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Original Research

Use of the Organic Fraction of Urban Solid Waste to Recover Degraded Areas in Chilca, Peru

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Abstract

The treatment of municipal solid waste (MSW) in Peru and some parts of the world is still incipient, mainly due to the lack of technologies implemented to recover this waste; another important cause in Peru is the lack of studies for the treatment of the organic fraction of municipal solid waste (OFMSW). The objectives of this work were: (i) to determine the generation of OFMSW, (ii) to produce quality compost and (iii) to estimate the application rate for the recovery of degraded surfaces. Tools and instruments acquired from the Institute of Sanitary Engineering of FIUBA and the Ministry of the Environment were used to measure physicochemical parameters and environmental estimates. The results showed a per capita MSW generation of 0.472 kg/inhab/day, of which 42.87% was composed of OFMSW or organic fraction of MSW; a feasible availability of organic matter for composting of 6783.79 t/year was determined. The composting experiment was carried out with waste segregated at the MSW treatment plant, installing composting piles with-structurants (WE) consisting of shavings, sawdust and garden waste, and no-structurants (NS). Despite the unfavorable climatic conditions of the region, the maturity and physicochemical properties of the compost were similar to MSW composts recorded elsewhere, with few differences between NS and WE. The main limitation of compost quality was the concentration of heavy metals Cd, Pb and Zn, which were close to or above the limits established in several regulations, which can be significantly reduced by segregating the OFMSW at source. Annual limits and cumulative load limits were used for 10-year applications, the calculated precautionary doses were 25 t/ha/year and 85 t/ha for 10 years in dry weight; correcting for moisture content, the precautionary dose was 40 t/ha/year in wet weight. Depending on the organic fraction of MSW available, compost production and the precautionary dose, 60 to 80 ha/year of degraded agricultural areas and forest plantation nurseries could be recovered with compost; using lower doses it

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is possible to cover a larger area. From the results, the work provides valuable information to elaborate an integrated MSW management plan, closing the cycle of production, treatment and beneficial use.

Keywords: municipal solid waste, organic fraction, compost quality, composting, heavy metals

Introduction

The treatment of municipal solid waste is of great importance. Globally, the aim is to reduce the amount of waste that ends up in landfills and minimize the environmental impact by using different methods and separation techniques [1]. The most common practices for managing household waste include incineration, landfilling and composting. However, in most developed cities, a combined approach is implemented in the collection, transportation, and treatment of household waste [2]. This leads to a decrease in the separation rate due to the sticking of different components, as well as the mixing of food waste, which reduces the calorific value and increases the moisture content of household waste [3].

There are various techniques for the treatment of municipal solid waste, including waste recovery and recycling, composting, and anaerobic digestion. European regulations stipulate that 55% of municipal waste should be recycled by 2025, increasing this figure to 65% by 2035 [4]. In addition, a limit is set for waste ending up in landfills, which may not exceed 10% of the total.

In recent decades, the accelerated growth of urban areas has produced a significant increase in waste generation, evidencing a worrisome disparity between the pace of urbanization and Peru's waste management capacity. This phenomenon is reflected in the proliferation of improvised landfills, poor treatment infrastructure, and the lack of sustainable practices in the final disposal of waste at the level of all the country's departments [5]. Inefficient management of municipal solid waste not only affects environmental quality but also has a direct impact on the health of the population and the preservation of local ecosystems. The lack of adequate separation at the source, as well as the limited implementation of recycling programs, contribute to the problem, exacerbating soil, water, and air contamination [6]. To address this situation, it is crucial to promote comprehensive policies that encourage waste reduction, reuse, and recycling while promoting environmental awareness in society.

There have been several studies on the generation of resources from OFMSW, considering different technologies used in practice to recover OFMSW, such as anaerobic digestion, composting, hydrothermal carbonization, pyrolysis and landfilling [7]. However, these technologies must meet regulatory requirements and receive support and commitment from national and local governments for successful implementation in local contexts. The analysis of 452 scientific articles published between 1980 and 2019 [8] shows that the relevance of composting technologies has increased, especially since 2014, when policies to reduce atmospheric emissions were intensified, with a focus on using the organic fraction of waste for biogas production. In literature reviews [9], it has been demonstrated that solid-state anaerobic digestion is more suitable for organic waste of municipal origin due to its high solids concentration (>15%) and more effective process performance; likewise, continuous digestion at thermophilic temperatures provides the optimal conditions for anaerobic digestion processes with high solids content. Proper selection of parameters throughout the process is critical to ensure the feasibility and economic sustainability of MSW anaerobic digestion [10]. While OFMSW anaerobic digestion could play a significant role in reducing waste and associated problems.

The implementation of innovative technologies, the active participation of the community, and collaboration between the public and private sectors are key elements to reverse the current trend and move towards a more sustainable urban solid waste management model in Peru. Within this framework, the Environmental Evaluation and Oversight Agency (OEFA) identifies two main causes of this situation [11]. First, it points out the existence of deficient or ineffective legislation on MSW treatment, which implies that the existing regulations are not strict or clear enough to guarantee adequate waste management; second, it highlights the lack of competent professionals in the field of waste management, which hinders the implementation of good practices and the adoption of appropriate technologies. In response to this problem, the OEFA proposes the implementation of differentiated solid waste disposal for optimal use. This implies the creation of specific deposits for different types of waste.

The Ministry of Environment and the Ministry of Economy and Finance of Peru (MEF) [12], 2019 established various regulations published and enacted, to promote the management of urban solid waste; with this objective, economic incentives were created for municipalities through the Incentives Plan for the Improvement of Municipal Management and Modernization, to facilitate compliance with goals 37 and 44 aimed at "Implementing the safe final disposal of solid waste collected by the municipal public cleaning service". In the following years, guidelines were developed to achieve these goals [13], such as goals 02 and 06 aimed at implementing a "Program for segregation at the source and selective collection of household solid waste in urban dwellings in the district" depending on the size of the municipalities, and goals 10 and 17 for the "Implementation of an Integrated Urban Solid Waste Management System" in the main cities categorized by size [14]. These goals have served to initiate an essential change in the treatment of MSW, since with these guidelines Peru's commitments to the effects of climate change have been valued and the State continues to offer incentives to municipalities for the implementation of MSW treatment and valorization, including composting.

It is necessary to implement the treatment of the organic fraction, and there are few studies on MSW characterization by the different municipalities in Peru. In general, there is a lack of data on the weight and volume of MSW, as well as on source segregation plans for its collection and differentiated transport, which is a problem for good management of solid waste generation. In this context, the work proposed to establish the basis for an integral study from the generation to the transformation of the OFMSW into compost and the calculation of areas to recover using the obtained compost, for this the objective of the state is the public and private investment in the conservation and sustainable use of fragile ecosystems since there are 1309 916.26 ha of degraded areas in Peru according to SERNANP-2022 [15].

The research developed in the city of Chilca (province of Huancayo, department of Junín) was carried out in three stages: a descriptive stage that includes the characterization of MSW from the district of Chilca and the determination of the amount of MSW generated that could be transformed into compost; a second experimental stage to determine the quality of the compost and a final stage to estimate the application rate and possible areas to be recovered in the department of Junín - Peru.

Composting was adopted as the best technological option, from the economic point of view, to treat large volumes of OFMSW without generating too many technological requirements [16]. In the development of this work, the feasibility of the process and the quality of the final product were evaluated under the climatic conditions prevailing in the region and the characteristics of the waste used as raw material, with or without the addition of structuring agents.

Materials and Methods

Generation of the Organic Fraction of Municipal Solid Waste

MSW generation is ever-increasing in urban areas and requires efficient management to minimize environmental impacts and maximize the sustainable use of resources. The quantity and composition of MSW varies according to demographics, consumption patterns, infrastructure, and local culture. In Peru, the population of the department of Lima produces the highest amount of MSW per capita, reaching 0.652 kg/inhab/day in 2022 (see Table 1), as it is a densely populated city. In the Pasco department, per capita MSW generation was only 0.404 kg/inhab/day that year. In the district of Chilca, per capita MSW production was 0.455 kg/inhab/day. These data were obtained from the National Environmental Information System (SINIA) [17]. These data give general information on MSW production per capita in the 24 departments of Peru, plus the constitutional province of Callao.

On the other hand, OFMSW is an important component of integrated waste management. It is mainly composed of biodegradable materials, such as food scraps, yard waste, and other organic wastes [18]. Its proper management is essential to reduce the amount of waste that ends up in landfills, minimize environmental pollution, and take advantage of the potential benefits of these materials. From the waste composition data presented in Fig. 1; at the level of Peru the highest amount of inorganic solid waste was generated in 2018 reaching 57.5%; during the years 2019-2021 it was in increased reaching 56.9%; while in 2022 about 55.5% of inorganic solid waste was generated. These data are the result of the statistical analysis of SINIA [19].

In the district of Huancayo in the department of Junín, which is close to the district of Chilca, the generation of organic solid waste is increasing: from 54.63% in 2019, it reached 68.20% in 2021, and in 2022 it reached 69.40%; these data are presented in Fig. 2, which were obtained from the statistical analysis of SINIA [19].

Similarly, in the district of Chilca, in the department of Junín, where the study was conducted, the generation of solid organic waste had a slight increase from 2019 (41.15%) to 2022 (42.87%), with small fluctuations in this period, as shown in Fig. 3, with slight variations in the rest of the solid waste components. These were obtained from the statistical analysis of SINIA [19].

The study was carried out in the province of Huancayo, district of Chilca, in the Villa Hermosa, property of the district municipality of Chilca, in the department of Junín - Peru, according to geographical coordinates the place is located at 12° 08' 46" South latitude and 75° 22' 18" West longitude. One of the climatic characteristics of the study area is that it has a higher rainfall during January and February (see Fig. 4); it can reach up to 190 mm accumulated monthly for January; being these months when it is necessary to have a roof or shed to cover the compost pile and avoid climatic interferences in the process.

In terms of temperature, due to the varied climate of the Peruvian highlands, the months with low temperatures are May, June, and July (see Fig. 5), which are not favorable for composting, as temperatures are close to or below 11°C.

Experimental Procedures for Producing and Determining Compost Quality

The research was divided into three stages. The first stage: the characterization of the OFMSW, the second stage: conducting a composting pilot test (experimental design and analysis of the maturity and quality of the compost), and the third stage is: the estimation

Table 1. Per capita generation of municipal solid waste (kg/inhab/day) by the department of Peru and the district of Chilca during the years 2019-2022.

Department	2019	2020	2021	2022	Average
Amazonas	0.470	0.520	0.460	0.530	0.495
Ancash	0.559	0.562	0.556	0.570	0.562
Apurimac	0.479	0.469	0.494	0.500	0.486
Arequipa	0.459	0.457	0.472	0.483	0.468
Ayacucho	0.529	0.530	0.532	0.519	0.528
Cajamarca	0.488	0.485	0.532	0.528	0.508
Callao	0.550	0.550	0.610	0.650	0.590
Cusco	0.503	0.506	0.506	0.501	0.504
Huancavelica	0.420	0.420	0.500	0.500	0.460
Huánuco	0.490	0.490	0.470	0.560	0.503
Ica	0.526	0.517	0.516	0.559	0.530
Junín	0.514	0.509	0.527	0.536	0.522
Junín-Huancayo-Huancayo	0.490	0.509	0.510	0.510	0.506
Junín-Huancayo-Chilca	0.425	0.450	0.460	0.470	0.455
La Libertad	0.526	0.526	0.532	0.539	0.531
Lambayeque	0.601	0.600	0.582	0.562	0.586
Lima	0.631	0.632	0.644	0.659	0.642
Loreto	0.637	0.636	0.624	0.635	0.633
Madre de Dios	0.530	0.510	0.550	0.610	0.550
Moquegua	0.460	0.460	0.530	0.540	0.498
Pasco	0.391	0.396	0.386	0.404	0.394
Piura	0.515	0.521	0.525	0.557	0.530
Puno	0.520	0.522	0.596	0.592	0.558
San Martin	0.593	0.596	0.612	0.616	0.604
Tacna	0.427	0.426	0.441	0.440	0.434
Tumbes	0.517	0.519	0.551	0.517	0.526
Ucayali	0.601	0.602	0.613	0.614	0.608

of the area to be remediated. To calculate the amount of compost produced, the following were taken into account: annual OFMSW production, a 50% reduction of the volume produced during the composting process, and a final average compost density of 0.5 t/m^3. OFMSW was calculated in mass, while density was determined using two possible OFMSW densities (0.6 and 0.8 t/m^3), which were taken from the literature to calculate the production volume [20].

Estimation of Compost Application Rates for Surface Reclamation

Based on the measured moisture content of the compost and the allowed annual dose of 25 t/ha in dry weight, the annual dose in wet weight and the feasible area to recover with this compost were determined.

Results and Discussion

For the Generation of the Organic Fraction of Municipal Solid Waste

When performing the characterization of MSW and its average per capita production (PCP) by socioeconomic level in the district of Chilca (see Table 2); it was found that the average PCP for all socioeconomic strata the PCP was 0.472 kg/inhab/day; the sampling was performed for 7 days using population

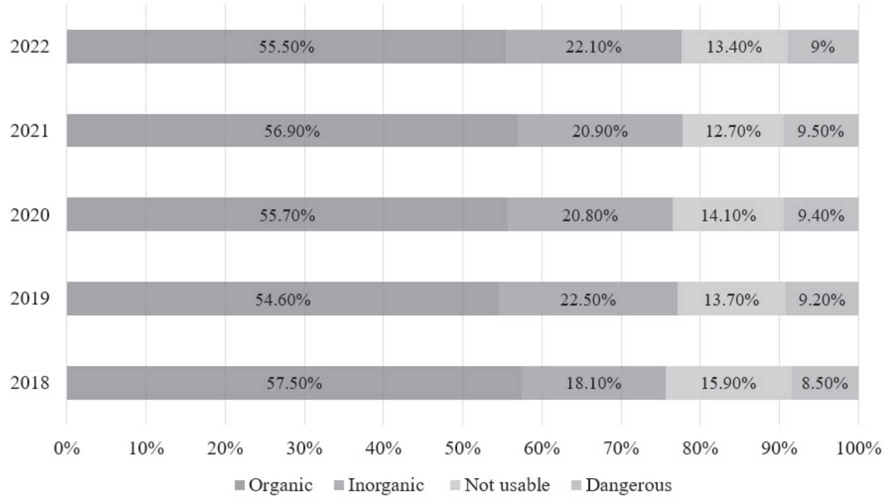

Fig. 1. Composition of solid waste generated in Peru in the years 2018-2022.

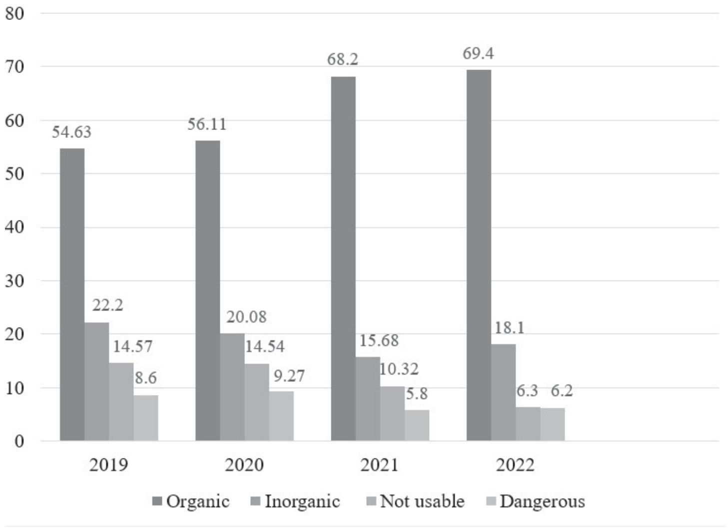

Fig. 2. Composition of solid waste (%) generated in the district of Huancayo in the years 2019-2022.

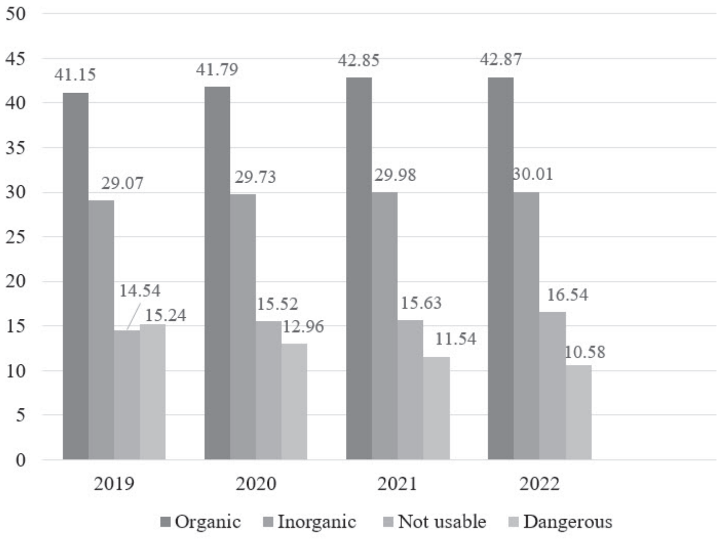

Fig. 3. Composition of solid waste (%) generated in the district of Chilca in the years 2019-2022.

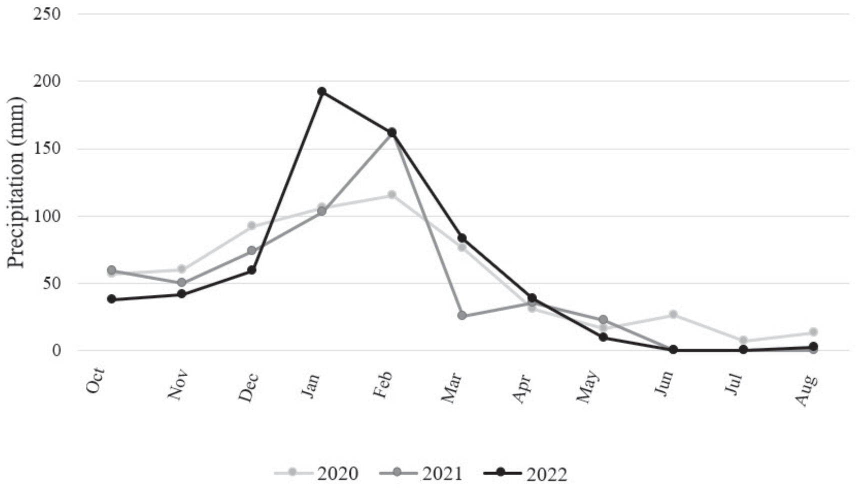

Fig. 4. Monthly accumulated rainfall behavior for the years 2020-2022.

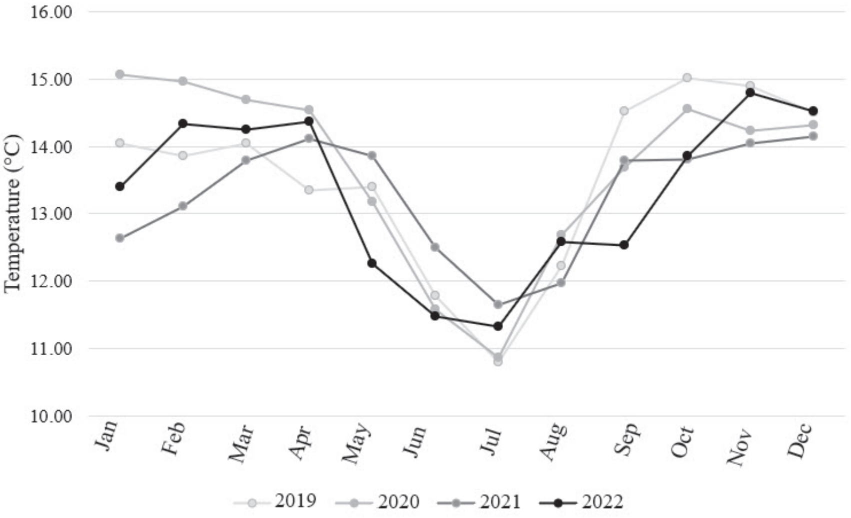

Fig. 5. Temperature behavior over the years 2019-2022.

data from the census conducted in 2017 by INEI (National Institute of Statistics and Informatics) [21]. In the socioeconomic stratum “Low C” the highest amount of MSW was produced with a PCP of 0.481 kg/inhab/day, in the strata “Medium B”, “Low E”, and “Low D” the average PCP are similar.

When comparing the result of the average PCP of the district of Chilca (0.472 kg/inhab/day) with the district of Huancayo (0.51 kg/inhab/day), according to SINIA data presented in Table 1, little difference was found, because these populations have similar consumption habits; as in the cities of the surrounding departments located in the central mountains of Peru; such as Huancavelica (0.460 kg/inhab/day), Pasco (0.394 kg/inhab/day), Cusco (0.504 kg/inhab/day) and Ayacucho (0.528 kg/inhab/day).

The daily and annual per capita MSW production (see Table 3) was calculated for a total population of 91851 inhabitants of the district of Chilca, with a daily MSW production of 43.354 t/day and annual production of 15824.09 t/year.

With the results presented in Table 4, we determined: the production, composition, density, and volume of MSW in the district of Chilca based on the average of the 7-day sampling and using population data from the census conducted in 2017 by INEI. The average MSW density (309.29 kg/m^3) is similar to that found in other developing countries 311.70 kg/m^3 in Oman [22] and in China 325 kg/m^3 which is the average of 31 provinces [23]. However, the daily MSW generation in these countries tends to be higher: 0.70 and 0.73 kg/inhab/day, respectively. When comparing MSW generation with other departments in Peru, it is observed that there are no significant differences, except for the departments of Ucayali and Lima which are above 0.60 kg/inhab/day [19].

Of the MSW components, organic matter (OM) was the most present, reaching 42.87% of the organic

Table 2. Characterization of MSW and average PCP according to socioeconomic level in the district of Chilca.

Socioeconomic strata	Zone	N° of dwellings	Population	Weekly production (kg)	Average PCP (kg/inhab/day)
Medium B	III	16	75	246.75	0.470
Low E	II	26	107	350.03	0.467
Low D	I	24	120	395.8	0.471
Low C	IV	5	27	90.83	0.481
Average			329	1083.41	0.472

Table 3. Daily and annual per capita MSW production as a function of the current population.

District	Total population	PCP (kg/inhab/day)	Production (kg/day)	Production (t/day)	Production (t/year)
Chilca	91851	0.472	43353.672	43.354	15824.090

Table 4. MSW density in the Chilca district for 7 days.

Evaluation days	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Residual weight (kg)	71.20	68.12	71.92	66.91	66.80	74.20	73.50
Residual density (kg/m^3)	317.04	298.07	312.88	292.77	292.29	328.47	323.48
Average density	309.29 kg/m^3						

Table 5. Daily and annual availability of OM in the district of Chilca.

Annual production MSW (t/year)	OFMSW (%)	Daily availability of OM (t/d)	The annual availability of OM (t/year)
15824.09	42.87	18.59	6783.79

fraction (see Table 5). Considering a utilization efficiency of approximately 80%, the availability of compostable organic matter was determined at 18.59 t/d and 6783.79 t/year.

For Compost Production and Quality

The production and quality of compost is dependent on several factors; apart from aeration, where the compost is regularly turned to provide oxygen and accelerate decomposition. Temperature affects quality; proper composting generally generates heat, so an ideal temperature for microbial activity must be maintained (between 45-55ºC). Adequate humidity facilitates microbial activity. Also, composting time is necessary to establish as the process can take several weeks to several months, depending on environmental conditions.

During the composting process, the temperature varies (see Fig. 6). The evolution of temperature in the NS and WS treatments for n = 3 (shavings, sawdust, and garden waste) showed differences. The ambient temperature at 7:00 h was close to 10ºC, and at 13:00 h it was close to 18ºC, showing small variations throughout the 183 days of the process. The WS treatment from day 40 to 85 presents high-temperature peaks reaching 45-49ºC; while the NS treatment from day 40 to 85 presents high-temperature peaks reaching up to 63ºC.

The evolution of the thermophilic composting temperatures of the NS and WS treatments for n = 3 are shown in Fig. 7. In the NS treatment, high temperatures were maintained longer than in the WS treatment, which was necessary for pathogen reduction. The temperature in WS varied with the 3 types of structurants used, and the best performance in terms of thermophilic temperatures above 45 ºC and the temperature required by the EPA standard [24], for pathogen reduction (>55ºC) was obtained with garden waste (grass + pruning), which provided more easily attackable energy sources than woody materials rich in recalcitrant carbon (C) (shavings and sawdust).

The temperature in the thermophilic state with n = 3 is shown in Fig. 8. The highest temperatures are observed during the thermophilic phase between 40 and 100 days as an average of 3 NS piles and in piles with shavings, sawdust or garden waste concerning thermophilic composting temperatures (>45ºC) and temperatures necessary for pathogen reduction (>55ºC).

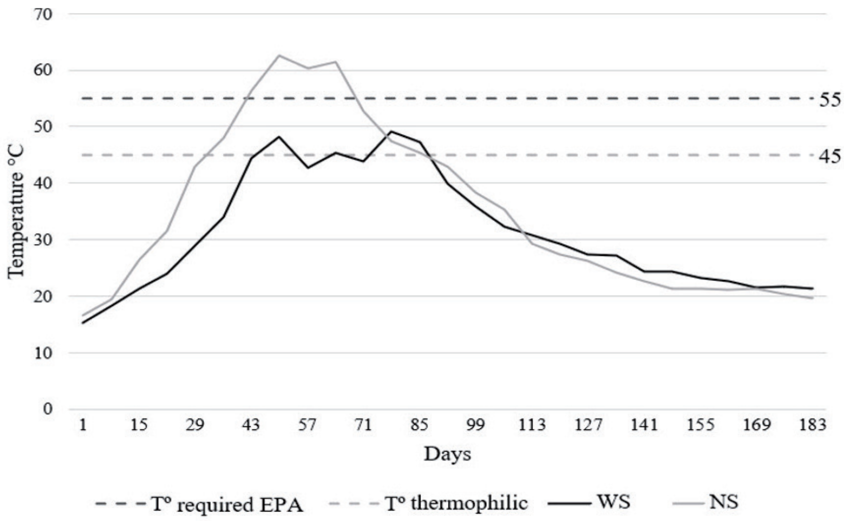

Fig. 6. Temperature evolution during the composting process.

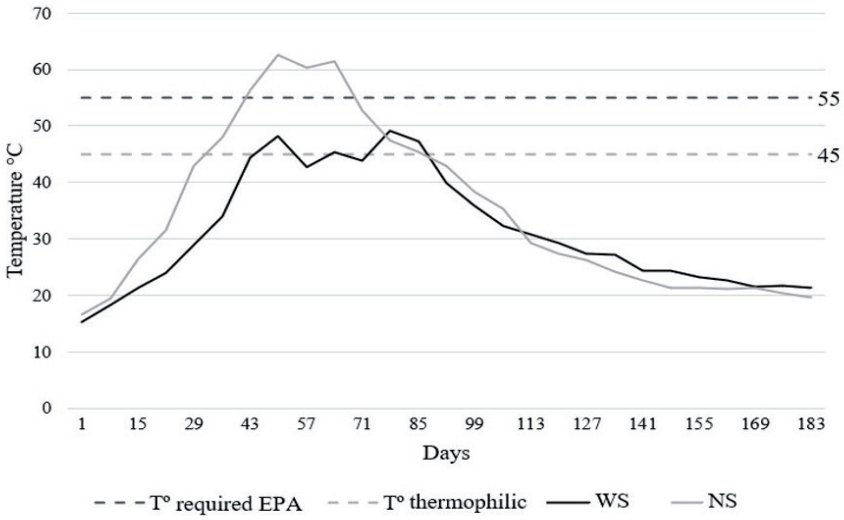

Fig. 7. Temperature evolution of WS and NS treatments.

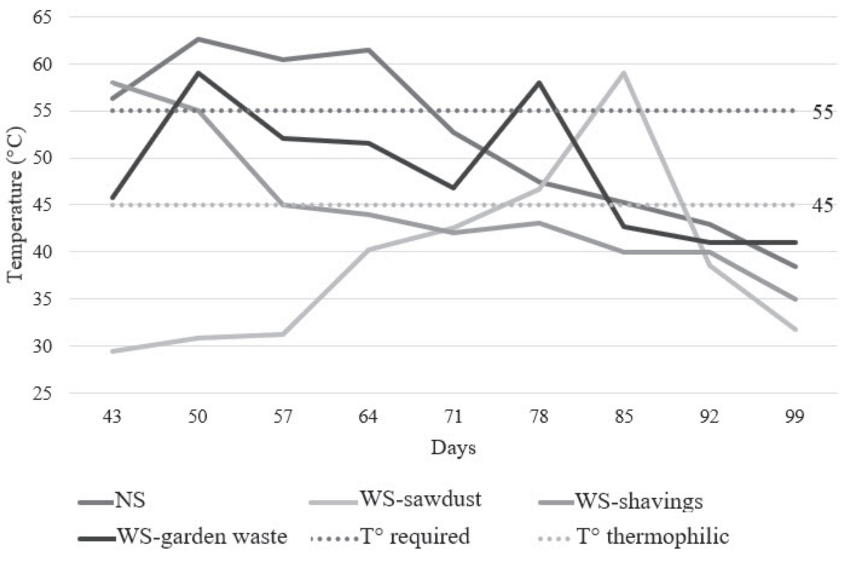

Fig. 8. Temperatures in the thermophilic phase with n = 3.

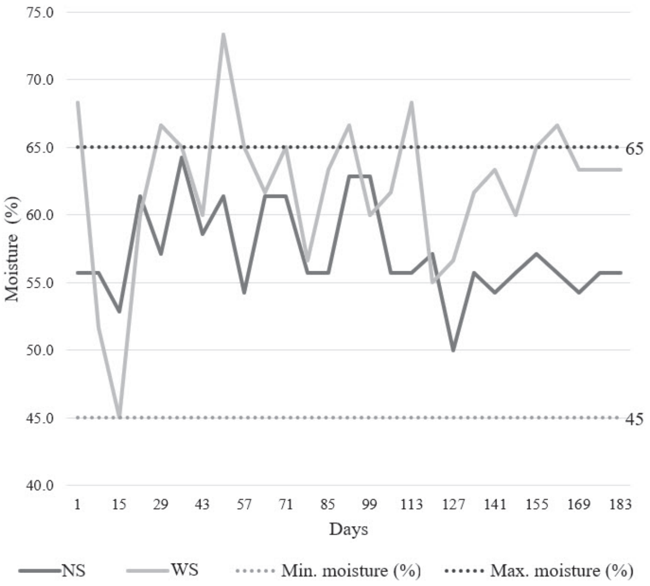

Fig. 9. Evolution of moisture in the compost in the NS and WS treatments with n = 3.

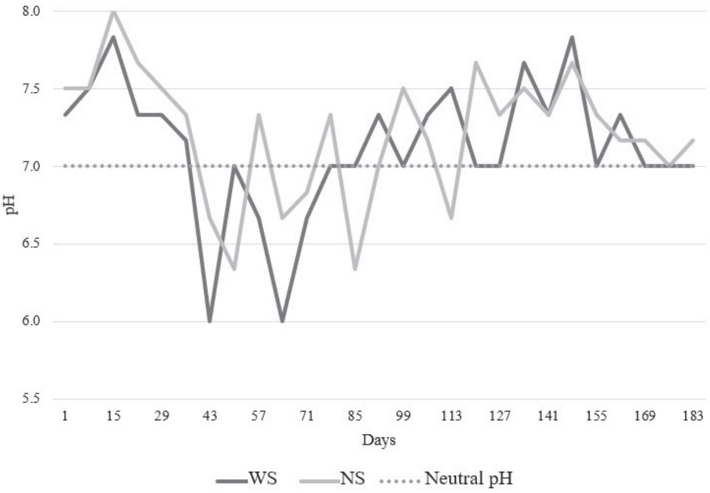

Fig. 10. Evolution of pH during composting in the treatments with WS and NS with n = 3 about neutral pH.

The NS treatment lasted longer than WS, providing the necessary temperatures for pathogen reduction. On some dates, WS maintained moisture above recommended values (>65%), which would have limited aeration for microbial activity. The pH showed a pattern characteristic of OFMSW composting. Composting involves several phases of the intensity of microbial activity, which are reflected in changes in temperature, the composition of microorganisms, and degradation and stabilization of organic matter among others [25].

The evolution of moisture in composting in the NS and WS treatments with n=3 is presented in Fig. 9. The moisture in the NS treatment in most cases was lower than in the WS treatment, remaining in the range of 55-77% moisture. As an optimum moisture range during composting, moisture values of 45–65% are recommended, which is obtained in this work; while other authors recommend 40–65% [26], considering that at lower values, the moisture is insufficient for the microorganisms and at higher values the oxygen concentration is insufficient [27]. Lower oxygen availability directly affects composting efficiency, which depends on the activity of aerobic microorganisms and increases fermentative processes and unpleasant odors.

During the composting process, the pH, regardless of the structuring agent, decreases at the beginning of the process and then increases again. This pattern is characteristic of OFMSW composting and has been explained by the production of organic acids by the intense microbial activity that decreases the pH at the beginning of the process (see Fig. 10), passing to a stage of production and accumulation of bicarbonate and calcium carbonate that increase the pH and maintain it at around 8.3-8.5 at the end of the process [28].

Table 6. Physicochemical characteristics of the three piles by treatment.

	NS			WS		
	1	2	3	Shavings	Sawdust	Garden waste
pH	8.4	8.4	8.4	8.5	8.5	8.3
EC (dS/m)	2.45	2.33	2.27	1.79	1.60	2.09
H (%)	34.8	35.6	32.1	43.9	45.0	32.4
OM(%)	28.6	27.9	26.0	34.8	30.8	30.0
C (%)	15.9	15.5	14.5	19.3	17.1	16.6
N (%)	0.98	1.12	1.08	1.34	1.25	1.36
C/N	16.2	13.8	13.4	14.4	13.7	12.2
P (%)	0.59	0.60	0.59	0.60	0.60	0.57
Ca (%)	4.4	4.9	4.7	5.6	5.4	4.5
Mg (%)	0.81	0.73	0.80	0.66	0.68	0.72
K (%)	1.7	1.9	1.8	1.9	1.9	2.0
Na (%)	0.28	0.34	0.31	0.41	0.34	0.29

Table 7. Concentration of heavy metals in the three piles per treatment.

Heavy metal mg/kg	NS			WS		
	1	2	3	Shavings	Sawdust	Garden waste
Cu	157	160	148	163	154	161
Zn	1078	1139	1156	1240	1189	1099
Pb	289	319	305	298	303	294
Cd	2	5	4	4	3	5
Cr	57	64	57	59	63	55

The physicochemical parameters of the three piles analyzed by treatment are presented in Table 6; where the data vary because the OM and nutrients are lost during the placement; most of the data of the physicochemical characteristics found are within these values, being better in content of OM [28, 29]. The average concentrations of organic matter and nutrients were: 16.50% organic C (equivalent to 30% organic matter), 1.20% total N, with a C/N ratio of 14%, 0.6% total P and 1.9% total K. These values are within those reported in the literature. These values are within those reported for OFMSW composts in the literature and place them within the high-quality composts according to the requirements of the standards for physicochemical characteristics, excluding heavy metals [28].

The analysis of five of the heavy metals (Cu, Zn, Pb, Cd, and Cr) shows the concentrations of these elements (see Table 7) in 3 NS piles and 3 WS piles (separated by type of structuring agent). All heavy metal concentrations are expressed as dry matter. The concentration of heavy metals in OFMSW composts is important for defining quality criteria to increase waste recycling through agricultural applications, and to avoid soil contamination and loss of quality [30].

MSW may contain chemical contaminants derived from plastics, metals, pigments, solvents, paper, wood preservatives, glass, petroleum products, and others. Not all trace elements that may be toxic to humans, animals, and plants meet this requirement [31]. The most controlled elements of concern are arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn). Some countries also include molybdenum (Mo) and selenium (Se) [32].

Several trace elements (Cu, Zn, Se, Mo, Ni) are essential for plants, animals or humans. The toxicity of a given element often varies according to the animal or plant species concerned, thus affecting both plants and animals. To protect soil quality and food safety, many standards take into account the tolerance of the most sensitive plants and animals to each element and, as a precautionary principle, analyze the total concentration of the element and not only the bioavailable forms, as well as the suitability of biowaste

Table 8. Comparison of agricultural value properties and heavy metals with other similar research.

Properties	Research results		Results of other research [34-36]
	NS	WS	NS
Properties of agricultural value			
pH	8.39a	8.45b	7.3±0.80
EC (dS/m)	2.35a	1.83a	2.60±0.49
H (%)	34.2a	40.4a	-
OM (%)	27.5a	31.8a	22.5±1.75
C (%)	15.3a	17.7a	15-17
N (%)	1.06a	1.32b	0.896±0.03
C/N	14.5a	13.5a	14.5±1.2
P (%)	0.59a	0.59a	0.6-0.9
Ca (%)	4.7a	5.2a	4.3 ±0.04
Mg (%)	0.78a	0.69b	0.76±0.02
K (%)	1.80a	1.93a	0.45±0.02
Na (%)	0.31a	0.35a	0.30±0.01
Heavy metals (mg/kg)			
Cu	155a	159a	39.68±2.52
Zn	1124a	1176a	141.64±3.58
Pb	304a	298a	48.88±2.67
Cd	3.7a	4.0a	0.39±0.025
Cr	59a	59a	47.15±1.38

and green waste for use in organic farming, as in Germany and other countries [33].

As for the results presented in Table 8, the only differences in the properties obtained with those of other researchers in treatments with and without structuring, correspond to pH and N, which were higher in WS, while the C/N ratio was practically the same. If we compare the data on the characteristics of the agricultural value with other authors who also worked in piles without structuring, it is observed that the values of pH, electrical conductivity, OM, N, and C/N are very similar. In the last column, the results of OFMSW compost from the same place are presented, in all cases of piles without structuring that were stationed between 1 and 5 years in the treatment plant [34, 35].

The main limitation of the compost obtained was the concentration of several heavy metals that are close to the maximum permissible limit of some standards that are different for each country. It should be noted that internationally it has been found that Pb and Zn are the elements found in the highest concentration in the OFMSW compost; this is what happened in this work, where the material to be composted was separated in the MSW treatment plant. The content of heavy metals can be significantly reduced by segregating the OFMSW at the source, thus avoiding the contact of OM with waste containing heavy metals [37].

For the Estimation of Compost Application Rates for Surface Reclamation

The annual and maximum compost dosage are calculated in Table 9 and according to the restrictions by annual limit value and maximum load of heavy metals admitted in the Argentine regulations for sewage sludge, the compost dosage was applied based on the annual load of heavy metals admitted, calculated based on the concentration in the compost and the annual limit value established for each of the elements analyzed, the element that establishes the most restrictive value was zinc, according to the European regulations, which also occurs for compost from other sources such as manure [38]. This type of compost obtained can also be applied

Table 9. Compost doses per annual limit value and maximum allowable load of heavy metals for NS and WS concentrations.

Heavy metal	Concentration (mg/kg)		Limit value (kg/ha/year)	Maximum load (kg/ha)	Annual doses (t/ha/year)	Maximum dose (t/ha)
Cd	NS	3.7	0.15	0.5	40.5	135
	WS	4.0			37.5	125
Cu	NS	155	12	40	77.0	258
	WS	159			75.5	251
Cr	NS	59	3	10	50.8	170
	WS	59			50.8	170
Zn	NS	1124	30	100	26.7	89
	WS	1176			25.5	85
Pb	NS	304	15	50	49.3	165
	WS	298			50.3	168

Table 10. FORSU density by type of source and process, for compost production.

Source OFMSW	Density OFMSW (t/m^3)
Manual separation at source	0.75
Mechanical separation	0.79-0.81
Dry sample (105 ºC)	0.66
Mechanically separated and chopped	0.33
Food scraps	0.51

at higher doses in degraded areas that are not intended for food production and grazing; e.g., sanitary landfill cover, landscape restoration in abandoned mining areas, road construction, oil spill remediation, and the like [39].

To calculate the annual compost production from the amount of OM (t/ha) available for composting, it was necessary to know the initial and final density of the material. In the present work, an initial OFMSW density of 0.6-0.8 t/m^3 was assumed; these densities are similar to the value of 0.75 t/m^3, presented in Table 10 adapted from a review based on the OFMSW source [40].

Based on the average moisture content of the compost and the allowed annual dose of 25 t/ha in dry weight, the annual dose in wet weight and the feasible surface area to be recovered with this compost was determined, which was 60-80 ha/year. It should be taken into account that the doses to be applied could be lower, which would allow covering a larger area. They could also be used as substrates in nurseries for forest and ornamental seedlings in a proportion between 30-50%.

Although composting is mostly beneficial, it must be done properly to avoid potential negative impacts such as odors, pest proliferation, or contamination of the compost with non-biodegradable materials. In addition, it is important to note that composting should be considered part of a broader waste management approach that includes source reduction and recycling of other materials.

Whether the effect of composting is good or bad depends on the = C/N ratio and its acceptable limits. The composting effect of the present investigation is good because it was determined with a temperature of 45 and 55ºC, which is the ideal Tº not to damage the beneficial microorganisms for the crops, and the C/N ratio was 13.5, which is within the permissible limits. On the other side, it is considered that MSW compost is more recommendable for areas degraded by mining activities and that it is not suitable for direct agricultural use because it does not comply with the adequate doses of NPK; therefore, it should be compensated with adequate amounts of N.

Conclusions

The average per capita MSW production was 0.472 kg/inhab/day. Using the average MSW density determined (309.3 kg/m^3), the total amount produced corresponded to an annual volume of 63.084 m^3. The organic matter achieved was 42.87% (organic fraction of MSW or OFMSW), considering that the efficiency of utilization of the material is approximately 80%, the availability of organic matter feasible to be composted was 18.59 t/d and 6783.79 t/year. The feasibility of the composting process with both types of open-air treatments was demonstrated from the experimentation with 3 m^3 piles of OFMSW without the addition of structuring agent (NS) and with the addition of shavings, sawdust, and garden pruning remains (WS). At the end of composting, a reduction of approximately 50% of the initial volume was observed, with a compost density between 0.48-0.51 t/m^3.

Both treatments showed very similar values in their physicochemical characteristics at the end of the process. The only significant differences were (a) a higher N concentration in the WS treatment due to a greater contribution and/or conservation of this nutrient (greater microbial immobilization) with the structurants, and (b) a higher Mg concentration in the NS treatment due to a possible dilution in the WS treatment. The pH of both composts was alkaline with a mean of 8.4, which was related to the high Ca concentrations (5% on average) and moisture was 37% on average. Electrical conductivity averaged 2.1 dS/m, indicating an abundance of soluble salts. The mean organic matter and nutrient concentrations were: 16.5% organic C (equivalent to 30% organic matter), 1.2% total N, C/N ratio of 14%, 0.6% total P, and 1.9% total K. Pb and Zn are elements found in higher concentrations in OFMSW compost; the concentrations of Cd, Pb and Zn are within the limits established by Chilean standards, considering the recommendations of Argentine standards for compost and sewage sludge. Annual compost production was 4761-6348 m^3 equivalent to 2381-3174 tons (in wet weight). The annual dose in wet weight and the feasible surface to recover with these composts was 60-80 ha/year.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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