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Municipal Solid Waste Management in a Decentralized Composting Scenario: Assessment of the Process Reproducibility and Quality of the Obtained Composts

Cristina Álvarez-Alonso [1], María Dolores Pérez-Murcia [1], Silvia Sánchez-Méndez [1], Encarnación Martínez-Sabater [1], Ignacio Irigoyen [2], Marga López [3], Isabel Nogués [4], Concepción Paredes [1], Luciano Orden [1,5], Ana García-Rández [1] and María Ángeles Bustamante [1,*]

[1] Centro de Investigación e Innovación Agroalimentaria y Agroambiental (CIAGRO-UMH), Universidad Miguel Hernández, EPS-Orihuela, Ctra. Beniel Km 3.2, 03312 Orihuela, Spain
[2] Department of Agricultural Production, Public University of Navarre (UPNA-NUP), 31006 Pamplona, Spain
[3] Department d'Enginyeria Agroalimentària i Biotecnologia, Universitat Politècnica de Catalunya (UPC), Campus del Baix Llobregat, Edifici D4, C. Esteve Terradas, 8, 08860 Castelldefels, Spain
[4] Research Institute of Terrestrial Ecosystems, National Research Council, Via Salaria km 29,300, 00015 Monterotondo, Italy
[5] Estación Experimental Agropecuaria INTA Ascasubi (EEA INTA Ascasubi), Ruta 3 Km 794, Hilario Ascasubi 8142, Argentina
* Correspondence: marian.bustamante@umh.es

Abstract: Over the last several years, the models for organic waste management have changed to implement circular economy in the productive cycle. In this context, new scenarios have emerged, where the management of different organic waste streams by composting is conducted with decentralized models that manage organic wastes in a more local way. However, in these new models, the standardization of the process control and of the end-product characteristics is necessary to guarantee the quality and agronomic value of the compost obtained, avoiding potential risks for human health and the environment. Thus, the aim of this work was to study two different scenarios of community composting of the organic fraction of municipal solid waste separately collected in order to guarantee the effectiveness and reproducibility of the composting processes and the quality of the composts obtained. For this, the development of the process and the characteristics of the composts at agronomic, hygienic–sanitary and environmental levels were assessed in real conditions and during three cycles of the process. The results obtained show high similarity among the different composting cycles, indicating an important degree of reproducibility among the processes. In addition, the composts obtained showed a good sanitary quality, absence of phytotoxicity and low contents of potentially toxic elements, which guarantee their use in agriculture without posing any risk to human health and to the environment.

Keywords: community composting; biowaste; organic fertilizer; agronomic quality; heavy metals; pathogens

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1. Introduction

Global population growth, economic development and urbanization have led to an increase in resource consumption and, consequently, in waste production, the management of such waste being a universally important issue [1]. As an example, 2010 million tons of municipal solid waste were generated worldwide in 2016, and at least 33% was inadequately managed [2]. In 2050, waste generation is expected to increase to 3400 million tons if no change occurs [3]. Biowaste, which includes the separate collection of municipal solid waste and pruning waste, accounts for a large share of the total waste generation that implies an occupation of space in waste treatment facilities or landfills, where it contributes to the increase of greenhouse gas emissions [4]. In addition, it supposes a waste of resources that can also lead to risks to the environment and human health [5]; therefore, this inadequately managed or unmanaged waste from decades of global economic growth requires urgent action [3]. The progressive implementation of circular economy in the productive cycle is producing a conceptual change on the models for organic waste management, where waste is now beginning to be considered as a resource [6]. For this reason, recovery technologies are recommended instead of conventional technologies (landfill, incineration) because they make it possible to recover valuable components that can be reintroduced into the productive cycle through agriculture [5]. Composting is an organic waste management technique based on the oxidative degradation of organic matter in aerobic conditions; when properly implemented, the process allows for obtaining a final material called compost, which has a high degree of maturity, is stable and humified, has low pathogen content, and can be used in agriculture without any environmental risk associated [7,8]. In this context, the European Union, through Directive 2018/851, established the obligation to collect municipal solid waste separately through different separate collection systems by 31 December 2023 in order to promote recycling and the use of quality secondary raw materials and to achieve a high level of environmental protection [9]. In Spain, the normative 7/2022 transposes the previous Directive and establishes the obligation of new separate collections for biowaste, among others [10]. Therefore, biowaste in Spain must be separated and recycled by biological treatment (composting or anaerobic digestion) at the source. Furthermore, the Autonomous Community of Valencia, by means of Regional normative 5/2022, established specific management measures for biowaste, including its separation and recycling through biological treatment, including treatment at the source through community composting, to obtain quality organic amendments [11]. Thus, new paradigms have appeared, where the treatment of different organic waste fractions by composting, such as those from household waste streams, garden and park waste and remains from fresh product markets (biowaste), is carried out locally using decentralized models, such as community composting [12]. However, currently, there is a lack of standardization concerning the control of the process and of the final product in these new composting scenarios, which is essential to guarantee the agronomic value, degree of stability and maturity, product quality and especially the hygienic conditions of the compost obtained [13] for its use in agriculture. In addition, when the composting process is not properly managed or controlled, it can induce the proliferation and spread of potentially pathogenic microorganisms, such as *Salmonella* and/or *Listeria* [14,15], as well as hinder seed germination by impeding plant growth [16]. Thus, this work aimed to study and monitor two examples of community composting of the organic fraction selectively collected from municipal solid waste generated in two municipalities located in the Valencian community (Spain) in real conditions and throughout three composting cycles in order to guarantee the efficiency of the composting processes at the community scale to produce a sanitized, stable, humified compost with properties that demonstrate its quality and assure its safe use in agriculture.

2. Materials and Methods

2.1. Composting Procedure

Six composting piles were prepared using the organic fraction from the selective collection of municipal solid waste (OFSMW), which were mainly composed of household waste and came from the municipalities of Fontanars dels Alforins and Carrícola (Valencia, Spain), both with a population of approximately 100 and 1000 inhabitants, respectively. The OFSMW samples were obtained from the fifth container and door-to-door collection systems, from the populations of Fontanars and Carrícola, respectively. Urban pruning waste (UPW) was produced during the maintenance activities of the public green areas of each municipality. In particular, in the case of the composting piles from Carrícola, the urban pruning waste (UPW) also contained approximately 10% (volume:volume) of donkey manure. The main characteristics of these raw materials are summarized in Tables 1 and 2.

Table 1. Main characteristics of the organic wastes used in the three corresponding composting cycles (1, 2 and 3) developed in the municipality of Fontanars (dry weight basis).

	OFSMW1	OFSMW2	OFSMW3	UPW1	UPW2	UPW3
Dry weight (%)	31.8 ± 5.6	27.7 ± 0.6	40.9 ± 7.1	78.6 ± 2.0	68.2 ± 1.6	52.6 ± 1.8
pH	6.5 ± 0.1	6.0 ± 0.0	5.6 ± 0.0	9.0 ± 0.1	6.9 ± 0.1	8.4 ± 0.1
EC (dS/m)	5.5 ± 0.0	6.1 ± 0.1	6.1 ± 0.1	3.3 ± 0.0	1.8 ± 0.0	1.7 ± 0.0
OM (%)	69.1 ± 0.5	75.7 ± 0.6	71.7 ± 1.2	78.2 ± 0.6	63.7 ± 0.6	47.5 ± 0.5
TOC (%)	39.1 ± 0.3	45.8 ± 0.3	44.4 ± 0.3	41.3 ± 0.3	38.8 ± 0.3	31.1 ± 0.2
TN (%)	2.4 ± 0.0	2.9 ± 0.0	3.1 ± 0.0	1.0 ± 0.0	1.1 ± 0.0	1.6 ± 0.0
TOC/TN ratio	16.4 ± 0.1	15.8 ± 0.1	14.5 ± 0.1	41.2 ± 0.8	35.0 ± 0.3	19.8 ± 0.2
P (g/kg)	6.3 ± 0.2	4.4 ± 0.1	9.6 ± 0.1	1.6 ± 0.1	1.0 ± 0.0	6.6 ± 0.1
Fe (mg/kg)	359 ± 7	274 ± 11	1880 ± 16	1315 ± 30	1720 ± 21	1832 ± 41
Cu (mg/kg)	11.3 ± 0.2	9.8 ± 0.1	11.1 ± 0.1	7.6 ± 0.1	9.1 ± 0.1	15.3 ± 0.6
Mn (mg/kg)	32.8 ± 0.3	34.0 ± 0.5	67.1 ± 0.5	53.8 ± 1.4	81.4 ± 0.7	109.9 ± 1.9
Zn (mg/kg)	39.9 ± 0.7	29.1 ± 1.0	44.9 ± 0.6	25.0 ± 0.6	32.2 ± 0.3	45.8 ± 0.4
Cd (mg/kg)	0.64 ± 0.01	0.37 ± 0.01	0.14 ± 0.01	0.07 ± 0.01	0.13 ± 0.01	0.14 ± 0.01
Cr (mg/kg)	11.1 ± 1.0	9.8 ± 1.4	43.0 ± 1.2	24.2 ± 4.5	26.3 ± 3.7	32.5 ± 2.3

OFSMW: organic fraction of municipal solid waste; UPW: pruning waste; EC: electrical conductivity; OM: organic matter; TOC: total organic carbon; TN: total nitrogen. Data values reported as mean value ± standard deviation.

Table 2. Main characteristics of the organic wastes used in the three corresponding composting cycles (4, 5 and 6) developed in the municipality of Carrícola (dry weight basis).

	OFSMW4	OFSMW5	OFSMW6	UPW4	UPW5	UPW6
Dry weight (%)	28.1 ± 3.0	17.7 ± 0.2	42.9 ± 4.0	81.1 ± 0.6	57.8 ± 3.9	69.0 ± 1.0
pH	7.7 ± 0.1	5.3 ± 0.0	5.8 ± 0.0	6.4 ± 0.1	7.1 ± 0.1	6.6 ± 0.1
EC (dS/m)	3.4 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.6 ± 0.1	2.7 ± 0.0	1.3 ± 0.0
OM (%)	62.5 ± 0.4	83.7 ± 0.7	77.4 ± 0.6	74.3 ± 0.5	63.0 ± 0.5	76.8 ± 0.6
TOC (%)	35.2 ± 0.3	44.0 ± 0.4	44.8 ± 0.4	41.7 ± 0.4	37.6 ± 0.3	41.1 ± 0.3
TN (%)	1.4 ± 0.0	2.5 ± 0.0	2.6 ± 0.0	2.5 ± 0.0	1.2 ± 0.0	1.6 ± 0.0
TOC/TN ratio	26.0 ± 0.3	17.7 ± 0.1	17.3 ± 0.1	16.9 ± 0.1	32.5 ± 0.3	25.9 ± 0.2
P (g/kg)	6.3 ± 0.3	4.3 ± 0.2	4.8 ± 0.0	3.8 ± 0.1	1.5 ± 0.1	2.0 ± 0.1
Fe (mg/kg)	1838 ± 60	421 ± 3.0	693 ± 5.0	740 ± 16	1254 ± 38	2684 ± 19
Cu (mg/kg)	25.1 ± 0.5	16.2 ± 0.9	15.2 ± 0.1	14.2 ± 0.3	32.0 ± 1.3	14.1 ± 0.2
Mn (mg/kg)	127.8 ± 4.2	44.0 ± 1.2	57.4 ± 0.4	49.3 ± 1.1	101.6 ± 4.9	120.6 ± 1.2
Zn (mg/kg)	39.3 ± 1.7	28.5 ± 2.3	35.0 ± 0.3	35.7 ± 0.8	28.1 ± 1.4	46.8 ± 0.5
Cd (mg/kg)	0.11 ± 0.01	0.05 ± 0.01	0.16 ± 0.01	0.08 ± 0.01	0.11 ± 0.01	0.59 ± 0.34
Cr (mg/kg)	30.8 ± 1.5	17.3 ± 1.9	32.6 ± 0.5	36.6 ± 0.7	22.3 ± 0.8	38.8 ± 0.5

For the abbreviations, see Table 1. Data values reported as mean value ± standard deviation.

The composting heaps were prepared and developed in real conditions at the community composting islands of the Consorcio de Residuos COR-V5 of the municipalities of Fontanars (pile 1, pile 2 and pile 3) and Carrícola (pile 4, pile 5 and pile 6), respectively. These facilities constitute a concrete floor, a system for collecting and storing the leachate produced during the process and an irrigation system. For the preparation of the composting heaps, the corresponding weekly collected OFSMW and the pruning waste (PW) were mixed in a proportion of 1:1 (volume:volume) and deposited in compost bins to control the moisture conditions and minimize odours and lixiviates. After four months of collecting the material in compost bins to assure that the amount of waste was enough to develop the composting process, the bins were removed, the material was homogenized by mechanical turning and the composting heaps were formed. The proportions of the starting materials in the composting mixtures, the weight of each pile (in kg) and their dimensions (in meters in terms of length, width and height) are shown in Table 3.

Table 3. Percentages of starting materials, weight and dimensions of the composting piles (piles 1, 2 and 3 at the municipality of Fontanars; piles 4, 5 and 6, at the municipality of Carrícola).

	OFSMW (%)	UPW (%)	Weight (kg)	Length (m)	Width (m)	Height (m)
Pile 1	84.2	15.8	10,496	12	2.8	1.2
Pile 2	85.8	14.2	6456	13	2.8	1.3
Pile 3	70.0	30.0	11,021	9.6	2.6	1.2
Pile 4	82.7	17.3	2663	7.5	2.5	1.4
Pile 5	76.1	23.9	2277	7.0	2.5	1.4
Pile 6	86.6	13.4	3075	4.6	2.6	1.0

OFSMW: organic fraction of municipal solid waste; UPW: pruning waste.

The composting heaps were composted in trapezoidal piles by the turned windrow composting system, with mechanical turnings every month until the end of the bio-oxidative phase. In the case of the Fontanars piles, the processes were developed outdoors, while the Carrícola heaps were conducted in a facility with a roof that protected the piles from rainfall. The moisture in the piles was controlled and adjusted at levels not lower than 40% by irrigation coinciding with every turning. The temperature of the piles was monitored twice a week by direct measurement with a thermometer, in three points of the pile and at two depths. The bio-oxidative phase was considered finished when the temperature of the composting heaps decreased to ambient temperature and a difference between the pile temperature and the ambient temperature was $\leq$10 °C during at least 10 consecutive days after a whirl. The duration of the bio-oxidative phase was 126, 112 and 142 days for Fontanars piles 1, 2 and 3, respectively, and 128, 110 and 140 days for the Carrícola piles. Then, the composts were left to mature for approximately a month. The piles were sampled on four occasions: initial phase (S1), thermophilic phase (S2), end of the bio-oxidative stage (S3) and maturity phase of composting (S4). Samples were taken by mixing seven subsamples from seven locations in the piles, from the entire profile (top to bottom of the pile), according to the methodology described by Bustamante et al. [17]. Each sample was divided into three fractions: one fraction of fresh sample was used for microbiological determinations; another fraction was air-dried and ground to 0.5 mm for the physico-chemical and chemical characterization; and the third fraction was immediately frozen and preserved for further analyses.

2.2. Analytical Determinations

2.2.1. Physico-Chemical and Chemical Determinations

The electrical conductivity (EC) and pH of the raw materials and composting samples were determined in a 1:10 (w/v) aqueous extract using a conductivity/pH meter (Crison Instruments, S.A., Barcelona, Spain) according to the standard method DIN EN 12176 [18]. The dry matter was calculated by drying the samples for 12 h at 105 °C, and the total organic matter (OM) was determined by loss on ignition at 550 °C for 24 h, in accordance with the standard method CEN13039 [19]. The total organic carbon (TOC) and total nitrogen (TN) were determined by dry combustion at 950 °C using an elemental analyser (Truspec CN, Leco, St. Joseph, MO, USA). The fractions of 0.1 M NaOH-extractable organic carbon (Cex), water-soluble carbon (Cw) and fulvic acid-like carbon (Cfa), the latter being obtained after precipitating the humic acid-like carbon (Cha) of the NaOH extract at pH 2.0 [17], were determined using an automatic carbon analyser (TOCVCSN, Shimadzu Corporation, Kyoto, Japan). The Cha was calculated by subtracting the Cfa from the Cex. In the final composts, the cation exchange capacity (CEC) was determined using the $BaCl_2$-triethanolamine procedure, according to the method described by Lax et al. [20]. In addition, in these samples, after $HNO_3/HClO_4$ digestion, the microelements, P and potentially toxic elements were measured by ICP-OES (ICAP 6500 DUO, Agilent Technologies, Inc., Santa Clara, CA, USA). The germination index (GI) was calculated combining measurements of seeds of *Lepidium sativum* L. and root elongation [21]. The evaluation of compost self-heating was conducted in the final composting samples using the Dewar test described by

Brinton et al. [22]. All the analytical determinations were carried out in triplicate. The MO losses were determined using the ash concentrations at the beginning (X_1) and at the end (X_2) of the process, following the equation used by Bustamante et al. [17]:

$$\text{OM loss (\%)} = 100 - 100\,[(X_1\,(100 - X_2))/(X_2\,(100 - X_1))] \quad (1)$$

2.2.2. Microbiological Determinations

Different microbial pathogen groups (*Salmonella*, *Listeria monocytogenes*, total and faecal Coliforms (*E. coli*)), faecal Streptococcus and *Clostridium perfringens*) were determined in the final composts. Briefly, *Salmonella* was determined after pre-enrichment in buffered peptone water for 24 h at 37 °C, followed by Salmonella Xpress warm incubation for 24 h at 41.5 °C with the VIDAS test; *Listeria monocytogenes* was determined after Fraser warm incubation for 24 h at 30 °C with the VIDAS test; faecal coliforms (*Escherichia coli* (*E. coli*) by TBX incubation for 24 h at 44 °C; *faecal Streptococcus* after KAA incubation for 24–48 h at 37 °C; and *Clostridium perfringens* after TSC incubation for 24 h at 44 °C. All these determinations were made in triplicate, and the results obtained were expressed as the number of colony-forming units per gram of fresh compost (CFU/g compost) for *Streptococcus faecalis* and *Clostridium perfringens*, most probable number (MPN/g compost) for total coliforms and *E. coli*. *Salmonella* and *Listeria* were expressed as presence/absence.

2.3. Statistical Methods

The organic matter loss data produced throughout the composting process were fitted to a kinetic function using the Marquardt–Levenberg algorithm, with Sigmaplot 10.0 software. A first-order kinetic model for OM degradation during composting was used [17]:

$$\text{OM losses (\%)} = A\,(1 - e^{-kt}) \quad (2)$$

Where k is the rate constant (d^{-1}), t corresponds to the composting time (days) and A is the maximum degradation of OM (% C). The RMS and F-values were determined to compare the fit of different functions and the statistical significance of curve fitting.

The quadratic exothermic index (EXI^2 index), based on the thermal profiles obtained from the studied piles, was calculated as the quadratic sum of the daily difference between the temperature inside the pile and the ambient temperature during the bio-oxidative phase of composting, according to Vico et al. [23].

For a statistical analysis of the data obtained, the Shapiro–Wilk and Levene tests were used to test for normality and homogeneity of the variances, respectively, prior to ANOVA and the least significant difference (LSD) test at $p < 0.05$. All the statistics were performed using SPSS 28.0 software.

3. Results and Discussion

3.1. Thermal Profile of the Composting Heaps

The evolution of the temperature in all the composting heaps showed a rapid increase during the first week of the process, reaching thermophilic values higher than 60 °C (Figure 1). The temperature increase during the composting process is associated with heat production produced by organic matter biodegradation [24]. Thus, a rapid increase in temperature indicates a high availability of nutrients for the microorganisms involved in the composting process [25]. Approximately one month after the beginning of the process, a significant temperature increase was observed after the first turning and subsequent water addition, but these temperatures did not exceed the temperatures reached during the first days in all the piles studied.

Thus, in the present study, the maximum temperatures observed were 72, 75, 75, 76, 73 and 72 °C for Fontanars piles 1, 2 and 3 and Carrícola piles 4, 5 and 6, respectively. In addition, the temperature values in all the piles were higher than 55 °C during more than 15 consecutive days. This behaviour fulfils the European requirements on compost sanitation [26], since these temperature ranges guarantee the maximum pathogen reduction.

This trend was also observed in a study of community composting of the organic fraction of municipal waste in a case study in Galicia (Spain) [27]. Furthermore, similar values were obtained by Miguel et al. [15] in a pilot scale OFMSW composting process with a turned pile, where the material reached 65 °C during the first days of the process. The degree of exotherm, evaluated by the cumulative quadratic exothermic index (EXI^2, Table 4) indicated that the intensity of the bio-oxidative phase followed this order: pile 1 (231,590) > pile 4 (187,289) > pile 2 (163,363) > pile 5 (148,275) > pile 3 (119,930) > pile 6 (110,565), these values being notably lower than those found by Vico et al. [23] during the co-composting of palm wastes with urban and agri-food sludge, which indicates a higher degree of exotherm in this type of material.

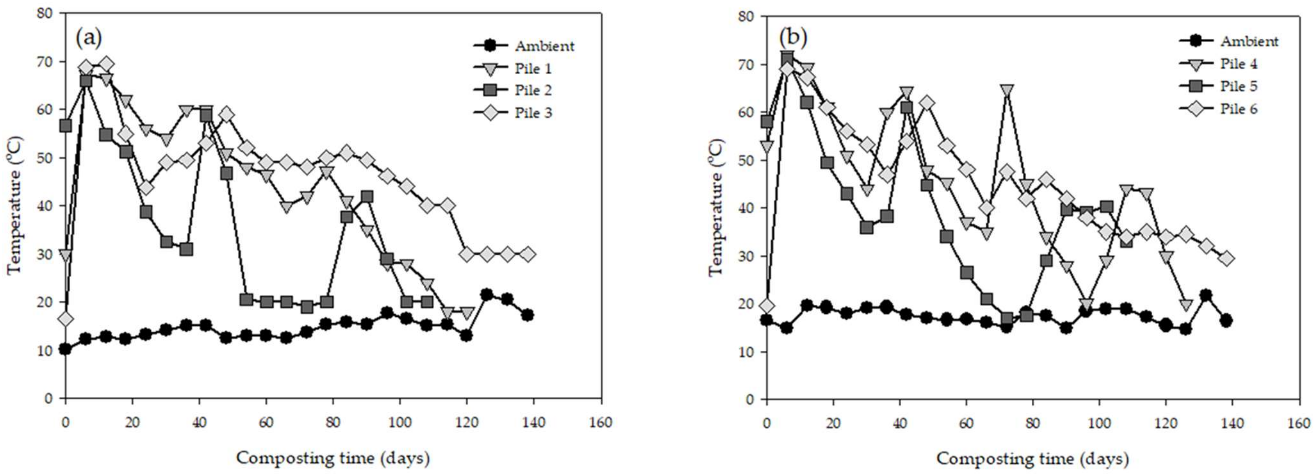

Figure 1. Temperature evolution of the composting piles. (**a**) Piles 1, 2 and 3 from Fontanars; (**b**) piles 4, 5 and 6 from Carrícola.

Table 4. Parameters associated with the exotermic profiles of the composting processes.

Thermal Parameters	Pile 1	Pile 2	Pile 3	Pile 4	Pile 5	Pile 6
No. days > 40 °C	84	58	119	94	67	100
No. days > 60 °C	43	32	29	38	24	40
Max. temperature	72	75	75	76	73	72
Average temperature	44.1	36.2	47.6	46.2	39.9	45.9
Bio-oxidative days	126	112	142	128	110	140
No. days > 40 °C/bio-oxidative	0.667	0.518	0.838	0.734	0.609	0.714
Cumulative EXI^2	231,590	163,363	119,930	187,289	148,275	110,656
EXI^2 Ratio/No. days bio-oxidative	1838	1459	845	1463	1348	790

EXI^2: quadratic exothermic index (quadratic sum of the daily difference between the average temperature of the pile and the ambient temperature). Piles 1, 2 and 3 from Fontanars, and piles 4, 5 and 6 from Carrícola.

3.2. Development of the Composting Processes

3.2.1. Changes of the Physico-Chemical and Chemical Parameters in the Composting Processes

The initial pH values in the piles studied ranged between 7.1 and 8.7 (Table 5), these values being within the suitable range (pH = 5.0–8.0) for the development of the bacteria and fungi typical of the composting process [28]. In all the piles, a progressive increase in pH was observed, reaching alkaline values (pH = 8.1–8.7) at the end of the composting process (Table 5), except for Pile 4, where the value remained practically constant. The pH final values observed were similar to those reported by Panaretou et al. [29] in a decentralized OFSMW composting experience in Tinos Island (Greece).

Table 5. Physico-chemical and chemical parameters in the composting samples (data expressed on a dry weight basis).

	pH	EC (dS m^{-1})	OM (%)	TN (%)	TOC (%)	TOC/TN	Na (g kg^{-1})	K (g kg^{-1})	P (g kg^{-1})
Fontanars Pile 1: 84.2% OFSMW1 + 15.8% UPW1									
S1	7.4 ± 0.1	3.7 ± 0.1	66.6 ± 0.5	1.66 ± 0.02	35.9 ± 0.3	21.7 ± 0.2	4.1 ± 0.0	9.2 ± 0.1	3.0 ± 0.1
S2	7.7 ± 0.1	3.8 ± 0.0	54.7 ± 0.5	1.78 ± 0.06	38.4 ± 1.1	21.9 ± 0.1	4.8 ± 0.1	11.4 ± 0.1	4.8 ± 0.3
S3	7.7 ± 0.1	3.9 ± 0.1	54.5 ± 0.3	1.70 ± 0.02	31.2 ± 0.2	18.4 ± 0.1	4.2 ± 0.1	9.0 ± 0.1	3.4 ± 0.1
S4	8.1 ± 0.1	3.6 ± 0.1	49.3 ± 0.4	1.71 ± 0.05	29.6 ± 0.7	17.4 ± 0.1	3.6 ± 0.0	8.9 ± 0.1	4.1 ± 0.0
LSD	*0.2*	*0.12*	*1.62*	*0.18*	*1.0*	*1.98*	*0.11*	*0.20*	*0.49*
Fontanars Pile 2: 85.8% OFSMW2 + 14.2% UPW2									
S1	7.1 ± 0.05	4.5 ± 0.04	56.4 ± 0.4	2.42 ± 0.02	36.1 ± 0.3	15.0 ± 0.2	5.5 ± 0.0	10.9 ± 0.5	6.4 ± 0.1
S2	8.2 ± 0.08	4.2 ± 0.04	53.4 ± 0.4	2.04 ± 0.02	32.6 ± 0.2	16.1 ± 0.1	5.8 ± 0.1	13.2 ± 0.2	7.0 ± 0.1
S3	8.4 ± 0.06	4.3 ± 0.06	52.2 ± 0.3	2.40 ± 0.02	32.0 ± 0.2	13.4 ± 0.1	6.1 ± 0.1	15.1 ± 0.3	8.0 ± 0.1
S4	8.1 ± 0.06	4.1 ± 0.09	51.8 ± 0.3	1.87 ± 0.02	29.8 ± 0.2	16.0 ± 0.1	5.0 ± 0.1	12.1 ± 0.2	5.8 ± 0.1
LSD	*0.1*	*0.14*	*1.4*	*0.08*	*1.4*	*0.97*	*0.27*	*0.48*	*0.24*
Fontanars Pile 3: 70% OFSMW3 + 30% UPW3									
S1	7.6 ± 0.06	3.4 ± 0.04	58.2 ± 0.8	2.42 ± 0.02	34.1 ± 0.2	14.2 ± 0.1	3.9 ± 0.0	11.6 ± 0.2	7.9 ± 0.1
S2	8.5 ± 0.07	2.9 ± 0.14	43.7 ± 1.1	1.61 ± 0.01	29.4 ± 0.2	18.4 ± 0.1	4.1 ± 0.1	10.4 ± 0.2	7.1 ± 0.1
S3	8.4 ± 0.06	3.3 ± 0.05	39.5 ± 1.1	1.66 ± 0.03	24.1 ± 0.3	14.6 ± 0.1	3.6 ± 0.1	9.3 ± 0.2	7.8 ± 0.1
S4	8.2 ± 0.06	3.2 ± 0.43	38.7 ± 2.8	1.78 ± 0.04	23.8 ± 0.5	13.4 ± 0.1	3.3 ± 0.1	8.9 ± 0.3	9.2 ± 0.1
LSD	*0.2*	*0.12*	*5.7*	*0.08*	*0.6*	*0.90*	*0.20*	*0.22*	*0.34*
Carrícola Pile 4: 82.7% OFSMW4 + 17.3% UPW4									
S1	8.7 ± 0.05	3.5 ± 0.03	59.0 ± 0.5	2.11 ± 0.01	33.1 ± 0.3	15.8 ± 0.2	4.6 ± 0.0	15.5 ± 0.1	6.6 ± 0.1
S2	8.4 ± 0.06	4.8 ± 0.03	48.9 ± 0.8	1.90 ± 0.10	31.8 ± 0.4	16.3 ± 1.5	4.8 ± 0.1	11.4 ± 0.1	4.7 ± 0.3
S3	8.6 ± 0.06	5.6 ± 0.04	45.3 ± 0.4	2.59 ± 0.02	29.5 ± 0.6	11.5 ± 0.2	4.2 ± 0.0	8.9 ± 0.1	3.4 ± 0.1
S4	8.6 ± 0.09	5.3 ± 0.04	40.8 ± 0.7	1.89 ± 0.01	43.94 ± 0.2	12.7 ± 0.1	3.5 ± 0.0	8.9 ± 0.1	4.1 ± 0.0
LSD	*0.1*	*0.17*	*1.07*	*0.11*	*1.8*	*0.32*	*0.11*	*0.24*	*0.48*
Carrícola Pile 5: 76.1% OFSMW5 + 23.9% UPW5									
S1	7.3 ± 0.05	5.3 ± 0.03	61.2 ± 0.7	1.93 ± 0.02	45.5 ± 0.4	23.7 ± 0.2	4.0 ± 0.1	23.3 ± 0.2	3.7 ± 0.1
S2	8.7 ± 0.06	5.4 ± 0.03	59.9 ± 0.6	2.14 ± 0.03	28.5 ± 0.9	13.4 ± 0.7	6.6 ± 0.1	20.1 ± 0.2	8.3 ± 0.1
S3	8.7 ± 0.06	5.0 ± 0.07	38.7 ± 0.4	2.17 ± 0.02	26.7 ± 0.2	12.4 ± 0.1	6.6 ± 0.1	21.3 ± 0.2	8.1 ± 0.1
S4	8.7 ± 0.06	6.1 ± 0.06	38.3 ± 0.4	2.14 ± 0.01	25.6 ± 0.3	12.1 ± 0.1	7.1 ± 0.1	21.0 ± 0.1	7.5 ± 0.1
LSD	*0.2*	*0.14*	*0.99*	*0.11*	*0.7*	*0.37*	*0.14*	*0.86*	*0.25*
Carrícola Pile 6: 86.6% OFSMW6 + 13.4% UPW6									
S1	8.1 ± 0.05	5.3 ± 0.03	53.3 ± 0.5	2.21 ± 0.02	32.6 ± 0.2	14.9 ± 0.1	6.3 ± 0.1	19.3 ± 0.2	6.7 ± 0.1
S2	8.9 ± 0.07	5.3 ± 0.04	47.9 ± 3.1	1.98 ± 0.01	28.5 ± 0.2	14.5 ± 0.2	6.8 ± 0.0	18.8 ± 0.1	7.8 ± 0.2
S3	8.5 ± 0.06	5.1 ± 0.02	42.8 ± 2.9	2.11 ± 0.06	26.9 ± 0.2	11.3 ± 0.6	6.5 ± 0.1	19.7 ± 0.2	11.8 ± 0.1
S4	8.5 ± 0.06	7.4 ± 0.06	38.6 ± 0.3	2.61 ± 0.01	23.6 ± 0.3	10.4 ± 0.2	8.3 ± 0.1	25.1 ± 0.2	7.9 ± 0.1
LSD	*0.2*	*0.61*	*4.39*	*0.05*	*0.9*	*0.31*	*0.20*	*0.56*	*0.22*

S1: initial stage; S2: thermophilic stage; S3: end of bio-oxidative stage; S4: end of maturity. For other abbreviations, see Tables 2 and 4. Data values reported as mean value ± standard error. LSD: least significant difference at $p < 0.05$.

The EC values showed a different trend in the two composting areas studied. In the Fontanars piles (piles 1, 2 and 3), the EC values decreased throughout the composting process, probably due to the loss of salts by leaching [17] as a consequence of rainfall, since these processes were conducted outdoors. On the other hand, in piles 4, 5 and 6 of Carrícola, which were developed indoors, this parameter increased as the composting time progressed, due to the degradation of OM and the concentration of ions by the mass loss of the pile [19]. High EC values in the compost can cause problems in seed germination, but this can be avoided by mixing it with other materials with low EC values to balance this parameter [30].

In general, the organic matter levels decreased during the composting processes, as did the TOC contents (Table 5), mainly during the thermophilic phase when higher temperature values were reached, indicating OM mineralization during the composting process. At the end of the process, the OM contents were between 38.3 and 51.8% (Table 5), these values being higher than the proposed minimum OM content (15%) for a final compost, according to the EU normative [26]. These OM contents in the composts can imply a benefit for agricultural soils since the use of composts rich in organic matter in soils improves their chemical and biological properties and prevents soil erosion, especially in Mediterranean climates where this phenomenon is widely prevalent [29].

The total nitrogen concentrations increased in piles 1, 5 and 6 as a consequence of the concentration effect due to the pile loss weight [17]. In contrast, a slight decrease in this parameter was observed in piles 2, 3 and 4 during the composting process (Table 5). In the case of piles 2 and 3, developed outdoors, this decrease can be associated with the previously mentioned leaching losses, also confirmed by the EC decrease. However, pile 4 was conducted indoors, so this decrease in the total N contents could be explained by other processes, such as immobilization by microorganisms, volatilization in the form of NH_3^-, nitrification–denitrification processes or adsorption of NH_4^+ on the surfaces of mineral or organic materials [31,32]. Sáez et al. [33] observed similar TN concentration/loss dynamics in the co-composting processes of the solid fraction of pig slurry, respectively. Regarding the TOC/TN ratio, all the composts had an initial value <20, except for piles 1 and 5, with 21.7 and 23.7, respectively, which decreased throughout the composting process, following the usual trend as a consequence of the organic matter losses during the composting process.

3.2.2. OM Decomposition

During the composting process, a significant degradation of OM was observed (Table 5). This decrease was especially important during the bio-oxidative phase (Figure 2), when microbial activity is maximal and temperatures reach the thermophilic range [17]. Furthermore, when the material to be composted is easily degradable, the rate of decomposition is faster [31].

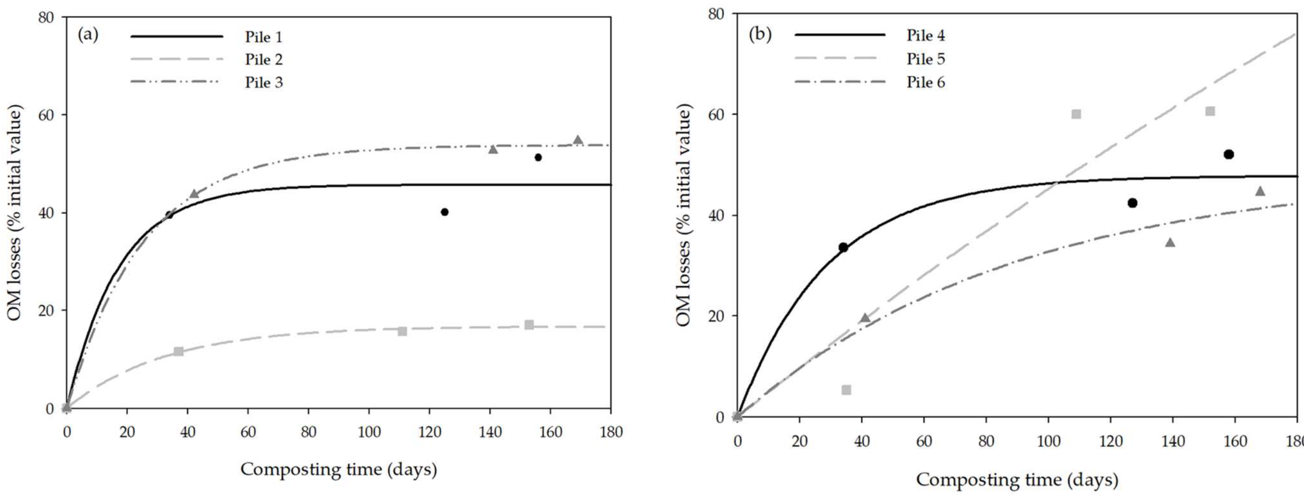

Figure 2. Organic matter (OM) losses during composting process. (**a**) Piles 1, 2 and 3 from Fontanars; (**b**) Piles 4, 5 and 6 from Carrícola. Lines represent curve-fitting.

In Fontanars piles 1 and 3 (Figure 2a), a rapid loss of OM was observed during the first few days of the process, followed by a stabilization around day 40 of the process. In contrast, in pile 2, a different trend was observed, since it did not exceed 20% loss of OM and stabilized approximately after 60 days of the process. This could be because this pile managed the least amount of waste (6456 kg) and had the lowest proportion of UPW (14.2%) of the three Fontanars piles, also showing the lowest average temperature (36.2 °C) and the shortest duration of the bio-oxidative phase (112 days compared to 126 and 142 for piles 1 and 3, respectively). In the Carrícola piles (Figure 2b), a heterogeneous evolution was observed. In pile 4, a rapid OM loss was observed during the first few days of the process, although less so than in the case of Fontanars pile 1, showing stability around day 60. In pile 6, although during the first days of the process, a linear trend in OM degradation similar to that observed in pile 5 was observed throughout the process, from day 30 onwards, a sustained loss of OM was observed during the rest of the process time. These results are similar to those obtained in previous composting experiments using municipal solid wastes [31]. The OM losses were fitted to a first order kinetic equation and the following parameter values were obtained (standard deviation in brackets; SEE: standard error of estimate and ***: significant at $p < 0.001$):

Pile 1: A = 45.73 (3.97), k = 0.058 (0.031), RMS = 30.89, F = 47.03 *, SEE = 5.56;
Pile 2: A = 16.75 (0.43), k = 0.031 (0.003), RMS = 0.25, F = 722.31 **, SEE = 0.5;
Pile 3: A = 53.84 (0.69), k = 0.040 (0.003), RMS = 0.87, F =2269.78 ***, SEE = 0.93;
Pile 4: A = 47.81 (3.62), k = 0.040 (0.011), RMS = 21.65, F = 69.04 *, SEE = 4.65;
Pile 5: A = 276.49 (1457.51), k = 0.002 (0.011), RMS = 140.61, F = 21.80 *, SEE = 11.86;
Pile 6: A = 49.10 (11.18), k = 0.011 (0.006), RMS = 14.65, F = 74.87 *, SEE = 3.83.

The A values obtained in piles 1, 3, 4 and 6 were slightly lower than the minimum values found by Bustamante et al. [17] and Vico et al. [23] in composting studies using agro-industrial wastes and date palm residues, respectively. However, pile 5 showed an extremely higher value than those found by other authors in experiments with similar wastes [8,31]. In contrast, pile 2 had the lowest value (16.75%), which could be associated with a shorter composting time and duration of the thermophilic stage, as well as possible anaerobic conditions within the pile that hinder degradation, as it was reported by Wang et al. [34] in a study about the composting processes in rural areas.

3.3. Quality of the Composts Obtained

3.3.1. Agronomic Value

Compost quality and its agronomic value are closely linked to process conditions such as pH, C/N ratio, moisture, particle size, aeration and porosity [5]. Thus, the control of the final parameters provides an idea of the degree of maturity, humification and stability of the compost, as well as its fertilizing capacity [7]. In Tables 6 and 7 are shown the agronomic characteristics and the main maturity and stability properties, respectively, of the final composts obtained. The EC values in the final composts were in the range of 3.2 dS m^{-1} (compost 3) to 7.4 dS m^{-1} (compost 6) (Table 6), these values being similar to those found in previous works with OFSMW [24,30].

Table 6. Agronomic characteristics of the final composts (data expressed on a dry weight basis).

Parameters	Compost 1	Compost 2	Compost 3	Compost 4	Compost 5	Compost 6
EC (dS m^{-1})	3.6 ± 0.1	4.1 ± 0.1	3.2 ± 0.4	5.3 ± 0.0	6.1 ± 0.1	7.4 ± 0.1
TOC/TN ratio	17.4 ± 0.1	16.0 ± 0.1	13.4 ± 0.1	12.7 ± 0.1	12.1 ± 0.1	10.4 ± 0.2
TN (g kg^{-1})	17.1 ± 0.1	18.7 ± 0.2	17.8 ± 0.0	18.9 ± 0.5	21.4 ± 0.2	26.1 ± 0.4
P (g kg^{-1})	4.1 ± 0.0	5.8 ± 0.1	9.2 ± 0.1	4.1 ± 0.0	7.5 ± 0.1	7.9 ± 0.1
K (g kg^{-1})	8.9 ± 0.1	12.1 ± 0.2	8.9 ± 0.3	8.9 ± 0.1	21.0 ± 0.1	25.1 ± 0.2
Na (g kg^{-1})	3.6 ± 0.0	5.0 ± 0.1	3.3 ± 0.1	3.5 ± 0.0	7.1 ± 0.1	8.3 ± 0.1
Ca (g kg^{-1})	98.5 ± 1.8	112.2 ± 1.4	153.8 ± 1.3	132.4 ± 2.9	137.9 ± 1.7	129.6 ± 1.6
Mg (g kg^{-1})	6.4 ± 0.1	7.0 ± 0.1	9.0 ± 0.2	10.6 ± 0.1	13.9 ± 0.1	12.9 ± 0.1
Fe (mg kg^{-1})	3253 ± 27	2855 ± 58	2390 ± 21	3284 ± 31	4358 ± 43	3029 ± 36
Mn (mg kg^{-1})	107.8 ± 0.9	120.5 ± 2.2	81.0 ± 1.7	171.1 ± 3.1	213.3 ± 2.9	155.2 ± 2.1
Cu (mg kg^{-1})	15.1 ± 0.3	19.8 ± 0.5	20.9 ± 0.3	34.7 ± 1.0	57.2 ± 0.7	68.1 ± 1.7
Zn (mg kg^{-1})	48.1 ± 1.6	56.9 ± 1.0	66.5 ± 1.0	79.1 ± 1.1	84.2 ± 0.8	109.3 ± 1.2

Composts 1, 2 and 3 from Fontanars; composts 4, 5 and 6 from Carrícola. For other abbreviations, see Table 2. Data values reported as mean value ± standard error.

Although Storino et al. [35] established that the addition of poultry manure to the co-composting of OFMSW with urban pruning waste did not increase the salinity of the final compost, in the present experiment, the addition of donkey manure to the mixture caused an increase in the EC of the final compost from 3.5, 5.3 and 5.3 to 5.3, 6.1 and 7.4 dS m^{-1} in the piles 4, 5 and 6 of Carrícola (Table 6), respectively.

Table 7. Maturity and stability parameters in the final composts (data expressed on a dry-weight basis).

Parameters	Compost 1	Compost 2	Compost 3	Compost 4	Compost 5	Compost 6
CEC (meq 100 g^{-1} OM)	92.8 ± 3.4	113.1 ± 1.1	101.9 ± 0.8	109.0 ± 1.0	102.8 ± 7.8	114.7 ± 0.9
Cha (%)	4.4 ± 0.2	5.1 ± 0.2	2.8 ± 0.0	5.5 ± 0.1	5.2 ± 0.1	5.3 ± 0.2
Cfa (%)	1.7 ± 0.0	1.7 ± 0.0	1.2 ± 0.0	1.7 ± 0.0	1.5 ± 0.0	1.6 ± 0.0
Cha/Chf	2.6 ± 0.1	3.0 ± 0.1	2.3 ± 0.0	3.2 ± 0.0	3.5 ± 0.0	3.3 ± 0.1
GI (%)	116.1 ± 0.1	64.0 ± 3.7	109.1 ± 0.8	96.2 ± 7.9	51.1 ± 1.2	95.5 ± 1.0
Stability test [1]	V, stable	V, stable	V, stable	V, stable	V, stable	V, stable

[1] Dewar test described by Brinton et al. [21]. Composts 1, 2 and 3 from Fontanars. Composts 4, 5 and 6 from Carrícola. CEC: cation exchange capacity; Cha: humic acid-like carbon; Cfa: fulvic acid-like carbon; GI: germination index. For other abbreviations, see Table 2. Data values reported as mean value ± standard error.

The final nutrient content of a mature compost defines its fertilizer capacity to improve agricultural crops and is determined by the heterogeneity of the starting materials [36]. Thus, it is important to avoid NPK losses in order to obtain a final product with high agronomic and economic value [17]. The final macronutrient concentrations were high in all the composts, the highest values for TN and K being found in Carrícola compost 6 (26.1 and 25.1 g kg^{-1} for TN and K respectively) (Table 6). Moreover, the values obtained are in line with those of other studies of biowaste composting [36–38].

Regarding the maturity and stability parameters, the final composts showed CEC values in the range of 92.8–114.7 meq 100 g^{-1} OM (Table 7), exceeding the minimum range (60–67 meq 100 g^{-1} OM) established for compost mature [39]. Jara-Samaniego et al. [40] also obtained values between 108 and 155 meq 100 g^{-1} OM in composts from municipal solid wastes, while Sáez et al. [33] obtained values in the range of 96–105 meq 100 g^{-1} OM for compost with slurry solid fraction. In addition, all the composts had a higher amount of the humic fraction compared to the fulvic fraction (Table 7). Likewise, the values recorded exceeded those found in previous studies using different starting materials [17]. Furthermore, all the final composts showed an adequate degree of stability, according to the self-heating test of Brinton et al. [22] and absence of phytotoxicity (GI > 50%) [21], with values similar or higher to those reported by Alves et al. [36] during an experiment of community composting.

3.3.2. Environmental Potential Risks: Potentially Toxic Elements (EPTs) and Microbial Pathogen Groups

High concentrations of certain substances in compost, such as EPTs, can cause problems for plant growth [41]. On the other hand, in order to avoid risks to human health and to the environment, compost used in agriculture also must meet certain microbiological criteria. Table 8 shows the concentration of potentially toxic elements and pathogen microbial groups in the final composts. All the composts showed EPT concentrations below the limits established by the European and Spanish legislations [26,42], these results being similar to those reported in previous studies of composting of municipal solid waste [30].

Regarding the pathogen content (Table 8), all the final composts showed absence of *Salmonella* spp. and *E. coli* contents below the limit value (1000 MPN/g compost) established in the European and Spanish legislation [26,42]. In relation to the rest of the microbial pathogen groups studied (total coliforms, *Streptococcus faecalis*, *Clostridium perfringens* and *Listeria monocytogenes*), in general, the contents were very low, especially of *Clostridium perfringens* and *Listeria monocytogenes*, except for Listeria in compost 1, also probably due to a recontamination of the pile during the maturity stage, which corroborates the effectiveness of the composting process and the absence of risk to human health [14]. The contents of these microbial groups were similar to those observed in previous works using municipal solid waste as raw material [14] and during the co-composting of OFSMW with pruning waste [15]. The relatively higher values for the microbial groups in compost 4 could be associated with the process conditions, as this pile had a low average temperature (39.9 °C), the shortest duration of the bio-oxidative phase (110 days) and the lowest number of days in which the temperature of the pile exceeded 60 °C (24 days). Miguel et al. [15] associated increases in microbiological parameters in an experiment with similar wastes using three different types of composting, namely, bacterial input through irrigation water and a lack of temperature homogeneity in the pile during the thermophilic phase, which can lead to an increase in bacterial populations.

Table 8. Potentially toxic elements and pathogen microbial groups in the final composts.

	Compost 1	Compost 2	Compost 3	Compost 4	Compost 5	Compost 6
Potentially toxic elements						
Co (mg kg^{-1})	2.3 ± 0.0	1.8 ± 0.1	1.4 ± 0.0	2.2 ± 0.1	2.0 ± 0.0	1.5 ± 0.2
Cr (mg kg^{-1})	24.3 ± 0.3	29.8 ± 0.8	22.1 ± 1.3	27.2 ± 0.3	54.5 ± 7.0	24.5 ± 0.5
Cd (mg kg^{-1})	0.38 ± 0.00	0.37 ± 0.00	0.37 ± 0.02	0.35 ± 0.01	0.35 ± 0.00	0.41 ± 0.01
Pb (mg kg^{-1})	6.6 ± 0.1	7.0 ± 0.1	9.2 ± 0.2	10.6 ± 0.1	20.8 ± 5.8	11.5 ± 0.2
Ni (mg kg^{-1})	8.3 ± 0.1	8.1 ± 0.1	7.4 ± 0.3	10.5 ± 0.2	18.3 ± 2.6	10.3 ± 0.1
As (mg kg^{-1})	2.6 ± 0.2	0.8 ± 0.8	2.4 ± 2.4	2.4 ± 0.2	1.3 ± 0.5	0.9 ± 0.5
Microbial pathogen groups						
Total coliforms	2.30×10^1	<3	1.50×10^2	2.40×10^3	1.10×10^3	4.30×10^1
Escherichia coli	<10	<10	<10	2.40×10^2	9.30×10^1	2.30×10^1
Clostridium perfringens	<10	<10	<10	<10	<10	<10
Streptococcus faecalis	3.50×10^2	<10	4.90×10^2	1.40×10^3	<10	1.70×10^4
Salmonella spp.	ND	ND	ND	ND	ND	ND
Listeria monocytogenes	D	ND	ND	ND	ND	ND

Pile 1, 2 and 3 from Fontanars. Piles 4, 5 and 6 from Carrícola. Data referred to microbial groups are expressed as CFU/g compost (*Streptococcus faecalis* and *Clostridium perfringens*) and MPN/g compost (total coliforms and *E. coli*). The rest of data are expressed on a dry weight basis. ND: not detected in 25 g compost; D: detected in 25 g compost. Data values reported as mean value ± standard error.

4. Conclusions

The decentralized composting of the organic fraction from the selective collection of municipal solid waste collected through the fifth container or door-to-door system, together with urban pruning waste carried out in the municipalities of Carrícola and Fontanars (Valencia, Spain) is presented as an optimal management method for this type of waste. This study has verified that with this type of management, is possible to obtain a high-quality product with suitable physico-chemical and chemical characteristics for its use in agriculture. The degree of maturity and stability, as well as the fertilizing richness in all the composts were adequate and demonstrated their added value as a substitute for mineral fertilizers in crops. In general, the composts showed an absence of phytotoxicity and a good sanitary quality, with levels of human pathogens below the maximum limit for the use of compost as a fertilizer in almost all cases. Moreover, the study of the different composting cycles has shown an important homogeneity in the development of the processes and in the characteristics of the end-products. Thus, the results obtained verify the reproducibility and effectiveness of the composting processes using this scenario, enhancing the adoption of criteria for the standardization of this model of municipal solid waste management, which provides environmental benefits within the framework of the circular economy, increasing the environmental awareness of citizens and reducing the impacts derived from the dumping and/or incineration of this organic waste.

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