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Characterization of Agro-Livestock Wastes for Composting in Rural Zones in Ecuador: The Case of the Parish of San Andrés

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Abstract: In Ecuador, the agriculture and livestock sectors are very important within the economy of rural areas. These activities generate a large amount of waste whose management is not optimized. Thus, the aim of this work was to characterize different agro-livestock wastes generated in a rural area, the parish of San Andrés (Chimborazo-Ecuador), in order to know their composition to design suitable composting processes for their treatment. To this end, different physicochemical and chemical parameters were determined in 24 crop residue samples and 18 manure samples, and two piles were elaborated with the same proportion of wastes (51% vegetable residue + 35% cow manure + 14% sawdust) and composted by turning or passive aeration. Throughout the composting process, the temperature and oxygen concentration were recorded and the evolution of different physicochemical, chemical, and biological parameters and the quality of the final composts were studied. The results indicated that the agro-livestock residues presented notable macro and micronutrient and organic matter contents and low levels of heavy metals, these properties being positive for their subsequent treatment in a co-composting experiment. This experiment demonstrated that the composting processes are a feasible strategy for the treatment of these residues and yield compost with an adequate agricultural quality (notable nitrogen content, low heavy metal and soluble mineral salt contents and 92–94% in germination index). Moreover, the passive aeration system can be recommended because this aeration method reduced composting times and the work associated with the process. However, more studies are required on this composting system and other agro-livestock wastes to establish a management protocol for all the waste generated, which will contribute to the sustainability of the agro-livestock sector in the area studied.

Keywords: crop residues; manures; macro and micronutrients; phytotoxic compounds; compost

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1. Introduction

Ecuador is divided into 24 provinces, which comprise a total of 221 cantons. The cantons are subdivided into parishes for local administration. There are two types of parishes: urban and rural. The rural parishes of Ecuador depend directly and mainly on crops and livestock, fundamental sectors of the Ecuadorian economy. Together, these two activities accounted for an average of 8.1% of the annual Ecuadorian gross domestic product in the period from 2011 to 2020 [1]. In 2020, the total cultivated land area in Ecuador was 5.2 million hectares, distributed among cultivated and natural pastures, permanent and transitory crops, and fallow [2]. In that same year, the livestock sector was led by poultry, with 27 million birds, followed by cattle, with 4.3 million heads, pigs, with 1.1 million heads, and other species such as sheep and horses [2].

The Ecuadorian agricultural sector is led by small producers [3] belonging to the rural population, which represented 35.8% of the total Ecuadorian population in 2020 [4].

They use traditional production techniques, generating significant amounts of solid wastes, whose management is not optimized. Most of this population lacks the knowledge, technology or financial capacity necessary for the adequate management of the wastes generated in the farms, since they live in poverty and have difficulties covering their basic needs [5]. The wastes from the agricultural activity include crop residues (branches, stems, leaves, roots, etc.), as well as products rejected because they do not meet the quality criteria necessary for commercialization. These wastes are often deposited on unoccupied land for drying and incineration, with the consequent environmental pollution, produced mainly by the emission of greenhouse gases [6]. The livestock waste is mainly composed of the manures (excreta, urine, and bedding material) of the different species reared. Most of these manures are deposited directly on the soils or are stored in nearby croplands for drying and subsequent incorporation into the soil without any dosage criteria. Hence, these practices lead to significant environmental impacts on the atmosphere, soil, and inland water masses, such as greenhouse gas emissions [7], and contamination of water sources and soils due to excess nutrients, pathogens, and the xenobiotics given to animals [8,9].

Agricultural crop wastes have a variable mineral content and a high organic load, including lipids, proteins, waxes, lignin, polyphenols, cellulose, and hemicellulose [10,11]. Additionally, manures have high contents of bioavailable nutrients, organic matter, and microelements that are important for plant growth [12]. The treatment of these residues by composting to obtain organic fertilizers would contribute to the reinvestment of these constituents in the agricultural production cycle, thus reducing chemical fertilizer use and the negative environmental impacts and production costs associated with it [13]. Composting is a very suitable method for waste treatment in developing countries because it can be performed with low-tech systems and it has low costs compared to other waste recycling technologies [14]. The composting of agro-livestock wastes can also reduce the environmental problems related to their management, due to the reduction of their volume [13], the degradation of phytotoxic compounds such as xenobiotics given to animals and polyphenols [6,15], and the potential elimination of pathogens [16]. However, due to the heterogeneous origin of agro-livestock residues, their composition is highly variable [10–12] and, therefore, before composting these residues, a systematic determination of their composition is necessary.

Hence, based on the above-mentioned considerations, the objective of this study was to evaluate the types of organic wastes from crops and livestock generated in a rural zone in Ecuador—specifically, the parish of San Andrés—and to determine their composition to be able to develop composting processes that contribute to the treatment of these residues. This information will allow the assessment of whether the composting of agro-livestock wastes can be applied to promote the sustainability of the agricultural sector in this area.

2. Materials and Methods

2.1. Study Area and Surveys

The study was carried out in the parish of San Andrés, located in the Guano canton, in the northwest of the province of Chimborazo (Ecuador). This parish has a total area of 159.9 km^2, in an elevation range between 2900 and 6310 m above sea level (a.s.l.), and a variety of climates, from that of the glacier in the Chimborazo volcano to a cold and temperate climate, with ranges of monthly average temperatures and annual total rainfall of 8–14 °C and 500–1000 mm, respectively. San Andrés has a population of more than 15,000 inhabitants, distributed in 32 communities and eight neighborhoods, whose economic activities are mainly agricultural (representing 57% of the total economic activities of this parish) [17].

In this study, 30 farmers were surveyed to obtain information on the crop and livestock species produced in the parish of San Andrés and the fates of the waste from agro-livestock activities. The surveys were conducted in the communities of Santa Lucía de Chuquipogyo, Sigsipamba, San José de la Silveria, Calshi Grande, Cuatro Esquinas, San Pablo, Pulinguí, 12 de Octubre, Tuntatacto, Uchanchi, Paquibug, Tahualág, El Quinual, and Batzacón because these communities have the largest area of agricultural production (from 200 to 1053 ha), and the largest number of animal breeders and hectares of land for breeding and grazing [17].

2.2. Agro-Livestock Wastes

The agro-livestock residues characterized were those from the most important crops and livestock in the parish of San Andrés. This information was obtained through surveys. Therefore, 24 crop residue samples and 18 manure samples were collected by subsampling a single large sample (Table 1). These subsamples were dried at 60 °C, ground, and sieved to 0.5 mm for later analysis. All determinations were made in triplicate.

Table 1. Origin and general characteristics of the agro-livestock wastes.

Sample Code	Residue	Sampling Site (Community)	Residue Characteristics
		Crop Residue	
CR-1	Maize (n = 3)	Santa Lucía de Chuquipogyo; Batzacón and Sigsipamba	Plant stems; leaves and roots
CR-2	Sweet corn (n = 2)	Calshi Grande and San José de la Silveria	Plant stems; leaves and roots
CR-3	Pea (n = 3)	Batzacón and Pulinguí	Plant stems; leaves; pods and roots
CR-4	Barley (n = 3)	Santa Lucía de Chuquipogyo; Tuntatacto and Uchanchi	Plant stems
CR-5	Broad bean (n = 5)	San José de la Silveria; Paquibug; Tahualág and Cuatro Esquinas	Plant stems; leaves; pods; roots and non-marketable vegetables
CR-6	Potato (n = 3)	Batzacón; Calshi Grande and San Pablo	Plant stems; leaves and roots
CR-7	Carrot (n = 5)	Santa Lucía de Chuquipogyo; Cuatro Esquinas and El Quinual	Plant stems and non-marketable vegetables
		Manure	
M-1	Cow manure (n = 10)	Batzacón; Calshi Grande; Cuatro Esquinas; San Pablo; Santa Lucía de Chuquipogyo and El Quinual	Excrement with straw litter
M-2	Cow manure-feed fed (n = 2)	12 de Octubre	Excrement with straw litter
M-3	Sheep manure (n = 2)	San José de la Silveria and Pulinguí	Excrement without litter
M-4	Pig manure (n = 2)	Calshi Grande and Pulinguí	Excrement without litter
M-5	Horse manure (n = 2)	Cuatro Esquinas and Tuntatacto	Excrement with straw litter

2.3. Co-Composting Experiment

To assess the feasibility of treating the studied wastes by composting, two mixtures of residues were formed, each one (approximately 1000 kg) with dimensions of 2 × 3 m at the base and a height of 1.5 m, using a mixture of vegetable residues (VR) from different horticultural crops (composed of non-marketable vegetables and crop residues—branches, stems, leaves, roots, etc.), cow manure (CM), and sawdust (SR). The proportions (on a fresh weight basis) in each pile were: 51% VR + 35% CM + 14% SR. These waste proportions were selected to achieve an initial total organic carbon (Corg)/total nitrogen (Nt) ratio of 25–35, suitable for an active composting process [18]. Two cost-effective and low-energy intensive aeration systems were used in these piles: turning aeration (TA) and passive aeration (PA). The PA system consisted of the use of perforated polyvinylchloride pipes that crossed longitudinally the bottom of the composting pile in order to provide aeration through natural processes of diffusion and convection, in a similar way to the experiment of Rasapoor et al. [19]. Figure 1 graphically shows the aeration systems used in this co-composting experiment.

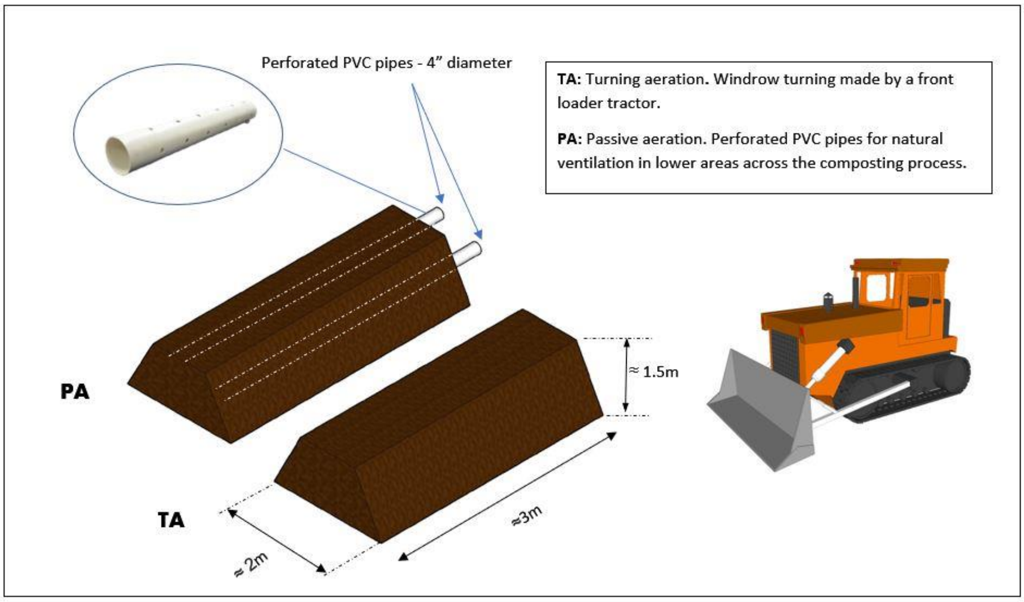


Figure 1. Graphical description of the set-up of co-composting experiment. PVC: polyvinylchloride.

Throughout the process, the moisture content of each pile was controlled to guarantee adequate values (40–60%). The leachate was not collected and reincorporated into the piles. The average temperature and oxygen concentration were recorded daily at five different points, at a depth of 30 cm from the top, using portable probes. The ambient temperature was also measured daily. In the TA pile a total of five turnings were carried out, while in the PA pile only two were carried out, with the purpose of homogenizing the mixture. The bio-oxidative phase lasted 190 days and 154 days for piles TA and PA, respectively. Both piles were allowed to mature for one month, during which time the moisture content of the mixtures was maintained between 40 and 60%. At the beginning of the composting process and at the end of the maturation stage, representative samples were obtained from each pile by taking and mixing seven sub-samples from seven different sites encompassing the whole pile profile. These samples were dried and treated in the same way as the samples obtained from agro-livestock wastes. All determinations were made in triplicate.

2.4. Analytical and Statistical Methods

In agro-livestock residue samples and samples from the composting piles, the pH and electrical conductivity (EC) were determined in a 1:10 (*w*/*v*) water extract. In a water-soluble extract of the samples, 1:20 (*w*/*v*), water-soluble anions (Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}), and water-soluble polyphenols were measured by ion chromatography and the modified Folin–Ciocalteu method, respectively. Organic matter (OM) was determined by loss on ignition at 430 °C for 24 h. Automatic elemental microanalysis was used to determine Corg and Nt. After $HNO_3/HClO_4$ digestion, P was measured colorimetrically as molybdovanadate phosphoric acid and K, micronutrients and heavy metals were determined by inductively coupled plasma mass spectrophotometry. In an aqueous extract of the samples vs. a control with deionized water, cress (*Lepidium sativum* L.) seed germination and root elongation were measured to calculate of germination index (GI) (GI = [(number of seeds germinated in the sample/number of seeds germinated in control × 100) × (root length of seeds germinated in the sample/root length of seeds germinated in the control × 100)]/100). All analytical methods used are described in detail by Gavilanes-Teran et al. [10].

The characterization data of the crop residues and manures were subjected to statistical analysis, considering the types of residues and the number of samples available. The mean value, the range of values, and the coefficient of variation (CV) of each parameter, considering the type of residue, were calculated. A one-way analysis of variance (ANOVA) was performed to test whether there were statistically significant differences in the mean value of each parameter studied among the different types of residue. When the F-ANOVA was significant, the Tukey-b test was performed as a post-hoc analysis to evaluate the differences among the specific means of the distinct residues, these being shown in the results using letters for a probability of 95% ($p < 0.05$). In the composting experiment, OM losses were calculated according to the formula used by Paredes et al. [20] and fitted to a first-order kinetic equation [21]: % OM losses = A $(1 - e^{-kt})$, where A is the OM potentially degradable (%), k the degradation rate constant (days^{-1}), and t the composting time (days). The adjusted R^2 values were calculated to compare the fit of different functions and to determine the statistical significance of the curves fitted to the experimental data. The least significant difference (LSD) test was used, at $p < 0.05$, to determine the significant differences between the values of each parameter studied in each pile during the composting process. All analyses were performed with the IBM SPSS 22 statistical program.

3. Results and Discussion

3.1. The Crop and Livestock Species Produced in the Parish of San Andrés and the Fates of the Waste Generated

The results obtained through the surveys show that the predominant crops in the parish of San Andrés were potato and broad bean, with 20.6% and 19.1% of the total crops produced, respectively. Maize and peas were also important crops, each representing 11.1% of the total crops produced, followed by carrot, barley, and sweet corn, each with 7.9% of the total percentage of cultivated products. Products such as alfalfa, onion, cilantro, and ulluco, among others, were also grown, each with less than 5% of the total crops produced. The crops with the highest waste generation were maize, sweet corn, broad bean, pea, potato, and ulluco, whereas carrot and barley produced a small amount of waste, since only the leaves and fine stems are discarded. Other crops, such as alfalfa, coriander, and onion generated practically no waste. Regarding the fates of the crop residues, 66.7% of the producers used them as feed for cattle and minor livestock species and 22.2% placed them on the ground to be crushed and incorporated into the soil for subsequent crops, without prior stabilization. The application of these fresh materials to the soil could cause different adverse effects, such as an increase in the mineralization rate of the soil endogenous organic C through increased microbial activity, the production of anaerobic conditions due to the consumption of oxygen in the mineralization of unstabilized OM and the modification of soil pH [22]. In addition, allelochemicals present in the crop residues, such as polyphenolic compounds, could inhibit the germination and seedling development of the following crop [23]. In addition, another fate of the plant residues was their burning (11.1%), which contributes to the release of greenhouse gases and aerosols into the atmosphere [24,25], the loss of nutrients during rainfall through runoff and decreased carbon storage in the soil [26].

The surveys of the livestock sector indicate that cattle for milk and meat production represented 48% of the livestock numbers in this area, while pig and sheep farming contributed 26% and 22% of the total livestock reared, respectively, horses represented only 2% of the livestock and the remaining 2% corresponded to other, minor species. Of the farmers surveyed, 75% considered manure as waste, 75% of this waste being returned to the farmland after drying, while the remainder stayed directly where it had been excreted by the cattle. These events generate important environmental impacts, such as greenhouse gas emissions [7] and contamination of water sources and soils due to excess nutrients, pathogens, and the xenobiotics given to animals [8,9]. This shows the urgent need to propose environmentally friendly treatments for agro-livestock residues, such as composting, that promote the sustainability of the agricultural sector of this area, thereby solving existing environmental problems and increasing the profitability of agricultural activities.

3.2. Composition of the Agro-Livestock Wastes

The physicochemical, chemical, and biological characteristics of the crop residues and manures are shown in Table 2. The average pH values of the crop residues ranged between

5.50 and 6.76, whereas the manures had slightly higher average values, from 6.89 to 7.86. Vegetable residues contain a large amount of organic acids, with different physiological roles within plants, which causes their low pH values [27]. However, manure has a high content of nitrogen in organic forms, whose mineralization produces ammoniacal nitrogen in the form of ammonium (NH_4^+) and ammonia (NH_3) [12], the latter contributing to an increase in its pH. In the case of the crop residues, the most acidic were pea, broad bean, and carrot (CR-3, CR-5, and CR-7), whereas among the livestock wastes, horse manure (M-5) showed the highest pH value, followed by pig and sheep manures (M-4 and M-3). The pH will not be a limiting factor for the composting of these agro-livestock wastes, since during this process the microbial activity is adequate in the pH range of 5.5–9.0 [28].

The average salt content, measured as EC, was significantly higher in CR-4 and CR-6 than in the other crop residues analyzed (EC = 6.21 and 6.98 dS/m for CR-4 and CR-6, respectively) (Table 2). In the case of the livestock wastes, M-5 was the most saline (EC = 5.55 dS/m). These high concentrations of mineral salts may limit the agricultural use of composts made from these residues, because during composting the salt concentration increases due to the mineralization of OM and the concentration effect caused by the loss of mass [28]. Therefore, the more saline wastes should be co-composted with less saline wastes so that the final compost has an EC value within the interval set by the US Composting Council [29] for different agricultural uses of compost (EC = 2.5–6.0 dS/m).

The soluble anions contributed to the salt content of the agro-livestock residues analyzed. The average contents of these ions, their ranges and their CV values are shown in Table 3. In the crop residues, the ranges of the average concentrations of Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-} were 18–75 g/kg, 1.7–4.9 g/kg, 1–36 g/kg, and 1.1–6.8 g/kg, respectively. The residues with the highest average content of Cl^- were those from the crops of maize, sweet corn, broad been, and potato (CR-1, CR-2, CR-5, and CR-6), the residues of barley and carrot (CR-4 and CR-7) had the highest average contents of NO_3^-, the maize residues (CR-1) showed the highest average SO_4^{2-} content, and the highest average PO_4^{3-} contents were found in the sweet corn, broad been, and carrot crop residues (CR-2, CR-5, and CR-7). For the livestock wastes, the average values of the soluble anions were in the ranges 15–28 g/kg, 2.5–3.4 g/kg, 1–13 g/kg, and 6.4–20.2 g/kg for Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}, respectively. The average Cl^- and PO_4^{3-} contents were highest for M-5, the average NO_3^- concentration was highest for M-3 and M-1, and the average SO_4^{2-} content was highest for M-2. Most of the crop residues showed higher average contents of soluble anions than the manures studied, except in the case of PO_4^{3-}, whose concentration was generally higher in the manures. This could be associated with the use of phosphates as animal feed supplements [30]. A great dispersion was found in the data of the soluble anions for some types of waste, with CV values greater than 100%, due to the wide variation in the soluble anion contents, from below the detection limit to very high values.

Table 2. Physicochemical, chemical, and biological parameters of the agro-livestock wastes (on a dry weight basis).

Residue	pH			EC			OM (%)			Corg (%)			Corg/Nt			Polyphenols (g/kg)			GI (%)		
	Mean	**Range**	**CV**	**Mean**	**Range**	**CV**	**Mean**	**Range**	**CV**	**Mean**	**Range**	**CV**	**Mean**	**Range**	**CV**	**Mean**	**Range**	**CV**	**Mean**	**Range**	**CV**
Crop Residue																					
CR-1	6.76 e	6.03–7.40	9	2.01 a	1.06–3.03	43	79.3 b	58.7–91.6	16	30.2 bc	16.0–42.9	42	42.8 b	3.0–130.8	135	8.8 a	2.8–12.1	52	26.2 a	0.1–78.4	172
CR-2	6.46 de	6.09–6.82	5	2.35 a	1.15–3.45	45	85.3 b	82.5–86.7	2	40.7 cd	37.1–44.6	8	18.2 ab	15.0–20.3	14	19.6 cd	16.3–22.7	17	0.1 a	0–0.1	141
CR-3	5.50 ab	5.07–5.88	4	2.91 a	2.78–3.05	3	89.9 b	87.1–92.5	2	41.8 d	32.5–45.7	12	7.0 a	5.3–10.5	27	23.6 d	20.7–25.2	9	0.0 a	0–0	-
CR-4	6.30 cde	5.97–6.58	3	6.21 c	2.15–8.19	43	86.5 b	85.1–87.4	1	44.4 d	43.1–46.3	2	6.4 a	4.8–9.7	32	19.1 cd	17.3–21.3	9	0.0 a	0–0	-
CR-5	5.86 ab	5.47–6.18	3	3.66 ab	1.2–4.94	34	86.7 b	79.5–90.4	4	37.8 cd	29.3–44.5	13	7.3 a	4.5–13.2	39	15.5 bc	9.8–18.4	20	0.5 a	0–1.5	144
CR-6	6.08 bcd	5.5–6.62	7	6.98 c	2.2–10.72	49	63.6 a	46.3–81.5	22	24.1 ab	10.4–41.8	54	32.1 ab	8.1–95.6	106	10.2 ab	7.6–11.6	19	1.3 a	0–3.1	125
CR-7	5.68 ab	4.99–6.40	9	3.03 a	1.34–7.93	73	66.0 a	55.4–80.6	15	20.2 a	15.3–27.0	15	7.4 a	2.8–32.7	139	16.0 bc	7.0–24.5	35	0.1 a	0–0.4	185
F-ANOVA	11.31 ***			6.67 ***			11.57 ***			15.99 ***			3.18 **			11.70 ***			1.23 ^{NS}		
Manure																					
M-1	7.09 ab	6.61–7.50	4	1.18 a	0.52–2.17	35	70.4 c	67.5–73.2	4	33.1 a	31.2–35.7	6	11.6 a	11.3–12.1	2	4.5 b	3.9–5.1	13	20.6 a	16.7–24.4	26
M-2	6.89 a	6.68–7.15	2	2.45 ab	1.07–3.96	57	68.9 c	59.4–79.8	8	29.7 a	0–42.9	32	9.8 a	4.5–15.7	34	2.9 a	1.3–4.5	30	28.1 a	11.9–40.5	35
M-3	7.28 bc	7.13–7.44	2	3.43 b	1.05–5.75	69	55.3 b	53.5–57.5	3	27.2 a	20.5–35.8	28	10.3 a	6.3–16.6	45	6.6 c	5.5–7.9	17	0.4 a	0.1–0.7	95
M-4	7.46 c	7.37–7.55	1	1.36 a	0.91–1.95	28	46.9 a	44.1–49.1	4	23.3 a	21.3–25.8	8	9.7 a	8.4–10.5	8	4.6 b	4.1–5.0	8	69.2 b	38.3–100	63
M-5	7.86 d	7.63–7.96	2	5.55 c	4.85–6.39	13	65.8 c	64.4–67.5	2	31.7 a	29.1–33.8	5	18.5 b	16.9–20.1	8	4.2 b	3.9–4.6	7	13.8 a	12.7–14.9	11
F-ANOVA	22.68 ***			21.02 ***			26.45 ***			1.36 ^{NS}			9.81 ***			19.10 ***			6.31 **		

EC: electrical conductivity; OM: organic matter; Corg: total organic C; Nt: total N; GI: germination index; CV: coefficient of variation. ** and ***: significant at $p < 0.01$ and 0.001, respectively. ^{NS}: not significant. Considering the crop residues and manures separately, mean values in columns followed by the same letter do not differ significantly ($p < 0.05$) (Tukey's b test). For other abbreviations see Table 1.

Table 3. Soluble anion contents (on a dry weight basis) of the agro-livestock wastes.

Residue	Cl^- (g/kg)			NO_3^- (g/kg)			SO_4^{2-} (g/kg)			PO_4^{3-} (g/kg)		
	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV
Crop Residue												
CR-1	51 bc	40–62	17	1.7 a	1.2–2.6	36	36 c	32–42	10	4.1 ab	2.4–7.2	58
CR-2	75 c	54–96	27	2.8 ab	1.4–4.2	54	14 b	<1–32	119	6.8 b	<0.1–9.2	67
CR-3	19 a	<3–28	51	3.8 ab	3.2–4.6	13	3 ab	<1–6	113	3.0 ab	2.6–3.6	13
CR-4	23 ab	20–25	9	4.5 b	4.0–5.2	11	8 ab	<1–12	78	1.1 a	0.2–1.8	65
CR-5	48 bc	<3–71	43	3.3 ab	<0.1–7.4	71	1 a	<1–2	110	5.6 b	2.4–9.0	43
CR-6	49 bc	<3–65	51	2.9 ab	2.0–3.6	23	14 b	<1–32	103	2.2 ab	1.6–3.0	25
CR-7	18 a	<3–40	108	4.9 b	3.0–6.8	25	16 b	<1–24	40	5.9 b	<0.1–12.2	70
F-ANOVA	8.68 ***			4.35 ***			12.19 ***			3.79 ***		
Manure												
M-1	17 a	14–20	14	2.5 a	2.4–2.6	5	13 b	<1–20	68	6.4 a	<0.1–11.0	75
M-2	15 a	<3–20	26	2.8 ab	2.2–3.6	15	12 b	<1–20	59	8.1 a	<0.1–15.2	39
M-3	17 a	17–17	-	3.4 b	3.2–3.6	5	2 a	<1–4	115	7.6 a	6.6–9.0	14
M-4	17 a	14–20	14	2.9 ab	2.6–3.2	9	1 a	<1–2	115	10.2 a	8.6–11.4	12
M-5	28 b	25–31	8	2.5 a	2.2–2.8	10	5 ab	2–8	69	20.2 b	17.8–22.8	12
F-ANOVA	13.96 ***			4.48 **			4.74 **			14.82 ***		

** and ***: significant at $p < 0.01$ and 0.001, respectively. Considering the crop residues and manures separately, mean values in columns followed by the same letter do not differ significantly ($p < 0.05$) (Tukey's b test). For abbreviations see Tables 1 and 2.

The materials CR-1, CR-2, CR-3, CR-4, and CR-5 and M-1, M-2, and M-5 showed the highest average OM contents within the crop residues and manures, respectively. These are above the range of values preferred by the US Composting Council [29] for various agricultural applications of composts (OM = 50–60%) (Table 2). This fact is important for the potential production of compost with an adequate OM content, since the concentration of OM is reduced during the composting process due to its degradation. The average content of Corg ranged between 20.2 and 44.4% in the crop residues, and from 23.3 to 33.1% for the livestock wastes, with no significant differences among the different types of manure analyzed. The CV of the Corg/Nt ratio values was greater in the crop residues than in the manures. For an active composting process, the waste ratios are adjusted to achieve a Corg/Nt ratio of 25–35. Lower initial Corg/Nt ratios lead to the loss of N by volatilization as NH_3 and through N_2O and N_2 emissions, with the consequent environmental impact and loss of nutrients. Meanwhile, higher initial Corg/Nt ratios delay the composting process due to the deficiency of N for the development of microorganisms [18]. Thus, for the adequate composting of the agro-livestock residues studied, co-composting mixtures combining wastes with high and low Corg/Nt ratios will have to be elaborated.

The crop residues had the highest concentrations of soluble polyphenols, with a wide range of average values (8.8–23.6 g/kg), whereas among the livestock residues the range was 2.9–6.6 g/kg (Table 2). The crop residues of sweet corn, pea, and barley (CR-2, CR-3, and CR-4) and the sheep manure (M-3) showed the highest concentrations of soluble polyphenols among the crop residues and manures, respectively. These compounds are phytotoxic and can inhibit germination and seedling development [23]. During composting, soluble polyphenols are degraded, especially in the thermophilic stage [31]. Therefore, the composting of these residues will be necessary for their detoxification before their agricultural use. The phytotoxicity of the residues was studied by determining the GI. The results show that all the residues analyzed, except M-4, had average values of this parameter below the minimum value established by Zucconi et al. [32] to indicate the absence of phytotoxicity (GI > 50%). The crop residues showed extremely low average GI values (0.0–26.2%), while the average GI value ranged from 0.4 to 28.1% for the livestock wastes M-1, M-2, M-3, and M-5. This could be explained by the high contents of salt and soluble polyphenols of these residues, as was observed also by Gavilanes-Terán et al. [10] in a study of different agro-industrial wastes of vegetable and animal origin. The wide range of GI values for the crop residues is also noteworthy, with CV values greater than 100%, possibly due to the wide variation in the values of this parameter, from 0% to GI measurable values.

The total nitrogen (Nt) content in the residues was also analyzed (Table 4), the range of average values being 1.09–7.51% and 1.74–3.38% for the crop residues and manures, respectively. The pea, barley, and broad bean residues (CR-3, CR-4, and CR-5) had the highest average Nt concentrations, while no significant differences were found among the values of the livestock residues. All the residues had average Nt contents higher than the minimum value established by the US Composting Council [29] for different agricultural uses of compost (Nt $\geq$ 1%). This fact is important for the potential production of compost with a high N fertilizing capacity from these residues, since during the composting process the concentration of this nutrient rises due to the mass loss of the composting mixture, provided the losses of this element due to volatilization, emission, and leaching have been controlled [18].

The average concentration of K in the crop residues was in the range of 8–23 g/kg, the highest values being found for CR-4, CR-6, and CR-7 (Table 4). The livestock residues had average K concentrations between 6 and 35 g/kg, the average value being higher in horse manure (M-5) than in the other manures studied. The average concentrations of micronutrients generally decreased in the following order: Fe > Mn > Zn > Cu, in both the crop residues and manures. In most cases, the average micronutrient contents were higher in the livestock residues than in the crop residues, probably due to the addition of nutritional supplements to the animal feed [33]. In general, among the crop residues studied, the potato residues (CR-6) showed the highest concentrations of micronutrients, reflecting the fact that this tubercle is considered one of the important vegetable sources of micronutrients in the human diet [34]. However, in the case of the manures, the cow and pig manures (M-1, M-2, and M-4) generally presented the highest average micronutrient contents. The significant contents of K and micronutrients will favor the agricultural use of the compost made from the agro-livestock residues studied.

The contents of heavy metals (average, range, and CV) are shown in Table 5. In general, the livestock residues had average Ni contents higher than those of the crop residues, M-3 having the highest average content of this heavy metal among the livestock residues studied. In all the residues, the contents of Cr and Cd were the lowest of the heavy metals determined, only traces or very low concentrations being detected. The average content of Pb was higher in the crop residues (5.2–36.4 mg/kg) than in the manures (<0.1–21.1 mg/kg). The maize residues (CR-1) and cow manure (M-1) had the highest concentrations of Pb among the crop and livestock residues studied, respectively. However, the concentrations of all the heavy metals were well below the limits established by the US Composting Council [29] for exceptional quality composts. This will contribute to the safe agricultural use of the composts derived from the agro-livestock residues studied, although the content of heavy metals increases during the composting process due to the loss of mass of the composting mixture [18]. A wide range of heavy metals contents was found for some types of waste, with values below and above the limit of detection, leading to CV values greater than 100%.

Table 4. Macro and micronutrient contents (on a dry weight basis) of the agro-livestock wastes.

Residue	Nt (%)			K (g/kg)			Fe (mg/kg)			Cu (mg/kg)			Mn (mg/kg)			Zn (mg/kg)		
	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV
Crop Residue																		
CR-1	2.99 ab	0.31–5.46	78	8 a	6–11	26	2829 ab	650–6190	85	12 ab	6–16	33	63 ab	21–93	51	42 ab	33–50	13
CR-2	2.32 a	1.94–2.96	19	8 a	5–11	29	705 a	648–778	8	11 ab	10–13	15	26 a	22–28	12	47 abc	36–59	22
CR-3	6.44 cd	3.09–8.21	30	8 a	6–10	18	857 a	671–1045	16	6 a	3–10	42	32 a	27–36	10	48 abc	44–54	8
CR-4	7.51 d	4.65–9.22	25	23 c	23–27	5	803 a	643–906	12	9 ab	8–9	6	26 a	24–28	7	35 a	31–40	10
CR-5	5.63 cd	3.05–7.15	23	17 b	13–25	20	1603 a	1089–2616	34	13 b	11–15	13	104 c	30–201	59	54 bc	36–82	25
CR-6	1.09 a	0.44–1.66	38	22 c	19–27	13	4652 b	1529–7219	53	22 c	11–33	44	130 c	122–141	5	74 d	58–85	14
CR-7	5.07 bc	0.70–6.87	39	21 bc	8–30	39	3037 ab	1276–8253	85	14 b	12–17	15	79 abc	44–129	42	59 c	48–76	17
F-ANOVA	13.19 ***			18.62 ***			4.51 **			9.27 ***			8.63 ***			11.06 ***		
Manure																		
M-1	3.38 a	2.05–7.29	51	7 a	2–13	44	2041 a	1092–2531	21	33 b	27–45	15	322 d	77–524	39	144 b	100–224	22
M-2	2.85 a	2.66–3.17	7	8 a	7–10	18	2106 a	2040–2243	5	35 b	31–38	8	252 c	208–287	17	131 ab	125–137	4
M-3	2.80 a	2.16–3.37	18	22 b	17–24	17	2553 a	2113–2714	12	22 a	20–24	7	154 ab	152–158	2	93 a	88–95	4
M-4	2.40 a	2.25–2.60	6	6 a	5–6	6	6612 b	6060–7008	6	28 ab	25–30	8	147 ab	139–150	4	116 ab	106–123	7
M-5	1.74 a	1.60–1.87	6	35 c	34–36	2	2027 a	1906–2145	5	22 a	21–22	2	127 a	124–131	3	102 a	97–107	4
F-ANOVA	1.86 NS			114.54 ***			130.42 ***			13.17 ***			6.28 ***			5.59 **		

** and ***: significant at $p < 0.01$ and 0.001, respectively. NS: not significant. Considering the crop residues and manures separately, mean values in columns followed by the same letter do not differ significantly ($p < 0.05$) (Tukey's b test). For abbreviations see Tables 1 and 2.

Table 5. Heavy metal contents (on a dry weight basis) of the agro-livestock wastes.

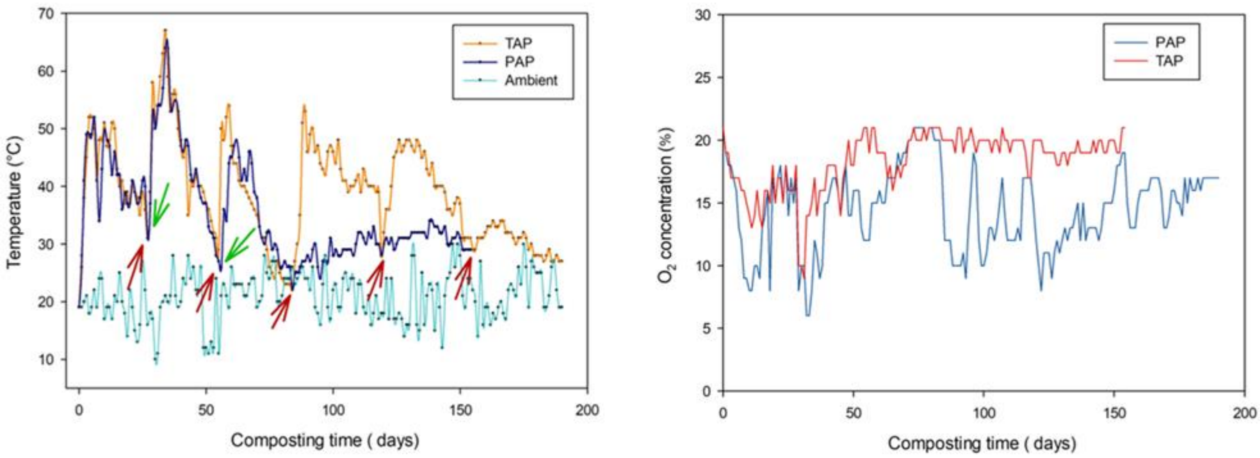
Residue	Ni (mg/kg)			Cr (mg/kg)			Cd (mg/kg)			Pb (mg/kg)		
	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV
Crop Residue												
CR-1	2.9 ab	1.0–6. 7	93	<0.1 a	<0.1–0.2	167	<0.1 a	<0.1	-	36.4 c	30.8–39.7	9
CR-2	<0.1 a	<0.1	-	<0.1 a	<0.1	-	<0.1 a	<0.1	-	32.6 bc	26.8–40.5	21
CR-3	0.7 a	<0.1–1.5	83	1.60 a	<0.1–5	155	0.5 b	0.4–0.6	22	11.0 ab	9.4–12.7	12
CR-4	1.8 a	<0.1–5.0	120	<0.1 a	<0.1	-	0.4 b	<0.1–0.7	90	15.8 ab	12.0–19.1	20
CR-5	2.4 a	<0.1–4.7	88	<0.1 a	<0.1	-	<0.1 a	<0.1	-	17.3 ab	<0.1–47.0	24
CR-6	3.8 ab	<0.1–6.2	78	<0.1 a	<0.1	-	<0.1 a	<0.1	-	25.4 abc	<0.1–42.0	79
CR-7	7.6 b	<0.1–14.5	70	3.49 a	<0.1–9.98	115	<0.1 a	<0.1	-	5.2 a	<0.1–14.7	130
F-ANOVA	4.99 ***			3.70 NS			9.95 ***			5.18 ***		
Manure												
M-1	2.9 a	<0.1–6.6	85	<0.1 a	<0.1	-	<0.1 a	<0.1	-	21.1 b	7.19–40.6	48
M-2	4.9 a	<0.1–10.0	113	<0.1 a	<0.1	-	<0.1 a	<0.1	-	14.7 ab	13–16.6	10
M-3	11.0 c	7.6–14.8	35	<0.1 a	<0.1	116	<0.1 a	<0.1	-	12.8 ab	6.4–20.1	54
M-4	10.2 bc	8.8–11.8	13	0.14 a	0.13–0.17	12	<0.1 a	<0.1	-	0.5 a	<0.1–1.1	116
M-5	5.6 ab	4.5–6.3	14	<0.1 a	<0.1	-	<0.1 a	<0.1	-	<0.1 a	<0.1	-
F-ANOVA	9.99 ***			6.87 NS			4.51 NS			9.15 ***		

***: significant at $p < 0.001$. NS: not significant. Considering the crop residues and manures separately, mean values in columns followed by the same letter do not differ significantly ($p < 0.05$) (Tukey's b test). For abbreviations see Tables 1 and 2.

3.3. Development of the Composting Process

In both piles, a rapid increase in temperature was observed during the first days of the composting process, reaching temperatures above 40 °C, and the thermophilic stage was maintained for approximately 27 days until the first turning (Figure 2a). Gavilanes-Terán et al. [6] and Afonso et al. [35] also observed a rapid increase in temperature at the beginning of the composting process, for mixtures of vegetable waste and manure. The turnings improved the oxygenation and homogenization of the mixture and therefore, after their completion, there was an increase in temperature. The TA pile showed higher temperatures than the PA pile. Other authors have also recorded higher temperatures during the composting process using the turning pile system compared to passive aeration system [19,36]. Additionally, the TA pile had a longer thermophilic stage than the PA pile. This fact could be due to the higher amount of O_2 supplied with the prolonged turnings during the process in the TA pile, as can be seen in Figure 2b. In the TA pile, the O_2 percentage remained within the range for optimal process development (15–20% [18]) throughout the entire process, except in the first 40 days, when the highest temperatures were reached, showing greater microbial activity and, therefore, a higher oxygen consumption corresponding to the initial stages of composting [18]. Neither of the two piles met the requirements established by EPA [37] for the sanitation of composted materials through the system of piles with aeration by turning (temperatures $\geq$ 55 °C for at least 15 consecutive days).

The microbial activity developed during the composting process produced a reduction in the content of OM, from 82.1 and 80.9% to 40.3 and 46.8% in piles TA and PA, respectively (Table 6). The OM losses were fitted to a first-order kinetic equation, as indicated in sub-Section 2.4 Analytical and Statistical Methods, obtaining the following values of the statistical parameters: A = 114.6%, k = 0.0095 days^{-1}, adjusted R^2 = 0.9890 for the TA pile; and A = 89.2%, k = 0.0113 days^{-1}, adjusted R^2 = 0.9595 for the PA pile. In the two piles, the variation explained by the model was greater than 95%, indicating that the proposed model was adequate. The A values obtained were above the ranges (76.6–86.8%) found by different authors for the composting of vegetable waste with manure [6,38]. However, the k values of the piles were below the ranges (0.0128–0.0554 days^{-1}) observed by the aforementioned authors. The A value and OM degradation rate (A $\times$ k) (data not shown, but calculable from the data provided) were higher in the TA pile than in the PA pile, indicating that the higher amount of oxygen provided by the turning aeration system (Figure 2b) favored the degradation of the OM. Pampuro et al. [36] also observed higher OM degradation during the co-composting of pig slurry solid fraction using the turning pile system, in comparison with the passive aeration system.



(**a**) (**b**)

Figure 2. (**a**) Temperature evolution during the composting process. TAP: turning aeration pile; PAP: passive aeration pile. The red arrows indicate the days on which the turnings were carried out in the TAP and the green arrows the days on which the turnings were carried out in the PAP. (**b**) O_2 concentration evolution during the composting process.

Table 6. Evolution of the main parameters during the composting process.

Composting Time	pH	EC (dS/m)	OM (%)	Nt (g/kg)	Corg/Nt	Polyphenols (g/kg)	GI (%)
			Turning Aeration Pile				
Beginning	7.67	3.49	82.1	15.2	27.5	1.98	16.0
Mature	8.94	3.08	40.3	17.8	10.4	0.50	94.4
LSD	0.34	0.30	1.4	0.5	2.7	0.25	3.3
			Passive Aeration Pile				
Beginning	7.97	3.85	80.9	14.7	27.8	1.62	16.3
Mature	8.77	2.17	46.8	17.4	9.2	0.76	91.7
LSD	0.20	0.43	1.3	0.4	8.7	0.10	4.3

LSD: Least Significant Difference. For other abbreviations see Table 2.

The degradation of organic nitrogen and acid-type compounds caused an increase in the pH values in both piles, with the final values of this parameter being above the range established by the US Composting Council [29] for the use of compost in agriculture (pH = 6.0–7.5) (Table 6). On the other hand, it is noteworthy that the mixture of residues was adequate, since the initial values of the EC were low (3.49 and 3.85 dS/m for piles TA and PA, respectively), so that the final salt contents of the composts were within the interval set by the US Composting Council [29] for different agricultural uses of compost (EC = 2.5–6.0 dS/m). The salt content decreased during composting, possibly due to the leaching of salts caused by the addition of water, since the leachate was not collected and reincorporated into the piles.

The Nt content, in both piles, increased throughout the process due to a concentration effect produced by the loss of mass of the composting mixture [18] (Table 6). In addition, the initial values of the Corg/Nt ratio of the mixtures of crop residues with cow manure and sawdust were within the range considered optimal to minimize both emissions of nitrogenous gases and any delay of the composting process (C/N ratio = 25–35) [18]. During the composting process, a reduction in the Corg/Nt ratio was observed in both piles, as a result of the loss of Corg and the relative rise in the Nt concentration, and the final values of this ratio were < 20, indicative of a good degree of maturity of the compost [39].

The content of soluble polyphenols was lower in the mature compost than at the beginning of the process, for both mixtures, thus achieving a detoxification of the initial materials. This detoxification of the initial materials was also verified with the increase of the GI throughout the composting process, reaching final values of this parameter above the limit established to indicate the absence of phytotoxicity in a mature compost (GI > 50% [32]) (Table 6). Therefore, the phytotoxicity observed in the agro-livestock residues studied (Table 2) may be reduced by their co-composting to obtain compost with a safe agricultural use.

Agronomic characteristics of the composts obtained are shown in Table 7. The percentages of OM and the phosphorus contents in both final composts were below the interval recommended by the American standards for different agricultural applications of compost [29]. However, OM contents of the composts obtained were within the range of values (OM = 24.1–57.5%) reported in previous experiments using vegetable wastes and manure [6,38], whereas P contents were below the ranges (P = 4.82–10.34 g/kg) found in the above-mentioned experiments. The contents of Nt were higher than those set for compost by US guidelines [29], indicating the outstanding nitrogenous fertilizer capacity of both composts obtained. The K content was slightly higher in the TA compost, whereas the contents of most of the micronutrients and heavy metals were higher in the PA compost. In both mature composts, the heavy metal contents were well below the limits established by the US Composting Council [29] for safe agricultural use of compost.

Table 7. Agronomic characteristics of the composts obtained.

	Turning Aeration Compost	**Passive Aeration Compost**	**US Composting Council Guidelines [28]**
OM (%)	40.3	46.8	50–60
Nt (g/kg)	17.8	17.4	>10
P (g/kg)	3.95	3.25	>10
K (g/kg)	12.3	9.5	-
Fe (mg/kg)	3547	5987	-
Cu (mg/kg)	39	35	1500
Mn (mg/kg)	124	148	-
Zn (mg/kg)	57	58	2800
Ni (mg/kg)	4.41	6.22	420
Cr (mg/kg)	39	65	-
Cd (mg/kg)	0.03	0.03	39
Pb (mg/kg)	0.85	1.33	300
As (mg/kg)	0.75	0.86	41
Se (mg/kg)	0.69	0.69	100
Hg (mg/kg)	0.11	0.11	17

For abbreviations see Table 1.

4. Conclusions

From the results obtained, it can be concluded that the agro-livestock residues analyzed in the rural agricultural area selected (the parish of San Andrés), possessed positive characteristics for their composting, such as adequate pH values for microbial activity during the process, significant contents of OM and macro and micronutrients, and very low contents of heavy metals. However, these residues showed Corg/Nt ratio values unsuitable for the initiation of the composting process and some had high salinity and an elevated presence of soluble anions. For this reason, the composting strategy designed for these residues must consider the co-composting of several residues in the appropriate proportions and avoid the unitary composting of only one of the residues studied. The waste mixture proposed for composting (51% vegetable residues + 35% cow manure + 14% sawdust) had an initial salinity and balance of nutrients that were optimal, and yielded composts with characteristics suitable for their agricultural use. The aeration system (turnings or passive aeration) did not produce relevant differences in the quality of the compost obtained. Therefore, the passive aeration system can be recommended for the composting of the studied wastes, because it permits a shorter composting time and the work associated with the process is reduced. However, further studies with this composting system and other agro-livestock wastes are required to contribute to the knowledge necessary for the promotion of on-farm composting among the associations of farmers, agricultural technicians, and local politicians, to improve the management of agro-livestock wastes in developing countries.

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