.00	66.00	54.00	54.10
Electrical conductivity (dS·m ⁻¹)	T1	1.14	1.57	1.33	1.39	1.40	1.45	1.71
	T2	1.17	1.57	1.32	1.28	1.50	1.45	1.72
	T3	2.28	1.47	1.38	1.39	2.15	2.15	1.70
	T4	1.60	1.43	1.27	1.33	2.62	2.60	1.71
	T5	1.53	1.69	1.38	1.30	2.15	2.15	1.71
	T6	1.47	1.39	1.33	1.42	2.62	2.58	1.70

Based on this criterion, it can be stated that all the compost variants in this experiment were class A. The initial moisture percentage was very high in all the piles due to the rainfall that occurred during the collection and piling of the OR, especially in treatments T1 and T2, whose material retained a large amount of moisture.

The optimal moisture percentage was found within a range of 40-60%, although this may vary since it depended on the material used. According to the Chilean standard NCh 2880, the maximum permissible limit for the moisture variable is set between 30 and 45% for class “A” and “B” compost, respectively, while compost with >45% moisture is considered immature. In this study, all the compost variants exceeded 45% moisture; therefore, they were considered immature; however, it should be taken into account that the composting process lasted 4 months, and according to what was reported by Mero and Barreiro (2021), compost maturation takes 3-6 months. With respect to electrical conductivity, a class “A” compost was obtained (<5), according to the Chilean standard NCh 2880. EC values in the composting piles reached 0.143 dS·m⁻¹ (with NEM) and 0.144 dS·m⁻¹ (without NEM), values similar to those obtained by Bailón and Florida (2021). These values were within the range established by NCh 2880 (2004) (< 3 dS·m⁻¹) and the NMX (2018), which establishes that a compost with an EC range between 0.5 and 1.2 dS·m⁻¹ is classified as class A compost.

Phytotoxicity analysis

Figure 6 showed that the compost variants were below 80% germination of radish seeds used as indicators in the compost produced. However, it can be observed that the values increased over time, which confirmed that the concentration of phytotoxic components in the compost decreased sequentially and that the substrate can be used for agronomic purposes. It should be noted that the treatment with the highest germination index corresponded to T5 (rice husk + bovine manure + NEM). Ideally, it should exceed 90% germination to be considered mature compost, according to the NCh 2880 standard.

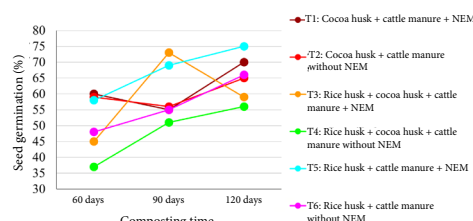


Figure 6. Seed germination index during the first three months of composting.

The results were similar to those reported by Delgado et al. (2019), who found a germination index below 80% in pile compost.

Analysis of the behavior of macro- and micronutrients during the composting process

In table 3, the mean values of the physicochemical variables evaluated at 60 and 120 days after the start of the composting process are presented. Of particular interest are the values at 120 days because the compost is used for agronomic purposes and must serve as a source of nutrients for cultivated plants. The mean macro- and micronutrient values were very similar in the two composting variants—with and without NEM—which confirmed that the nutrient content of the organic fertilizer depended on the starting materials. Nitrogen was highlighted, as it fell within the ranges established by NCh 2880 (2004), which indicates that the nitrogen content for mature compost should be $\geq 0.80\%$; these results were comparable to those obtained in the study conducted by Delgado et al. (2019), where values between 2.0 and 3.5% were reported. Likewise, phosphorus must be $\geq 0.1\%$ on a dry basis; potassium values were consistent with Colombian Technical Standard 5167 (2004), which states that mature compost should have values greater than 1.5%. Within this component, only treatments T1, T2, T3, and T4 met the parameters established by this standard.

In table 3, the micronutrient values reported for the different types of compost evaluated are presented. Boron was found in ranges below those evidenced in the study by Álvarez et al. (2021), whose values fluctuated between 34 and 36 ppm; therefore, all treatments were declared deficient in this nutritional component. Zinc is one of the essential nutrients in crop production; its permissible values range between 10 and 1000 ppm, values that were consistent with all the treatments in this study and were higher than those reported by Álvarez et al. (2021) and Dawar et al. (2022).

With respect to copper content, treatments T1 (14 ppm) and T2 (42 ppm) met the permissible ranges and can be classified as class A compost. In the case of iron, the nutritional load exceeded the standard in all treatments (standard values between 573 and 603 ppm); manganese likewise exceeded the permissible values established by the standard. These results were consistent with the high Fe and Mn values reported in the study by Álvarez et al. (2021) and did not comply with the Chilean Standard NCh 2880.

Organic matter (OM) in the compost with NEM showed values of 31.9 and 40.8% at 60 and 120 days of the composting process, respectively; in the compost without NEM, the OM averages were 33.9 and 45.03% at the two evaluation times. In the case

Table 3. Values of OM, macro- and micronutrients in compost with and without NEM.

Element	Unit	Composting time (days)												
		T1 (with EMA)		T2 (without EMA)		T3 (with EMA)		T4 (without EMA)		T5 (with EMA)		T6 (without EMA)		
		60	120	60	120	60	120	60	120	60	120	60	120	
Macronutrients														
Nitrogen	N	1.77	1.49	1.79	1.31	1.12	1.07	1.11	1.07	0.96	0.98	0.99	1.02	
Phosphorus	P	0.86	0.87	0.88	0.92	0.68	0.68	0.72	0.68	0.58	0.54	0.59	0.58	
Potassium	K	2.81	2.88	3.17	2.94	1.44	1.31	1.24	1.31	0.90	0.99	0.95	0.97	
Calcium	Ca	2.00	2.29	1.99	2.08	1.55	1.57	1.50	1.57	1.37	1.54	1.41	1.52	
Magnesium	Mg	0.77	0.84	0.81	0.85	0.78	0.78	0.67	0.78	0.74	0.81	0.78	0.81	
Sulfur	S	0.27	0.28	0.29	0.29	0.20	0.19	0.20	0.19	0.17	0.19	0.19	0.20	
Micronutrients														
Boron	B	12.5	7.3	15.6	12.5	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	
Zinc	Zn	168.8	153.3	158.9	154.9	160.4	154.8	162.8	154.8	149.0	155.5	149.1	145.8	
Copper	Cu	32.3	35.5	31.2	35.3	52.4	54.3	59.4	54.3	54.1	55.3	53.1	53.0	
Iron	Fe	9331	10937	8272	10103	15859	19507	16473	19507	17245	18609	18273	17237	
Manganese	Mn	338.7	340.0	319.8	322.2	417.4	474.5	459.7	474.5	505.1	499.3	477.0	449.6	
Organic Matter	OM	%	54.99	52.87	57.22	53.76	35.75	33.37	37.26	33.37	33.33	31.66	34.81	36.77
Organic Matter	%	31.90	30.67	33.19	31.18	20.73	19.36	21.61	19.36	19.33	18.36	20.19	21.33	
Ratio C/N	%	18.02	20.58	18.54	23.80	18.51	18.09	19.47	18.09	20.14	18.74	20.43	20.91	



of organic matter, the values ranged between 31.66 and 57.22%, which were lower than the results obtained by Jara et al. (2020), who reported values between 68.50 and 91.48%; however, according to NCh 2880 (2004), for a compost to be considered mature, OM must be equal to or greater than 25%. Therefore, the compost obtained was classified as class A.

According to Delgado et al. (2019), it should be taken into account that composting is a technique for the digestion of organic matter, which traditionally takes between 16 and 24 weeks; therefore, the composting process is of utmost importance to consider, since any intervening factor may affect or cause serious consequences at the time of compost harvest. In some cases, the composting process lasts longer due to the type of material used and the climatic conditions present during its preparation.

On the other hand, the nutritional contribution of compost is of utmost importance for agronomic purposes. The results achieved in the present study were consistent with those reported by Huapaya (2024), who documented adequate nutritional contents of organic matter, total nitrogen, and phosphorus, which could be considered high due to the substrate used—rice husk, cocoa husk, and bovine manure. In addition, it should be understood that organic fertilizer often forms the basis for the successful use of mineral fertilizers.

According to Casas and Guerra (2020), the combination of organic fertilizer/organic matter and mineral fertilizers offers ideal environmental conditions for crop production; however, it must be considered that the moisture content of the compost is at values >45%, which resulted in the material potentially being toxic when applied directly to the soil. In such cases, a technique that can be applied is the one proposed by Ciudades Verdes (2025), which mentioned that compost can be used as a mixture of 50% agricultural topsoil, 30% compost, and 20% screened coarse sand. Among these alternative solutions is the proposal by Brempong et al. (2019), who detailed that in semi-arid regions, compost with high moisture content can benefit soil carbon and nitrogen dynamics.

Conclusions

The main residues generated at ESPAM-MFL and in its area of influence are cocoa husk, rice husk, pig manure, and bovine manure. There is a continuous production of these residues in considerable quantities for the preparation of organic fertilizers. In the universities of Manabí, there is experience in research with efficient microorganisms, such as degraders of organic materials, plant growth promoters, antagonists, and bioremediators.

The organic residues and efficient microorganisms selected for the composting process (T2: cocoa husk + bovine manure without NEM; T4: rice husk + cocoa husk + bovine manure without NEM; and T5: rice husk + bovine manure + NEM) made it possible to obtain a category A compost, according to international standards.

Conflict of interest

The authors declare that they have no conflicts of interest in any stage of this publication.

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Author contribution statement according to CRediT

Jesús Eduardo Vázquez Quirumbay: formal analysis, original draft writing, research, manuscript editing. **Ángel Monserrate Guzmán Cedeño:** outline writing of the document, methodology editing, manuscript draft editing, formal analysis, writing—review and editing.

