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Agronomic, Economic and Environmental Comparative of Different Aeration Systems for On-Farm Composting

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Abstract: On-farm composting of agro-livestock wastes can be considered the most appropriate method for their recycling. Pile turning (PW) is one of the most widely used aeration systems for composting. However, this system has long composting periods and is inefficient at supplying oxygen and controlling the temperature. To minimize these drawbacks, the combination of turnings with forced aeration (PR) is an option; in this work, this combination was compared to PW as an aeration system for the co-composting of vegetable waste with different manures. In this comparative study, the evolution of the process, the compost quality and the economic and environmental impacts of the process were evaluated. The PR system was more appropriate for obtaining sanitized composts (the temperature was ≥55 °C for at least three consecutive days) with an adequate degree of maturity. Furthermore, this system reduced the organic matter and nutrient losses, yielding composts with higher agronomic value and a higher total combined value of the nutrients than those obtained using the PW system. However, the energy consumption and associated CO_2 emissions were lower for the PW system, since this aeration system was based only on turnings without the use of forced aeration, as in the case of the PR system. Agricultural valorization of composts will offset this energy consumption and its impact, since it will contribute to reducing the use of synthetic fertilizers. However, more studies are required on the PR composting system and other agro-livestock wastes for the creation of centralized on-farm composting sites, where all steps of the composting chain are optimized.

Keywords: agro-livestock wastes; compost; forced aeration; pile turning; combined aeration system

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1. Introduction

In 2021, South America produced approximately 417 million tons of edible plant products (cereals, fruits and vegetables) and had a cattle herd of around 3192 million heads. In that year, Ecuador was the sixth greatest producer, with 12.7 million tons of agricultural products and 177.2 million heads of live animals [1]. Crops and livestock are fundamental sectors of the economy of this country, accounting for 8.2% of the gross domestic product in 2021 [2]. These sectors constitute the main livelihood of the rural population, which comprised 35.6% of the total Ecuadorian population in 2021 [3]. This population generally has no knowledge of, and no technology or financial capacity for, the proper management of the waste generated on farms. The main residues generated by arable activity are plant and pruning residues and non-marketable products, which are often deposited on unoccupied land for drying and subsequent burning, producing impacts on the environment, such as the emission of greenhouse gases [4]. Additionally, the main destination of manure is its application to the soil without any technical criteria. This manure application to farmland could cause environmental damage, including atmospheric pollution by greenhouse gas emission [5] and contamination of soils and water resources due to the spread of pathogens and pharmaceutical products [6], as well as to the excess of nutrients [7,8].

Therefore, a great challenge is to achieve sustainable family farming production through better use of natural resources, especially in the context of climate change, which requires technological and institutional innovations to increase the resilience of the livelihoods of rural populations [9].

In this context, on-farm composting is considered a strategic technology for the sustainability of agricultural activities that can solve critical problems such as the elimination of vegetable wastes and manure. The composts obtained can be used as organic amendments or fertilizers within the area in which these wastes are generated, thus increasing the fertility and health of the soil and the carbon sequestration in the soil [10], as well as reducing inorganic fertilizer use and promoting efficient economic growth with reduced environmental impacts [10–13].

The co-composting of vegetable wastes and manure favors their degradation and recycling. Vegetable wastes are characterized by several aspects that complicate their composting; for example, the presence of components whose degradation is slow (waxes, lignins, other polyphenols, etc.) and a high C/N ratio, especially in the case of cereal and pruning residues, condition the biodegradability of these materials and prolong the composting process [14]. Moreover, manure contains antibiotics and pathogens that can be degraded and reduced in abundance, respectively, during the composting process [15,16]. Additionally, these residues can be considered a source of microorganisms and nitrogen [17]. Thereby, in several works, it has been reported that the addition of easily degradable residues, such as manure, to co-compost vegetable wastes increased the activity of microorganisms and the maintenance of the thermophilic stage, yielding a sanitized final material free of phytotoxins and with stabilized and humified organic matter (OM) [4,18–20].

Several on-farm composting methods can be applied, such as composting in open-air piles with different aeration systems or in confined systems. The investment and operational costs, the composting time, the availability of the necessary space and the amount of material to be composted are the main factors involved in the selection of the method of composting [11]. Among the composting systems for open-air piles, the aeration systems used most widely for the co-composting of vegetable waste and manure are pile turning and forced aeration. Pile turning is the prime candidate for the co-composting of these residues because it is considered a low-tech, energy-efficient and cost-effective aeration system. However, this system is more time-consuming than the forced aeration system [21,22]. Furthermore, forced aeration is the most efficient system with regard to the supply of oxygen and temperature control during composting [23,24] and reduces greenhouse gas emissions associated with the OM degradation [21]. On the other hand, the homogeneity of the composting mixture is low in forced aeration systems, since the material on the surface and at the bottom of the pile undergoes less degradation due to its lower temperature. This homogeneity of the materials during composting can be achieved by turning. The combination of both aeration systems could partially diminish the drawbacks of each of them when used separately. However, there are few studies on combinations of different aeration systems. Pergola et al. [11,13] composted crop residues using the combination of forced aeration with turnings and found positive economic and environmental results compared to the commercial green compost production. Rasapoor et al. [25] compared different aeration systems with the combination of pile turning and natural ventilation for municipal solid waste composting and they concluded that this aeration system could solve the problem of long degradation time and guarantee the obtaining of quality compost for agricultural use. Lim et al. [21] carried out a review of the existing works on the combination of in-vessel composting with pile turning and observed that the combination of these aeration systems reduced the drawbacks of each system separately, related to the investment and operational costs, the composting time, the availability of the necessary land area and the power consumption. Therefore, the efficiency and effectiveness of composting with combined aeration systems have been poorly explored. This work was intended to compare pile turning with the combination of forced aeration and turnings for mixtures of crop waste and different fresh manures, with regard to the effects on the composting process, on the thermal profile and the principal physicochemical and biological parameters of the piles, on the agronomic and economic value of the final composts produced and on the energy consumption and its associated carbon emissions.

2. Materials and Methods

2.1. Experimental Procedure for the Composting Process

The composting experiment was performed at the installations of the agricultural farm "La Inmaculada" in Guano canton (Chimborazo, Ecuador). This farm has an area of 4 hectares, in which herbaceous and horticultural crops and fruit trees (apricot, cherry and citrus) are cultivated. The residues to be composted were vegetable wastes (VW), composed of plant and pruning residues and non-marketable vegetables and fruits from previous crops, and three different manures from nearby farms: broiler chicken manure (BCM), guinea pig manure (GPM) and cow manure (CM). The BCM came from a farm with a production of 100 fowls/year, where rice husk is used as the bedding material and about 4.4 tons/year of manure are generated. The GPM was obtained from a farm where 80 guinea pigs/year are raised, with ground corn cob, wood chip and cocoa husk as the bedding material, giving an annual production of 2.6 tons of manure. The CM was collected from a dairy farm with 30 head of cattle, Jersey breed, with a production of manure + straw (bedding material) of 328 tons/year. The characteristics of these initial materials are shown in Table 1.

Table 1. Characteristics of the initial materials: vegetable wastes (VW), broiler chicken manure (BCM), guinea pig manure (GPM) and cow manure (CM) (dry weight basis).

	VW	BCM	GPM	CM
Corg (%)	36.0	28.4	48.8	35.6
Nt (%)	0.53	2.44	2.62	2.60
Corg/Nt	67.9	11.6	18.6	13.7
P (g kg^{-1})	3.72	8.36	5.80	9.26
K (g kg^{-1})	29.6	12.2	34.2	10.1
Ca (g kg^{-1})	13.0	7.6	10.0	18.8
Mg (g kg^{-1})	6.44	7.10	3.52	9.26
Na (g kg^{-1})	0.87	4.45	2.06	1.02
Fe (mg kg^{-1})	1130	3002	560	2387
Mn (mg kg^{-1})	67	167	40	151
Cu (mg kg^{-1})	10	39	9	24
Zn (mg kg^{-1})	49	126	83	51

Corg: total organic carbon, Nt: total nitrogen.

Six trapezoidal piles (approximately 1000 kg, with a base of 2 m × 3 m and a height of 1.5 m) were made by combining VW and manure to obtain a suitable Corg/Nt ratio (close to 25). The mixtures were made as follows on a fresh weight basis: Pile PW1: 76% VW + 24% BCM; Pile PR1: 76% VW + 24% BCM; Pile PW2: 76% VW + 24% GPM; Pile PR2: 76% VW + 24% GPM; Pile PW3: 76% VW + 24% CM; Pile PR3: 76% VW + 24% CM. Three of them (PW1, PW2, PW3) were composted using the aeration system with turnings (PW), and the others (PR1, PR2, PR3), with a system that combined turnings and forced aeration (PR). For the forced aeration, the air was blown from the base of the pile through three perforated PVC tubes of 3 m length and 12 cm diameter. Forced aeration was provided for 30 min every 12 h, to reach an aeration rate of 0.6 L min^{-1} kg^{-1}. Figure 1 shows a schematic presentation of the composting experiment design. All the piles were turned five times with a front-loading tractor. Figure 2 shows the days of the turnings. In each pile, the temperature was measured daily at five different points throughout the pile profile, using a temperature probe. When the temperatures of the piles were close to the ambient and re-heating was absent, it was considered that the active phase had ended. The manual and forced aeration were ceased at this point and the composts were allowed to mature.

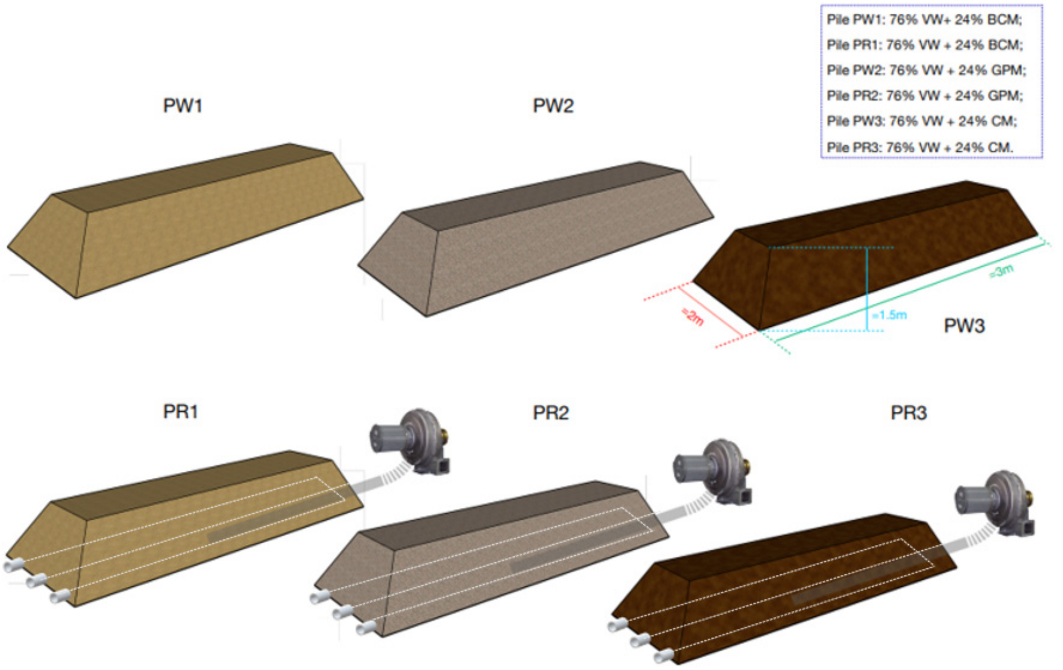

Figure 1. Schematic presentation of the composting experiment design. VW: Vegetable wastes, BCM: broiler chicken manure, GPM: guinea pig manure, CM: cow manure.

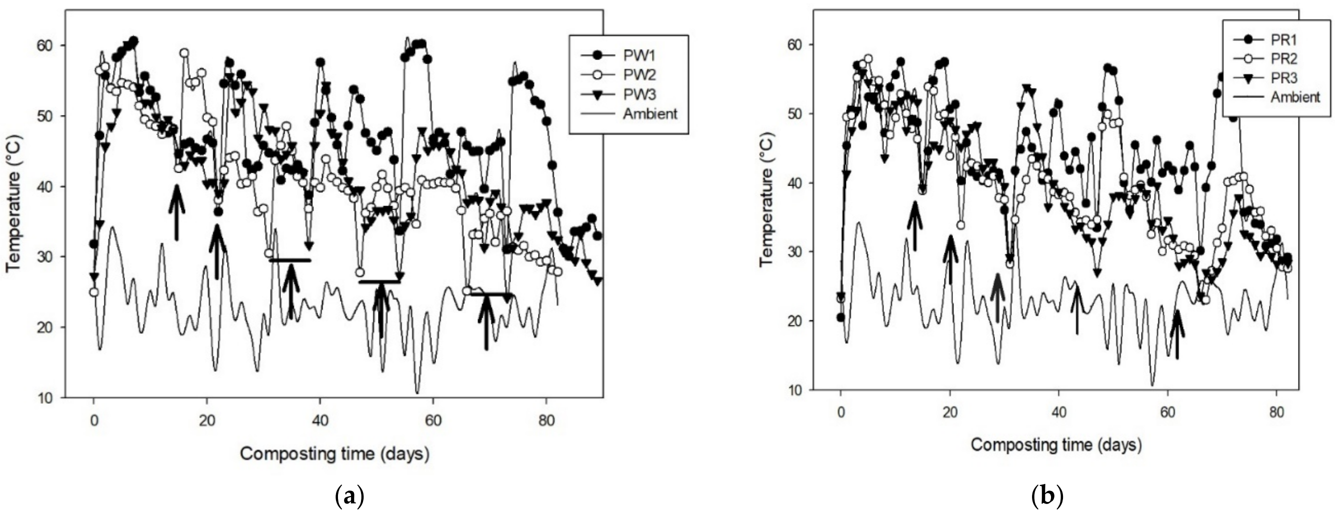

Figure 2. Temperature profiles, throughout the composting process, of the piles composted by the windrow system: (**a**) piles PW1 [76% vegetable wastes (VW) + 24% broiler chicken manure (BCM)], PW2 [76% VW + 24% guinea pig manure (GPM)] and PW3 [76% VW + 24% cow manure (CM)]; and (**b**) of the piles composted with a combined system of turning and forced aeration: piles PR1 [76% VW + 24% BCM], PR2 [76% VW + 24% GPM] and PR3 [76% VW + 24% CM]. For other abbreviations, see Figure 1. The arrows indicate the days of the turnings.

All the piles were composted under roofs to avoid the generation of leachates due to rain washing. The moisture contents of the piles were maintained at values higher than

40% throughout the process by using a sprinkler system when necessary. The leachates were not collected and re-incorporated into the piles. A total of four samplings were carried out in the six piles throughout the composting process. These samples corresponded to the beginning of the process: I (composting time = 0 days), the thermophilic phase: TP (composting time = 15 days), the end of the bio-oxidative phase: EBP (composting time = 82 days) and the mature compost: M (composting time = 142 days). In each pile, sampling was carried out by taking and mixing seven sub-samples from seven different sites encompassing the whole pile profile, to make the final sample representative. The collected samples were dried, ground and sieved to a size smaller than 0.5 mm, prior to their analysis.

2.2. Economic Value of the Final Composts

The economic value of the nutrients in the composts obtained was calculated based on the value of the N, P_2O_5 and K_2O fertilizing units of commercial mineral fertilizers, such as urea, diammonium phosphate (DAP) and potassium chloride (KCl). For all the composts a moisture content of 45% was considered, this being the mean value of the range established by US Composting Council [26] (moisture = 40–50%) for different applications of composts and field conditions. As established by Idrovo-Novillo et al. [19], the value of the fertilizing units of the above-mentioned fertilizers was calculated from their percentages (46% N, 46% P_2O_5 and 60% K_2O, respectively, for urea, DAP, and KCl) and the mean value of these fertilizers provided by Ministerio de Agricultura y Ganadería [27] in the months of January–December 2022 (1051, 1126 and 1100 US dollar tonne^{-1} for urea, DAP and KCl, respectively). Thus, the values of the N, P_2O_5 and K_2O fertilizing units were estimated to be 22.84, 55.63 and 22.10 US dollar tonne^{-1}, respectively.

2.3. Environmental Assessment of the Composting Process

For the environmental assessment of the two composting systems used (pile turning (PW) and forced aeration combined with turnings (PR)), only the CO_2 emissions associated with the energy consumption during the composting process were considered. According to IPCC [28], CO_2 emissions deriving from the composting process are biogenic and part of the short-term carbon cycle, so these emissions were not considered in this study. In each pile, the energy consumption due to the formation of the pile, turning and forced aeration was used to estimate the CO_2 emissions associated with the energy consumption. In order to make a justified comparison, the method used by Levis and Barlaz [29] and Rasapoor et al. [25] was employed to define the specific energy consumption per unit mass ($U_{E,C}$) of finished compost, as follows:

$$U_{E,C} = \sum{}^{E} / m_{dry\ compost} = \sum P_i t_i Lf_i / \left[m_{compost} (1 - MC) \right] \quad (1)$$

In this equation, E is the consumed energy (kWh o MJ), m is the mass of dry compost, P is the nominal power (in kW), t is the working time (in hours), Lf is the load factor (in percentage terms) of the equipment that consumes energy and MC is the average moisture content of the compost. To form the waste piles, a front-loading tractor with a 35.6 hp (26.20 kW) engine (designed to work on small farms and in crops with limited space to manoeuver) was used. The working time for the mixture preparation was 1.5 h for each pile. For the turning of the piles, an ST-200 model trailing turning machine was used; its material processing capacity was 11.65 m^3 kW^{-1} and it had an energy consumption of 0.26 kW in each turning of the compost piles.

The emissions associated with the energy use per unit mass of the finished compost ($U_{P,C}$) were defined using the emission factor (EF) for each type of energy consumed (in g-pollutant per kWh), as follows [28]:

$$U_{P,C} = \sum E_i EF_i / m_{dry\ compost} \quad (2)$$

The mean CO_2 emission factors were adopted from the study of Rasapoor et al. [25], where 767.48 g kWh^{-1} were considered for electric energy (150 W blower consumption) and the emission factor for diesel fuel was 70.1 g MJ^{-1} (74 kg $mmBtu^{-1}$).

2.4. Analytical and Statistical Methods

For the samples of initial materials and the samples taken over the course of the composting process, the pH, the electrical conductivity (EC), the germination index (GI), the dry matter and OM contents and the concentrations of total nitrogen (Nt), organic carbon (Corg), water-soluble organic carbon (Cw), 0.1 M NaOH-extractable organic carbon (Cex), fulvic and humic acid-like carbon (Cfa and Cha, respectively), water-soluble polyphenols, macro and micronutrients, Na and heavy metals were determined according to the methods described by Idrovo-Novillo et al. [19]. All analyses of the initial materials and the samples from the composting piles were made in triplicate. The humification indices were calculated as follows [30]: the humification index (HI) = (Cha/Corg) × 100; the humification ratio (HR) = (Cex/Corg) × 100; the percentage of humic acids (Pha) = (Cha/Cex) × 100; and the polymerization rate = Cha/Cfa. The percentage loss of OM was calculated according to the formula used by Paredes et al. [31]:

$$\text{OM loss (\%)} = 100 - 100[X_1(100 - X_2]/[X_2(100 - X_1)] \tag{3}$$

where X_1 and X_2 are the initial and final ash contents, respectively. For each of the piles, the SigmaPlot 14.5 computer program (Systat Software Inc. (SSI), San Jose, CA, USA) was used to calculate the loss of OM during composting, according to the following first-order kinetic function [32]:

$$\text{OM loss (\%)} = A\,(1 - e^{-kt}) \tag{4}$$

In this equation, A is the maximum degradation of OM (%), k is the rate constant ($days^{-1}$) and t is the composting time (days). The values of the adjusted R-Squared (R^2 adj) and F were used to fit the curve to the function and show the statistical significance of the curve fitting.

To calculate the significances of the differences among the mean values of each parameter studied during the composting process, the least significant difference (LSD) test at $p < 0.05$ was used. A one-way analysis of variance (ANOVA) at $p < 0.05$ was used to calculate the differences in the agronomic value among the final composts. A Tukey-*b* test was used to separate the mean values. All these analyses were carried out with the statistical software package of SPSS v 27.0 (IBM Software, Armonk, NY, USA).

3. Results and Discussion

3.1. Effect of the Aeration System on the Thermal Profile of the Piles

Temperature is considered one of the most important parameters in the composting process, since the evolution of this parameter during the process indicates whether sanitization, loss of moisture and degradation and humification of the OM in the waste mixture have been achieved [33]. A rapid increase in temperature was observed in all the piles during the first days of the composting process; temperatures higher than 40 °C were reached and the thermophilic stage was maintained for approximately 15 days until the first turning (Figure 2). This rapid increase in temperature at the beginning of the composting of vegetable wastes with manure has also been observed by other authors [4,18,20]. This is probably due to the reduction of the Corg/Nt ratio of vegetable wastes by the addition of manure, forming an easily degradable substrate that favors an increase in microbial activity and thus in temperature [20]. After each turning, the temperature increased, due to improved oxygenation and homogenization of the mixture. In general, the windrow piles (PW) had a longer thermophilic stage and higher temperatures than the piles with combined system of turning and forced aeration (PR), the average maximum temperatures being 60.3–60.7 °C and 55.9–57.9 °C for the PW and PR piles, respectively. The shorter duration of the thermophilic stage and the lower temperatures observed in the PR piles were probably due to the fact that forced aeration is the most efficient system with respect to the supply of oxygen and the control of temperature during composting [23,24].

With respect to the sanitization of piles, the United States Environmental Protection Agency (EPA) has established different requirements depending on the composting system used. In forced aeration piles, pathogen reduction is ensured when the temperature of the composted material is ≥55 °C for at least three consecutive days, while in turned piles, the temperature has to be kept at 55 °C or higher for 15 consecutive days with a minimum of five turns, thus ensuring that all the material of the pile is moved by the turnings into the core to undergo pathogen reduction [34]. In this study, all the PR piles met the EPA requirements for biosolids compost sanitation. However, in the PW piles these requirements were not satisfied, since the temperatures were ≥55 °C only during a period of 3 to 5 consecutive days. Finally, the bio-oxidative phase lasted approximately 82 days and the piles were then allowed to mature for around two months.

3.2. Effect of the Aeration System on the Evolution of the Principal Physicochemical and Biological Parameters of the Piles during Composting

A marked increase in pH with time was observed in all the composting piles (Table 2), probably the result of the release of ammonia from the mineralization of organic nitrogen in proteins, amino acids and peptides during the composting, the degradation of acid-type compounds such as carboxylic and phenolic groups [35] and the decrease in CO_2 within the mixture due to the aeration of the pile by turning and/or forced aeration [18].

Table 2. Evolution of the principal parameters during the composting of piles by the windrow system (PW) and with a combined system of turning and forced aeration (PR) (dry weight basis).

Composting Phase	pH	EC (dS m^{-1})	OM (%)	Corg/Nt	Nt (%)	Cw (%)	Polyphenols (mg kg^{-1})
PW1: vegetable wastes + broiler chicken manure							
I	7.0	3.52	69.9	23.6	1.70	7.07	11,003
TP	6.6	3.38	62.3	18.3	2.02	5.31	10,869
EBP	8.4	3.43	47.4	12.5	2.11	1.34	6564
M	8.6	3.30	41.7	12.4	2.02	1.36	5894
LSD	0.4	0.46	7.4	0.5	0.09	1.13	1219
PW2: vegetable wastes + guinea pig manure							
I	8.0	5.86	80.1	23.8	1.99	4.70	9745
TP	8.5	5.53	71.7	21.4	1.99	4.66	9470
EBP	9.7	5.38	53.5	14.6	2.00	1.09	7385
M	9.8	5.38	53.3	15.1	1.73	1.40	6581
LSD	0.5	0.20	11.5	0.4	0.09	0.91	1436
PW3: vegetable wastes + cow manure							
I	7.2	4.06	78.4	24.5	1.87	5.91	7622
TP	7.7	3.83	73.6	23.0	1.81	5.29	5716
EBP	9.2	3.07	44.4	13.4	1.88	1.37	2757
M	9.4	3.12	40.9	15.0	1.63	1.03	2116
LSD	0.3	0.31	9.5	0.6	0.08	0.96	700
PR1: vegetable wastes + broiler chicken manure							
I	6.8	3.90	73.2	23.2	1.77	6.83	10,257
TP	7.1	4.25	67.5	18.6	2.12	4.97	9028
EBP	8.9	4.41	53.5	13.1	2.35	2.22	7722
M	9.1	5.10	49.1	12.6	2.41	1.61	5946
LSD	0.4	0.37	11.9	0.5	0.10	1.33	2005

Table 2. *Cont.*

Composting Phase	pH	EC (dS m^{-1})	OM (%)	Corg/Nt	Nt (%)	Cw (%)	Polyphenols (mg kg^{-1})
			PR2: vegetable wastes + guinea pig manure				
I	7.9	5.24	79.5	24.6	1.91	4.53	8399
TP	8.5	4.58	72.1	21.9	1.97	4.33	7131
EBP	9.7	5.09	60.3	15.4	2.26	1.97	6430
M	9.8	5.83	59.4	14.5	2.39	1.61	6203
LSD	0.2	0.32	7.5	0.6	0.13	1.41	1242
			PR3: vegetable wastes + cow manure				
I	7.1	3.90	78.5	24.1	1.86	6.26	8439
TP	7.7	3.83	76.1	23.0	1.91	5.57	7234
EBP	9.3	3.81	48.7	15.3	2.04	2.18	3753
M	9.2	4.86	48.2	13.7	2.06	1.39	2889
LSD	0.3	0.33	5.7	0.6	0.10	1.00	346

I: initial phase of composting process, TP: thermophilic phase, EBP: end of bio-oxidative phase, M: end of maturation phase, EC: electrical conductivity, OM: organic matter, Cw: water-soluble organic carbon. For other abbreviations, see Table 1. LSD: least significant difference at $p < 0.05$.

This pH increase was lower during the maturation phase; this might have been due to the release of hydrogen ions by the nitrification process during maturation [25]. The final pH values were in the range of 8.6–9.8. Gavilanes-Terán et al. [4] and Ali et al. [18] co-composted vegetable residues with laying hen manure or cow, respectively, and these authors also observed a pH increase during the process, obtaining composts with a basic pH. In the PR piles, the breakdown of the OM caused the EC values to rise, probably due to the release of mineral salts and the increase in the relative concentration of ions caused by the loss of mass [36]. Conversely, in the PW piles, the salt content (EC) decreased during composting, possibly due to the leaching of salts caused by the addition of water. This phenomenon did not occur in the PR piles since the forced aeration resulted in greater drying of the waste mixtures.

The OM contents were reduced during composting, from 69.9, 80.1, 78.4, 73.2, 79.5 and 78.5% to 41.7, 53.3, 40.9, 49.1, 59.4 and 48.2% in piles PW1, PW2, PW3, PR1, PR2 and PR3, respectively, showing the degradation of the OM (Table 2). The initial and final OM values were higher in the piles with GPM, in comparison with the other piles, possibly due to the large proportion of lignocellulosic materials contained in this type of manure and used as litter for guinea pig breeding (Table 1). The lowest OM values were identified in the maturation phase, which is an indicator of the relative stability of the products after the completion of the bio-oxidative phase. This has been observed also in other composting processes with vegetable wastes and manure, such as horticultural waste, sawdust and laying hen manure [4] and rose waste, sawdust and different fowl manures [19].

The fit of the experimental OM loss data to the first-order kinetic equation was satisfactory and the statistical parameters are shown in Table 3. All the equations were significant at $p < 0.001$ or $p < 0.01$, with a good fit of the experimental data to the first-order kinetic equation, as shown by the values of F, R^2 adj and standard error of estimate (SEE). When comparing piles with the same composition, the A values and the degradation rate of the OM (A $\times$ k) (data calculable with the data provided in Table 3) were higher in the PW piles than in the PR piles. This could be related to the shorter duration of the thermophilic stage and the lower temperatures observed in the present experiment when the forced aeration + turning system was used, the temperature control being greater with the forced aeration system [24].

Regarding the Nt content, all the piles showed increases in the concentration of this nutrient during composting, except in the case of PW2 and PW3 (Table 2). The average loss of Nt in these piles was 13.0%, which could be attributed to the fact that the volatilization of ammonia and leaching of nitrogenous compounds were greater in these piles than in the rest [37]. In the comparison of piles with the same composition, the Nt loss was lower in PR piles than in PW piles, since in the former there was a higher concentration of this nutrient at the end of the composting process, with increases of 11–36% compared to the initial values. This could be due to the lower temperatures and OM mineralization of the PR piles compared to the PW piles.

Table 3. Values of the parameters of the first-order kinetic equation for the piles composted by the windrow system: piles PW1 [76% vegetable wastes (VW) + 24% broiler chicken manure (BCM)], PW2 [76% VW + 24% guinea pig manure (GPM)] and PW3 [76% VW + 24% cow manure (CM)]; and the piles composted with a combined system of turning and forced aeration: piles PR1 [76% VW + 24% BCM], PR2 [76% VW + 24% GPM] and PR3 [76% VW + 24% CM].

Piles	A (%)	k (Days^{-1})	R^2 Adj	F	SEE
PW1	69.9	0.0320	0.9738	223.60 ***	4.06
PW2	72.3	0.0462	0.9957	1393.53 ***	1.73
PW3	85.4	0.0287	0.9855	408.21 ***	3.73
PR1	66.1	0.0260	0.9901	598.88 ***	2.28
PR2	64.2	0.0338	0.9258	75.83 **	6.30
PR3	80.8	0.0291	0.9227	72.63 **	8.71

A: maximum degradation of OM, k: rate constant, R^2 Adj.: adjusted R-Squared, SEE: standard error of estimate. ***, **: significant at $p < 0.001$ and $p < 0.01$, respectively.

In all the piles, there was a decline in the Corg/Nt ratio along the composting process, a result of the loss of organic carbon—in leachate and as gaseous emissions in the form of CO_2—and the relative rise in the Nt concentration seen in the majority of piles [25] (Table 2).

Additionally, the Cw concentration decreased in all the piles during the composting process, from initial values of 4.53–7.07% to 1.03–1.61% (Table 2), possibly due to the use of this easily degradable carbon for the metabolic processes of microorganisms, thus improving the degradation of OM [37]. In most of the piles, the Cw content did not differ significantly between the end of the bioxidative phase and the maturation phase, indicating the stability of the OM at the end of the latter. This has been observed also by other authors during the co-composting of vegetable wastes with manure [4,19,37]. The Cw degradation rate was 70–83% for the PW piles, compared to 65–78% for the PR piles, indicating that the higher temperatures and longer duration of the thermophilic stage in the PW piles could have been due to greater microbial consumption of easily degradable organic compounds [38]. This was possibly related to the poorer temperature control in the piles that were aerated only by turning, compared to the PR piles.

The content of soluble polyphenols, a specific class of phytochemical antioxidant naturally present in all vegetable wastes [39], decreased over time in all the piles, reaching a total loss at the end of the process of 46, 33, 72, 42, 26 and 66% for PW1, PW2, PW3, PR1, PR2 and PR3, respectively. Thus, the PW piles showed a markedly greater reduction compared to the PR piles. The higher temperatures reached in the PW piles could be responsible for the greater degradation of soluble polyphenols, including thermo-stable polyphenols, compared to the PR piles of the same composition, due to their breakdown by thermophilic microorganisms [40].

The values of the majority of the OM humification parameters measured—HI, HR, Pha and Cha/Cfa—rose during the composting process in the piles (Table 4). This increase in OM humification shows that in all the piles simple organic molecules underwent polymerization to form humic substances [35]. For piles with the same composition, the final values of the OM humification indices were higher in the PW piles than in the PR piles, probably due to the longer thermophilic stage and higher temperatures in the former, which could have favored the proliferation of thermophilic microorganisms that degrade lignocellulosic compounds, yielding metabolites that promote the formation of humic substances [41].

Table 4. Evolution of the humification indexes and germination index (GI) during the composting of the piles by the windrow system (PW) and with a combined system of turning and forced aeration (PR) (dry weight basis).

Composting Phase	HI (%)	HR (%)	Pha	Cha/Cfa	GI (%)
PW1: vegetable wastes + broiler chicken manure					
I	13.7	37.4	36.8	0.58	0
TP	14.7	36.3	39.9	0.67	1
EBP	28.6	37.9	74.6	3.00	32
M	33.5	42.4	78.6	3.67	51
LSD	2.1	2.4	3.3	0.12	11
PW2: vegetable wastes + guinea pig manure					
I	10.0	29.4	34.0	0.52	0
TP	12.3	27.0	45.5	0.83	0
EBP	28.2	36.9	76.5	3.25	16
M	45.3	53.7	84.6	5.50	22
LSD	1.8	3.5	4.6	0.50	8
PW3: vegetable wastes + cow manure					
I	10.6	31.7	33.6	0.51	0
TP	15.7	32.2	48.5	0.94	0
EBP	27.0	35.0	77.1	3.40	23
M	27.2	34.8	77.2	3.40	38
LSD	2.7	2.2	3.7	0.23	5
PR1: vegetable wastes + broiler chicken manure					
I	12.7	36.8	34.5	0.53	0
TP	15.9	36.1	44.2	0.79	0
EBP	28.3	37.3	76.6	3.28	14
M	29.4	36.9	79.2	3.82	36
LSD	4.4	2.7	3.6	0.29	3
PR2: vegetable wastes + guinea pig manure					
I	10.1	27.8	35.9	0.56	0
TP	18.0	33.2	54.1	1.18	0
EBP	23.5	31.1	75.3	3.09	12
M	25.7	32.6	78.4	3.63	9
LSD	1.5	2.6	4.4	1.20	3
PR3: vegetable wastes + cow manure					
I	10.1	33.6	29.9	0.43	0
TP	13.3	28.6	46.5	0.88	0
EBP	23.4	32.1	72.4	2.64	14
M	24.0	32.0	74.2	2.88	14
LSD	3.0	4.8	5.3	0.70	5

HI: humification index, HR: humification ratio, Pha: percentage of humic acid-like carbon, Cha/Cfa: ratio of humic acid-like C/fulvic acid-like carbon; for other abbreviations, see Table 2.

Regarding the GI, the greatest reduction of phytotoxicity occurred in the PW piles, since the final GI values were higher in these piles (Table 4). This is in accordance with the greater degradation of phytotoxic compounds, such as soluble polyphenols, observed in these piles. In addition, it should be noted that the use of BCM produced compost with less phytotoxicity. However, among the composts produced, only PW1 reached the minimum value of GI (>50%) considered by Zucconi et al. [42] to show the absence of phytotoxicity in mature composts. This high phytotoxicity of the composts could be due to the high percentage of plant residues composted (76%), their high content of soluble polyphenols being characteristic of these residues [43].

3.3. Agronomic and Economic Value of the Final Composts

Table 5 shows the main characteristics of the final composts. They all had alkaline values of pH, the values of this parameter being significantly higher and lower in the composts with GPM (PW2 and PR2) and in the compost with BCM and aeration by turning (PW1), respectively. All the pH values of the final composts were well above those recommended by US Composting Council [26] for various applications of compost and average field conditions (pH = 6.0–7.5). The use of the forced aeration + turning system produced composts with higher EC values compared to the composts with the same composition that received aeration only by turnings. The use of GPM yielded the composts with the highest salinity values. Additionally, only composts PW1, PW3 and PR3 did not exceed the EC value of <5 dS m^{-1} suggested by US Composting Council [26] for composts destined for agricultural use.

Table 5. The main characteristics of the mature composts (dry weight basis).

	Compost PW1	Compost PW2	Compost PW3	Compost PR1	Compost PR2	Compost PR3	F-ANOVA	US Guidelines [a]
pH	8.6 a	9.8 c	9.4 b	9.1 b	9.8 c	9.2 b	34.8 ***	6.0–7.5
EC (dS m^{-1})	3.30 a	5.38 c	3.12 a	5.10 b	5.83 d	4.86 b	413.8 ***	<5
OM (%)	41.7 a	53.3 c	40.9 a	49.1 b	59.3 d	48.2 b	465.8 ***	50–60
Cw (%)	1.36 ab	1.40 ab	1.03 a	1.61 b	1.61 b	1.39 ab	4.8 *	
Corg/Nt	12.4 a	15.1 d	15.0 d	12.6 a	14.5 c	13.7 b	593.8 ***	
HI (%)	33.5 c	45.3 d	27.2 b	29.4 b	25.7 a	24.0 a	53.8 ***	
Nt (%)	2.02 c	1.73 b	1.63 a	2.41 d	2.39 d	2.06 c	663.2 ***	≥1.0
P (%)	0.87 b	0.66 ab	0.59 a	1.15 c	0.92 bc	0.95 bc	11.7 **	≥1.0
P_2O_5 (%)	1.99 b	1.52 ab	1.35 a	2.65 c	2.10 bc	2.19 bc	11.7 **	
Na (%)	0.45 ab	0.54 bc	0.40 a	0.64 cd	0.66 d	0.52 b	18.9 **	-
K (%)	2.16 a	4.57 cd	2.83 ab	3.31 bc	4.96 d	3.90 bcd	16.7 **	-
K_2O (%)	2.61 a	5.51 cd	3.41 ab	3.99 bc	5.97 d	4.70 bcd	16.7 **	-
Fe (mg kg^{-1})	6362 b	6040 b	6641 b	4005 a	3358 a	5616 b	38.9 ***	-
Cu (mg kg^{-1})	183 c	36 a	49 b	353 d	33 a	34 a	9407.2 ***	1500
Mn (mg kg^{-1})	328 d	139 b	182 c	583 e	103 a	172 bc	568.4 ***	-
Zn (mg kg^{-1})	320 c	183 ab	240 b	439 d	152 a	139 a	57.7 ***	2800
Ni (mg kg^{-1})	20 b	16 b	9 a	8 a	4 a	3 a	35.2 ***	420
Cr (mg kg^{-1})	16 b	10 a	28 c	7 a	6 a	8 a	48.5 ***	-
Cd (mg kg^{-1})	0.92 b	0.65 ab	0.53 a	0.46 a	0.41 a	0.30 a	8.3 *	39
Pb (mg kg^{-1})	30 a	33 ab	40 ab	44 b	49 b	48 b	6.5 *	300

For the abbreviations, see Tables 1, 2 and 4. ***, ** and *: significant at $p < 0.001$, $p < 0.01$ and $p < 0.05$, respectively. Values in a row followed by the same letter are not statistically different according to Tukey's *b* test at $p < 0.05$.
[a] According to US Composting Council [26].

Regarding the composts prepared with an initial mixture of the same composition, the OM content of the final composts was statistically higher in the PR than in the PW composts (Table 5), probably due to the greater degradation of OM in the PW piles, as mentioned in the previous subsection. Furthermore, only the PW2 and PR2 composts (both elaborated with VW + GPM) had OM contents within the range of values preferred by US Composting Council [26] for various agricultural applications of composts (OM = 50–60%).

No great differences were found in the Cw values among the composts obtained, and the maximum limit established for mature composts (Cw < 1.7%; [44]) was not exceeded (Table 5). The Corg/Nt ratio of the composts ranged from 12.4 to 15.1, PW2 and PW3 having the highest values and PW1 and PR1 the lowest values (Table 5). However, all the composts reached an adequate degree of maturity, since their Corg/Nt ratio values were < 20 [44]. In addition, the HI values of all the composts exceeded the minimum reference value for mature compost (HI > 13%; [45]) (Table 5). However, for the mixtures with the same initial composition, these values were significantly higher in the PW than in the PR composts, indicating increased OM humification in the PW piles, as discussed in the previous subsection.

In general, the concentrations of the macronutrients (Nt, P and K) and Na in the PR composts exceeded those in the PW composts, when considering pairs of composts derived from the same initial mixture (Table 5). This could be due to greater volatilization of ammonia and leaching of salts of these elements in the PW piles, since these composts had lower EC values. In general, the macronutrient contents of all the composts were within the range of values reported in other research into the composting of vegetable wastes and manure, while the Na concentrations were above this range in most of the composts obtained (Nt = 0.92–2.92%; P = 0.19–1.03%; K = 1.28–11.54% and Na = 0.29–0.42%) [4,19,20]. The minimum contents of Nt and P in composts intended for agricultural use should be 1.0% according to US Composting Council [26]; all the composts exceeded this value in the case of Nt, while only the PR1 compost satisfied it in the case of P.

In relation to the micronutrients, the PW and PR3 composts had the highest Fe contents while the PR1 compost had the highest concentrations, statistically so, of the rest of the micronutrients (Cu, Mn and Zn) (Table 5). Additionally, the maximum heavy metal content permitted in composts by the American guidelines [26] was not exceeded by any of the composts.

The economic value of each nutrient in the composts elaborated and the total combined value (US dollar tonne^{-1}) are shown in Table 6. The total combined value of the composts declined in the order PR2 > PR1 > PR3 > PW2 > PW1 > PW3, due, in general, to the greater content of macronutrients in the PR composts (Table 5). This fact shows the advantages of the use of forced aeration regarding the marketable value of the compost obtained. Regarding the nutrient values, nitrogen, phosphorus and potassium contributed 16–22%, 34–52% and 27–50% of the combined value of the composts, respectively. Idrovo-Novillo et al. [19] also found that P was the nutrient that contributed the most to the total value of the compost, 50–60% of the total combined value. When comparing the composts prepared with the same aeration system, but with different manures, the marketable value was higher for those prepared with GPM, mainly due to its higher K_2O content (Table 5). The compost nutrient values obtained in this study show that these materials are an alternative source of macro and micronutrients that can be supplementary or complementary to the use of inorganic fertilizers, generating considerable economic returns.

Table 6. Economic value of the composts obtained, based on the nutrient content (Nt, P_2O_5 and K_2O), (US dollar tonne^{-1}).

Nutrient [a]	Compost PW1	Compost PW2	Compost PW3	Compost PR1	Compost PR2	Compost PR3	F-ANOVA
Nt	25.38 ab	21.74 a	20.48 a	30.28 b	30.03 b	25.88 ab	9.90 **
P_2O_5	60.89 b	46.36 ab	41.15 a	80.93 c	64.10 bc	66.70 bc	11.75 **
K_2O	31.72 a	66.96 cd	41.44 ab	48.43 bc	72.55 d	57.18 bcd	16.81 **
Total combined value	117.99	135.05	103.08	159.64	166.68	149.76	

[a] The economic values of the nutrient contents were estimated based on a value of 45% moisture in the composts (the average value of the range established by US Composting Council [26]: 40–50%, for various applications of composts and field conditions). Values in a row followed by the same letter are not statistically different according to Tukey's *b* test at $p < 0.05$. **: significant at $p < 0.01$. For the abbreviations, see Tables 1 and 2.

3.4. Energy Consumption and Its Associated Carbon Emissions According to the Aeration System Used

Under our experimental conditions, the production of 1 kg of compost dry matter by the PW and PR systems needed 0.2224 and 0.2905 MJ of energy and caused a total emission of 15.59 and 30.11 g of CO_2, respectively (Table 7). The composting operations considered in the calculation of these values were the pile conformation and the aeration of the pile (forced aeration and turnings). The CO_2 emission was highest for the PR system, mainly due to the greater electricity consumption of this system in comparison to the PW system (31% greater energy consumption), a consequence of the use of a blower for the forced aeration. In a comparative study of aeration methods for municipal solid waste composting (forced aeration, natural ventilation, aeration by means of turnings and a combination of turnings with natural ventilation), Rasapoor et al. [25] also observed that forced aeration was the aeration method with the highest energy use and associated carbon emissions. However, the combination of forced aeration with turnings in our study (the

PR system) had a lower energy consumption than that found by Pergola et al. [11] in an on-farm composting study with forced aeration and weekly turning cycles (0.4429 MJ per kilogram of compost produced). This could be due to the longer duration of the composting process and the longer cycle of forced ventilation and turnings in the study of the previous authors. Together, these new and earlier results show that the energy use during composting depends on the duration of the composting process and the level of aeration. Among the composting operations, the initial pile preparation consumed the largest amount of energy, with the consequent high values of the associated CO_2 emissions, representing 98% and 75% of the total energy use and 98% and 51% of the total climate impact for the PW and PR systems, respectively.

Table 7. The energy consumption and its associated CO_2 emission per unit of mass of compost in the studied aeration systems (PW: pile turning; PR: forced aeration combined with turnings).

Operation	PW	PR
Energy use in pile conformation (MJ kg dry matter^{-1})	0.2177	0.2177
Associated emissions (g-CO_2 kg dry matter^{-1})	15.26	15.26
Forced aeration energy use (MJ kg dry matter^{-1})	0.0000	0.0681
Associated emissions (g-CO_2 kg dry matter^{-1})	0.00	14.52
Pile turning energy use (MJ kg dry matter^{-1})	0.0047	0.0047
Associated emissions (g-CO_2 kg dry matter^{-1})	0.33	0.33
Total energy use (MJ kg dry matter^{-1})	0.2224	0.2905
Total associated emissions (g-CO_2 kg dry matter^{-1})	15.59	30.11

Nonetheless, it is important to indicate that the energy consumption and its associated emissions during the composting process are often offset by the agricultural use of the compost, which can replace or reduce the use of inorganic fertilizers, the latter accounting for most of the energy used in the life cycle of different crops [25].

4. Conclusions

The results of this study, with two aeration systems (pile turning (PW) and forced aeration combined with turnings (PR)), indicate that the PR composting system was the most suitable for the on-farm composting of vegetable wastes and manure. All the PR piles met the requirements for the maintenance of high temperatures for compost sanitation. Additionally, with this aeration system, greater control of the temperature was achieved, which reduced the degradation of OM, thus yielding composts of higher agronomic value. On the other hand, the forced aeration system combined with turnings reduced nutrient losses due to ammonia emissions and salt leaching. Thus, the composts obtained with the PR system had a higher macronutrient content, giving them a higher marketable value. Furthermore, all the PR composts had final values of different parameters that indicated an adequate degree of maturity (Cw < 1.7%; Corg/Nt < 20; HI > 13%). However, the energy consumption and associated CO_2 emissions were higher for the PR system. The agricultural use of composts will compensate this energy consumption and its impact, since it will contribute to reducing the use of synthetic fertilizers, whose production is responsible for most of the energy use and emissions associated with agricultural production.

Therefore, these results indicate that on-farm composting with forced aeration combined with turnings is a viable alternative to recycle agro-livestock wastes and to obtain quality composts, allowing closure of the productive cycle of the farms, thus helping to achieve their environmental and economic sustainability. However, more studies are required on this composting system and other agro-livestock wastes to optimize all steps of the composting chain in centralized on-farm composting sites.

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data curation, C.P., I.G.-T. and V.V.-O.; writing—original draft preparation, V.V.-O., C.P. and I.G.-T.; writing—review and editing, C.P. and I.G.-T.; visualization, C.P., I.G.-T. and J.I.-N.; supervision, C.P. and I.G.-T.; project administration, I.G.-T.; funding acquisition, I.G.-T. All authors have read and agreed to the published version of the manuscript.

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