Environmental Technology & Innovation 36 (2024) 103799

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Optimization of industrial-scale composting of dewatered pig slurry and olive mill waste using discarded tennis balls as an inert bulking agent

Juan Aviñó-Calero [a], Ernesto Santateresa [a], Luciano Orden [b,c], Evan A.N. Marks [b,*], Encarnación Martínez Sabater [b], Javier Andreu-Rodriguez [b], José Antonio Saéz-Tovar [b], María Dolores Pérez-Murcia [b], María Ángeles Bustamante [b], Raúl Moral [b]

[a] Sociedad de Fomento Agrícola Castellonense S.A. (FACSA), C/ Mayor 82-84, Castellón de la Plana, Castellón 12001, Spain
[b] Centro de Investigación e Innovación Agroalimentaria y Agroambiental (CIAGRO-UMH), Universidad Miguel Hernández, Carretera de Beniel Km 3.2, Orihuela, Alicante 03312, Spain
[c] Estación Experimental Agropecuaria INTA Ascasubi (EEA INTA Ascasubi), Ruta 3 Km 794, Hilario Ascasubi, Buenos Aires 8142, Argentina

ARTICLE INFO

Keywords:
Agri-food waste
Circular economy
Compost
Recyclable bulking agent

ABSTRACT

Material shortages in composting may pose limits or logistical problems in certain regions, which can be addressed with inert and reusable wastes. Very little research has been conducted on the subject of using alternative synthetic wastes as structuring agents to improve composting process parameters. The present work aimed to evaluate the use of used tennis balls (TB) as an inert bulking agent. Composting was carried out in an industrial composting plant with a ternary mixture of olive mill waste, the solid fraction of dewatered pig slurry, urban pruning residues, with the addition of TB as a synthetic bulking agent. Composting process parameters, monitored throughout the composting cycle, showed that TB significantly affected the thermal composting process parameters, with increases in operating temperatures, exothermic index, and mineralization of organic matter. Also, compost properties were seen to be of equal or superior quality at the end of the composting with addition of TB. These are the first experimental results testing the effect of a spherical synthetic reutilized product such as TB on composting processes, which was additionally carried out at an industrial scale, showing that using discarded materials such as used tennis balls can improve the efficiency and economy of composting.

1. Introduction

Composting is a globally widespread waste treatment technology and is considered a key solution for recycling organic wastes into organic fertilizers (Haug, 2018). To ensure the generation of suitable organic matter (OM) and to achieve an optimal carbon/nitrogen ratio (C:N; typically 10–20) in the composting of certain wastes with high moisture contents and small particle size, bulking agents are crucial (Casado et al., 2023). Bulking agents help regulate moisture content and promote free air circulation to ensure successful composting, conditioning the efficiency of aerobic bio-oxidation and the quality of the final product during composting (van der Wurff

* Corresponding author.
E-mail address: emarks@umh.es (E.A.N. Marks).

https://doi.org/10.1016/j.eti.2024.103799
Received 10 June 2024; Received in revised form 31 July 2024; Accepted 17 August 2024
Available online 23 August 2024

et al., 2016). In some circumstances, appropriate sources of organic bulking agents may not be available; in these cases, forced aeration can supply improved bio-oxidative conditions within the composting pile. Forced aeration offers a number of advantages to the composting process, typically leading to lower overall composting times (acceleration), permitting achievement of sanitization temperatures which guarantee compost quality, improving temperature regulation and consistency throughout the compost pile, overall promoting greater efficiency in terms of management of throughput for the composting plant. The main disadvantage of forced aeration are high initial investment, requiring the installation of blowers, piping, and air ducting in the installation. Also, the energy requirements of forced air are substantial. As such, the use of bulking agents instead of forced air systems may significantly reduce costs for industrial composting plants.

Organic bulking agents not only improve aeration, but also supplement carbon, since bulking agents are often woody, lignocellulosic materials such as prunings, wood chips, or straw, serving as a carbon source and equilibrating nutrient stoichiometries. However, excessive use of organic bulking agents can inadvertently prolong composting time and compromise efficiency (El Fels et al., 2014). Furthermore, the type and particle size of bulking agents have a significant impact on composting performance (Gea et al., 2007; Cheng et al., 2022). Previous studies have investigated the use of naturally-occurring inorganic bulking agents such as zeolites, medical stone and pumice (Wang et al., 2018, 2019, 2020). In addition, efforts have been made to control the particle size and porosity of bulking agents, including synthetic plastic, CTB, and recyclable plastic bulking agents (McGuckin et al., 1999; Zhou et al., 2014). However, none of these studies considered a case for the practical and viable large-scale implementation of inorganic bulking agents which may be reused.

Tennis balls, composed of rubber and nylon fibers, have a high elasticity to absorb impact forces, but their durability is quite susceptible to a demand for high performance. As a result, tennis balls are produced and disposed of in very large quantities, due to the short use of life which they are given. For instance, in Spain alone around 14 million units are sold each year, these currently having no clear end-of-life use, and at the same time generating a large amount of synthetic waste. Though efforts have been made to recycle tennis balls, one of the most important hindrances is the separation of rubber and nylon components. Unpublished results from our research group demonstrate that the mechanical separation of these two materials is enhanced by incubation in composting piles, which renders the glue binding them ineffective.

This study addresses advancements in the industrial-scale composting of organic wastes of primary importance in the region in which the study was carried out. Pig slurry is often separated into solid and liquid fractions, the liquid fraction treated in lagoons, and the solid fraction (PSSF) is often composted. As a nutrient-laden material, pig slurry requires the addition of carbon sources, and aeration must be improved with bulking agents. Also, two-phase olive mill waste (OMW), known as "alperujo" locally, is produced in high quantities throughout the study region, extensively in Spain, and in other Mediterranean countries as well (Marks et al., 2020). Studies highlight composting as an efficient and cost-effective method for the treatment OMW, which is often used as an organic amendment and fertilizer in agricultural soils (Tortosa et al., 2012; Bari Chowdhury et al., 2013; Regni et al., 2017). However, it is advantageous if OMW is composted to reduce the concentrations polyphenol compounds (degraded during the bio-oxidative composting phase) which otherwise can provoke phytotoxicity if the waste is applied in large quantities directly to soil without previous biological treatment. While composting of OMW and PSSF has been extensively studied separately, we are aware of no studies (and especially industrial-scale studies) which have tested the co-composting of these materials. Therefore, in order to promote the co-composting of these abundant organic wastes, it is necessary to test and validate appropriate mixtures. Secondly, since these materials have a relatively small particle size and when heaped leave little interstitial space for gas exchange, bulking agents must be used. With this basis, here we propose an innovation for the composting of such materials consisting in the addition of a new bulking agent. Technical advances have been made regarding the composting of similar wastes including the effect of different organic bulking agents (Bustamante et al., 2012; Santos et al., 2018), however what has not been addressed is the incorporation of inert bulking agents to reduce reliance on organic bulking agents which may in fact increase the complexity and costs of composting depending on the local availabilities and context. To our knowledge, composting with discarded tennis balls as a bulking agent (hereafter TB) - a relevant and unresolved waste stream - has not been attempted either at bench or industrial scale.

With this background, the overall study objective has been to evaluate improvements in industrial-scale composting of problematic organic wastes with the addition of an inert spherical waste as a bulking agent. To this end, as a necessary first step for identification of an adequate ternary mixture, a first experiment (Experiment A) tested increasing proportions of OMW with PSSF and a common bulking agent (pruning wastes). Thereafter, having identified an appropriate ternary mixture, the main study objective was to evaluate how composting may be improved with addition of the inert recoverable structuring agent (TB), and to determine an optimum quantity of added TB for incorporation into industrial-scale windrows (Experiment B). To evaluate improvements in the composting process, we carried out continuous monitoring of process parameters to characterize any improvements. Also, we analyzed the resulting composts to understand changes in chemical properties and agronomic quality.

2. Materials and methods

2.1. Experimental installations and procedure

As mentioned in the introduction above, the materials to be composted were organic wastes of high relevance considering the local agroindustry (OMW, PSSF, and UPR; Figure S1 a and b). OMW and PSSF are generated in large quantities in the study region in consideration and are of low potential agronomic or economic value being that they require biological treatment (i.e. composting). While OMW and PSSF are found in abundance, the study region is a low-rainfall semi-arid zone with a predominance of rainfed crops typical to the Mediterranean, and under these conditions high-carbon content bulking agents are available at cost or require transport.

For the acquisition of the inert bulking agent, through the recycling initiative of a well-known tennis ball distributor (Decathlon "double-bounce" initiative), approximately 17,000 used tennis balls were collected. These were transported from Getafe (Madrid, Spain) to Todolella (Castellón, Spain), where this study was carried out.

In Experiment A, OMW was added to mixtures in increasing concentrations of 20 %, 30 %, and 40 % mass, reducing the PSSF fraction, while pruning residue amounts were held equal at 20 % (Table S1). In Experiment B, TB were added to the mixture at one concentration of OMW (40 %; determined following results of Experiment A described below) in increasing amounts of 1 %, 2.5 %, 5 %, and 10 % (vol./vol; Table S1). The tennis balls were added unaltered, in the same form as received when collected as waste. The mixtures were identified and prepared considering previous experience and modeling efforts, to obtain an optimal combination of volume, porosity, fresh and dry matter, based on the values of moisture and apparent density values of each component. Considering the industrial setting and so as not to impede normal functioning of the composting plant, for each treatment one windrow was prepared, but multiple semi-independent measurements were made along the length of this windrow (described in greater detail below).

The composting experiments were carried out in a covered warehouse at the Todolella treatment plant (Castellón, Spain), simultaneously and at industrial scale, in seven windrows between July and November 2021. The composting piles (18 m^3, 5 m length x 2.4 m width x 1.5 m height) were made using the different ratios of OMW:PSSF:UPR or TB as inert bulking agent. The composting process consisted of a 60-day of bio-oxidation phase followed by a 30-day maturation phase. The piles were turned and aerated using a large mechanical trench-type compost turner (HUMOFAC, EMMEPI®; Figure S1 c and d), whereas each pile was turned eight times at 7, 12, 20, 27, 34, 41, 48 and 55 days. The Todolella composting system was equipped for collecting all the leachates from composting facilities which were piped to an evaporation pond. However, leachate production only occurred significantly during the beginning of the bio-oxidative phase (0–7 days).

2.2. Monitoring, sampling and analyses

Temperature was measured every day during the bio-oxidative phase (0–60 d), and every three days during the maturation phase (60–90 d) at five different points at two depths (0.3 m and 1 m) along the pile profile using probes for automatic temperature monitoring. The exothermic index (EXI^2) was calculated as the quadratic sum of the daily difference between the temperature inside the pile as compared to that in the surrounding environment during the bio-oxidative phase of composting (Vico et al., 2018). The moisture content of the piles was maintained at values around 60 % (van der Wurff et al., 2016) throughout the process by using a sprinkler system when necessary.

Six longitudinal samples were taken from each of the seven compost piles during the composting process at 0, 15, 30, 45, 60 and 90 days. At each sampling date, four subsamples were taken from different sites along the pile profile to make the final sample representative. The collected samples were dried (60 ºC), ground, and sieved to 0.5 mm prior to their chemical analysis. Samples were analyzed according to the methods used by Bustamante et al. (2007): the raw materials and the compost samples were analyzed for EC and pH in a 1:10 (w/v) water soluble extract. TOC was assessed by determining loss on ignition at 430° C for 24 h. TN was determined by automized elemental microanalysis according to Martínez-Sabater, (2022). Soluble polyphenols (PPH) were determined by the modified Folin–Ciocalteu method in a 1:20 (w/v) water extract (Paredes et al., 2009). After microwave acid digestion, total elemental contents of P, K, Ca, Mg, Na and heavy metals were analyzed by atomic absorption spectrometry. Losses of OM and TN were calculated based on the initial (day 0) and succeeding samples' ash contents (Paredes et al., 2000). Physicochemical properties of the raw materials used in the initial composting mix are shown in Table S2.

For the calculation of economic value of the composts based on nutrient contents, this was based on the value of the N, P_2O_5 and K_2O fertilizing units of commercial mineral fertilizers which were considered to be urea (46−0−0), triple super phosphate (TSP; 0–46–0) and potassium chloride (KCl; 0–0–60; Jara-Samaniego et al., 2017). Approximate current standard fertilizer prices were ascertained: the reference value of reference fertilizers was 350, 418, and 330 € ton^{-1} for urea, TSP and KCl, respectively (European Commission, 2022). Thus, the values of the N, P_2O_5 and K_2O fertilizing units were estimated to be 760, 908, and 550 € ton^{-1}, respectively (Tröster, 2023). Calculations are therefore based on the elemental contents which have been transformed to equivalencies in N, P_2O_5, and K_2O. For this calculation a standard compost moisture content of 25 % was used, this being a common reference value as established by Spanish Real Decreto (law) 999/2017.

Statistical analyses of experimental data were performed using the R programming environment (R Core Team, 2023). Repeated measures one-way analysis of variance (ANOVA) were first used to analyze temperature measurements in compost piles, as well as samplings within piles, and Tukey HSD test at $p < 0.05$ were used to assess the significance of differences between experimental treatments (type of mixtures and percent of tennis balls).

3. Results and discussion

3.1. Process indicators

3.1.1. OMW addition (Experiment A)

Based on monitoring data (Figure S2), there were typical daily temperature fluctuations due to heap turning as part of the normal composting process, in addition to watering (moisture conditions were maintained at optimum values for the process, between 50 % and 70 %; van der Wurff et al., 2016). Piles with 20 %, 30 % and 40 % OMW showed a typical evolution of composting temperatures, reaching thermophilic temperatures (>55 ºC) within the first 7 d of composting and with a maintenance of the thermophilic phase for about 45 d in each pile (Figure S2). This behavior of the bio-oxidation phase was typical, comparable to mixtures with OMW in large-scale open windrow piles (Alfano et al., 2008; Droussi et al., 2009; Hachicha et al., 2009; Ekinci et al., 2021), and permitting sanitization of the mixtures. Temperatures measured during the bio-oxidative phase were consistently higher at 0.3 m as compared to 1 m depth (Fig. 1a,b), showing an accumulation of temperature towards the top of the piles. With the different amounts of OMW, average temperatures taken at 0.3 m showed a slight increasing trend with more OMW, but these differences were not significant. However, at 1 m depth the temperature differences were significant (Fig. 1b), with averages of 35.5℃, 39.8 ℃, and 40.5 ℃, for 20 %, 30 %, and 40 % OMW, respectively, and in general thermal indicators increased with increasing OMW % (Table 1). Particularly notable are the increases in number of days with pile temperatures > 60 ℃ at 0.3 m, and days with temperatures > 40 ℃ at 1 m. However, differences in EXI^2 were not clear, particularly a 0.3 m (Table 1, Fig. 3a,b). Overall, the greatest differences were found in the measurement of average temperatures of the piles, and the recorded high temperature days. Based on these thermal process indicators, it may be concluded that the highest OMW additions were those which most favored the composting process.

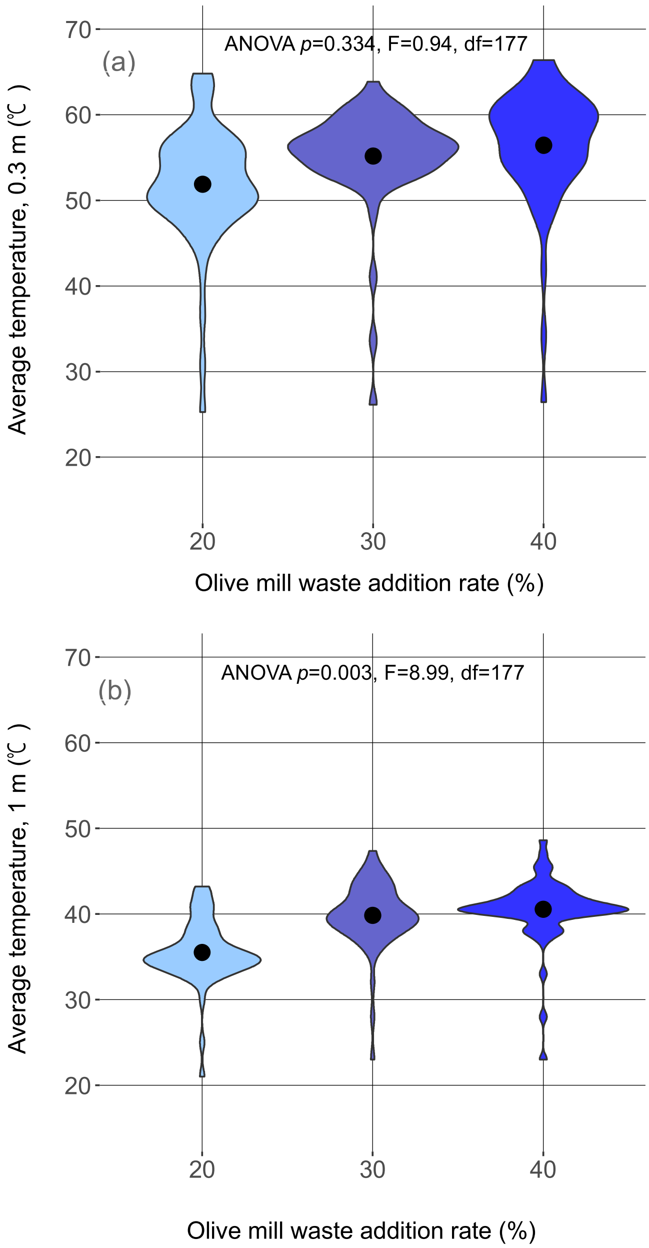

Fig. 1. Violin plots of average temperatures observed in Experiment A testing OMW concentrations at two depths.

Table 1
Exothermic behaviour during the biooxidative phase of the composting process in the experimental composting piles.

	Depth	Treatment	Tmax (℃)	Days > 40 ℃	Days > 50 ℃	Days > 60 ℃	EXI^2 at end (x100)
Experiment A	0.3 m	OMW 20 %	64.8	57	39	5	22.70
	0.3 m	OMW 30 %	63.85	58	56	7	19.7
	0.3 m	OMW 40 %	66.35	58	53	18	22.5
	1 m	OMW 20 %	43.2	8	0	0	4.8
	1 m	OMW 30 %	47.4	27	0	0	7.7
	1 m	OMW 40 %	48.6	46	0	0	7.2
Experiment B	0.3 m	TB 1 %	57.3	48	24	0	15.9
	0.3 m	TB 2.5 %	56.8	55	35	0	14.9
	0.3 m	TB 5 %	65.6	58	54	11	20.6
	0.3 m	TB 10 %	60.1	58	57	1	17.1
	1 m	TB 1 %	43.5	4	0	0	4.4
	1 m	TB 2.5 %	41.1	3	0	0	5.0
	1 m	TB 5 %	58.2	27	8	0	15.3
	1 m	TB 10 %	51.5	10	8	0	11.2

TMax: highest average temperature observed; Days > 40 ℃, 50 ℃, 60 ℃: observations with average temperatures over stated temperature; EXI^2 (*x100*): quadratic exothermic index result at the end of the biooxidative phase.

3.1.2. TB addition (Experiment B)

The overall dynamics of process temperatures in Experiment B were similar to those in Experiment A (Figure S3). As seen in Experiment A, temperatures measured during the bio-oxidative phase in Experiment B were consistently higher at 0.3 m as compared to 1 m depth (Fig. 2a,b). Temperature increases with TB addition were observed both at 0.3 m and 1 m depth (Fig. 2a,b); for 1 %, 2.5 %, 5 %, and 10 % TB, at 0.3 m averages were 47.8℃, 49.6 ℃, and 55.3 ℃, and 55.6 ℃, respectively, and 1 m averages were 33.4 ℃, 34.9 ℃, and 40.8 ℃, and 44.4 ℃, respectively. Better performance in terms of maximum temperatures can also be observed in the measurements made at 1 m, particularly for 5 %, whereas 27 days exceeded 40 ℃ as compared to only 4 in the control heap (0 % TB), and both the 5 % and 10 % treatments had 8 days which exceeded 50 ℃, whereas none were found in the control heap. Also, in contrast to Experiment A, EXI^2 was greatly increased with TB addition, whereas it was seen that additions of 5 % and 10 % achieved similar results (Fig. 3c,d; Table 1). Overall, in terms of the process temperature indicators, positive effects of TB addition were found, confirming the advantages of using the inert bulking agent, in agreement with the results of other authors (Zhou et al., 2014; Wang et al., 2020; Hamid et al., 2020), whereas the higher TB additions (5 % and 10 %) showed improved thermal indexes at both depths. Considering all the thermal parameters, it might be concluded that no improvements are achieved with TB additions greater or equal to 5 %. In fact, considering the data in Table 1, it appears that thermal indicators were not as favorable at 10 % as compared to 5 %, with notable decreases in the majority of the monitored parameters.

3.2. Compost maturation

3.2.1. Experiment A (OMW)

The mineralization dynamics depended greatly on the mixtures of the feedstocks in the tertiary process; mineralization of the composts progressed more quickly in the mixes with less OMW (Fig. 4a). The changes following the bio-oxidative stage were very indicative, with practically no change in mineralization for 20 % OMW (4 % increase), a moderate change for 30 % OMW (15 % increase), and a very significant change for 40 % OMW (58 % increase during the maturation phase). Observing Fig. 4a, these differences became evident as early as 15 d, whereas the degrees of mineralization of the organic matter became increasingly differentiated over time. On one hand, this information indicates that mineralization in treatments with increasing OMW was quite delayed owing to the constituents of the mixtures. This is expected, due to the polyphenolic substances in OMW which when present in large concentrations limit microbial activity, and the curves of mineralization are slower and more time for compost maturity is required, as seen in the mixtures with 30 % and 40 %. This is precisely the challenge posed in composting of OMW, which can benefit from technological solutions which accelerate the bio-oxidative phase and the efficiency of the composting process. Temperatures monitored during the maturation phase show the effect of mixing of the compost piles; it is observed that temperature peaks were progressively higher with more OMW, showing that these mixtures had lower degrees of maturation (Figure S2).

3.2.2. Experiment B (TB)

In Experiment B, in which all mixtures had 40 % OMW and different concentrations of TB, the effect of OMW suppressing biological activity was also notable (Fig. 2), whereas the initiation of the bio-oxidative phase and organic matter loss was delayed. From 0–45 days, the piles with least OM loss were 1 % and 10 % TB, but from > 45 days 5 % TB had the greatest OM loss. Based on OM loss shown in Fig. 4b, it is seen that 5 % TB promoted the greatest mineralization of the organic matter, which at 45 days had an average value of 24 %, much greater than the other treatments (11 %, 13 %, and 14 % for 1 %, 2.5 %, and 10 % TB, respectively. Differences of this magnitude were also evident at 60 days (Fig. 4b). It is relevant that temperatures during the beginning of the bio-oxidative phase were generally highest in 5 %, followed by 10 %, and lowest at 1 % and 2 %. Based on this temperature and mineralization information, it would seem that TB assisted bio-oxidation up to a limit (in our experiment seen at 5 %), after which increased amounts of TB did not aid but hindered the process. This may be, for instance, because the air flow at 5 % achieved an optimum compromise between

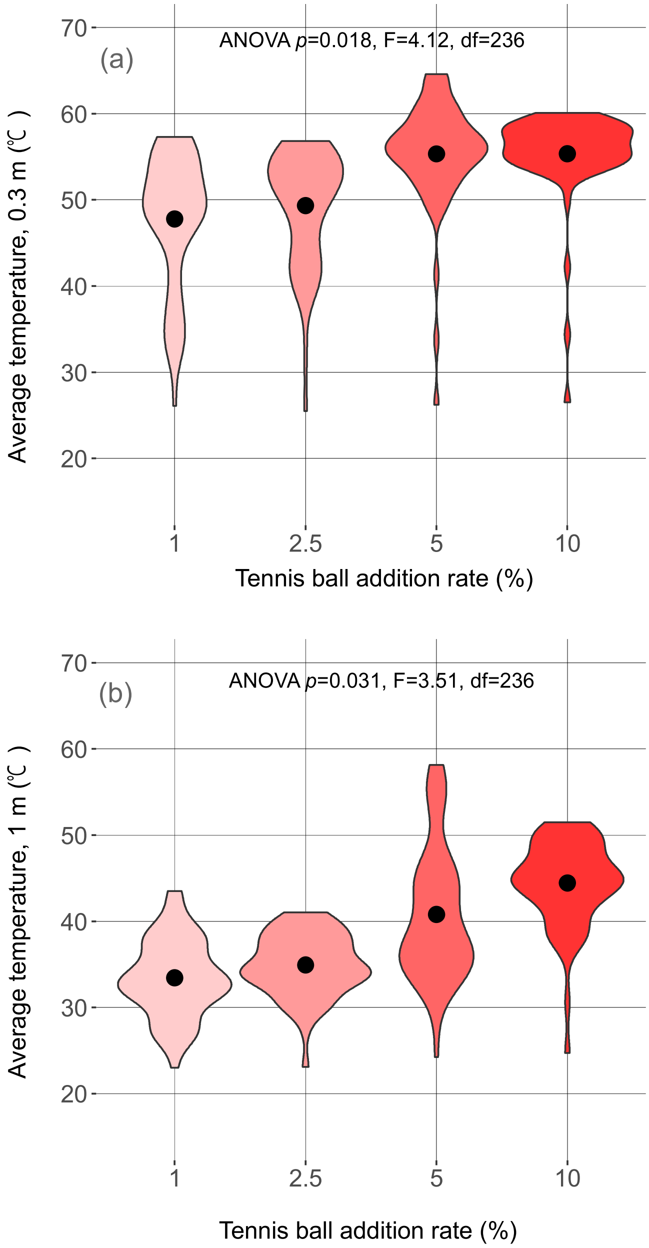

Fig. 2. Violin plots of average temperatures observed in Experiment B testing TB concentrations at two depths.

temperature conservation and aeration. A study investigating the use of bamboo spheres found that increasing additions up to 6 % (weight basis) aided in humification and degradation of food waste composting process, but that 9 % sphere addition led to lower process temperatures and water accumulation, indicating that the rate of bulking agent addition was excessive (Wu et al., 2022).

OM is an essential parameter indicating the maturity of compost (Zahra et al., 2023). The average OM loss observed for all compost piles was 27 %; this result is similar to that found by other authors using inert bulking agents in short-term composting (Jolanun and Towprayoon, 2010). However, the values are lower than those reported by García-Gomez et al. (2003), who reported OM losses of 55–68 % for composting OMW. In some cases, low OM losses may be due to the presence of relatively stable organic compounds usually consisting of lipids, polyphenols, lignin, cellulose, hemicellulose and pectin (Tortosa et al., 2012). In contrast to other authors (Bustamante et al., 2012; Pelegrín et al., 2018; Sáez-Tovar et al., 2021), the dynamics of OM loss did not seem to fit a first-order exponential model (data not shown), partly due to the short composting time of this experiment (90 days), which does not allow achievement of a constant loss rate observed in longer processes (150 days; data not shown). However, the use of inert structuring material on an industrial scale makes it possible to obtain a high-quality product in shorter timeframes, related to the variables discussed above.

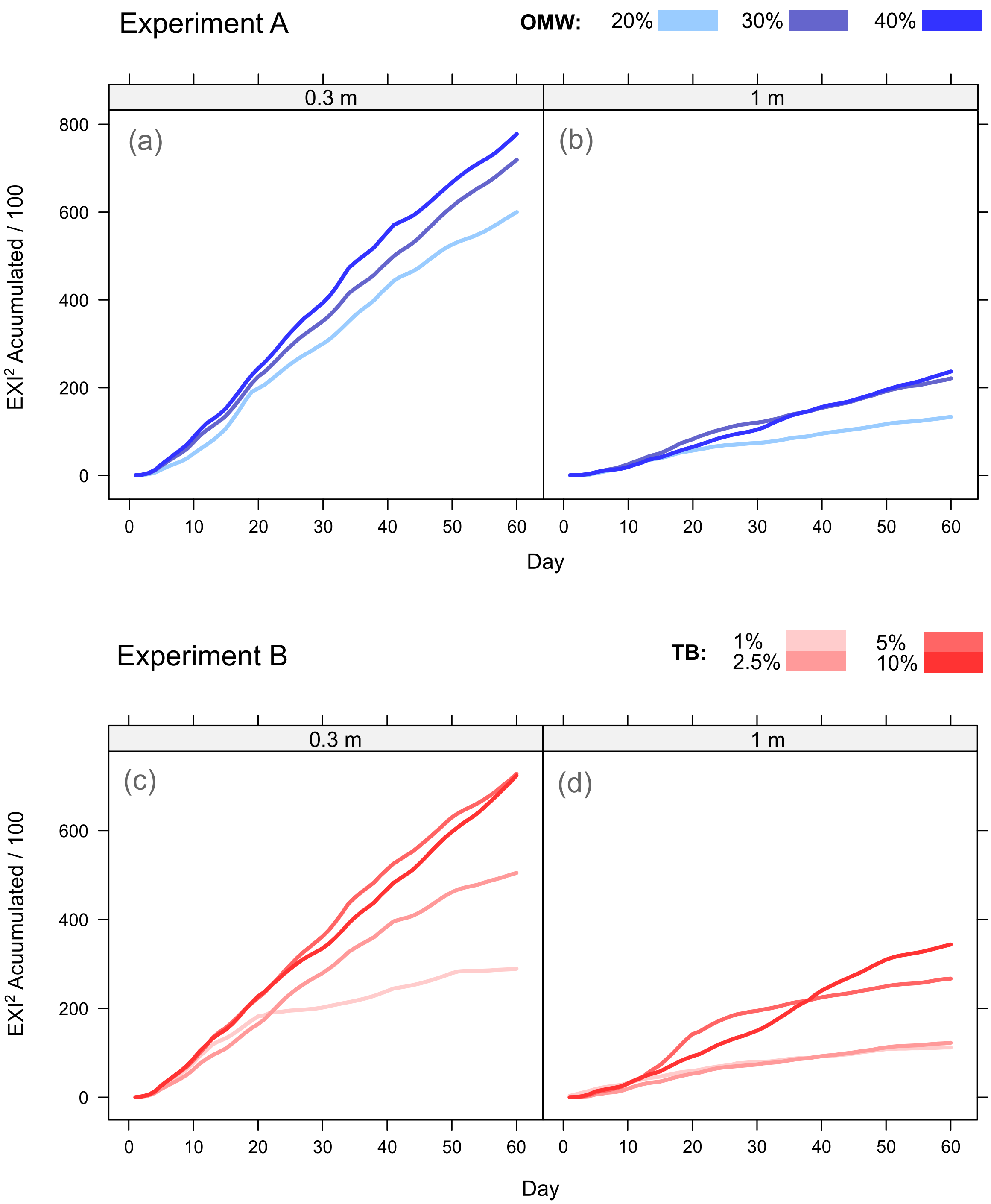

Fig. 3. Evolution of EXI^2 for each of the heaps with OMW (upper panel) and TB (lower panel) treatments evaluated.

3.3. Longitudinal monitoring of physico-chemical parameters in experiments A and B

The initial pH values in the composting piles ranged from 7.12 to 7.78, and pH decreased slightly in all piles at the initial stages of composting, whereas the piles with less OMW had the lowest values (Tables S3 and S4). pH is an important parameter affecting microbial activity during composting, and in general, a neutral pH (6.5–8.0) is recommended (Haug, 2018). During the bio-oxidation phase, all piles showed a decrease in EC, while during the maturation phase a decrease in soluble salts was observed for both experimental groups (OMW and TB). The increase in salinity that usually occurs in composting processes is directly related to the

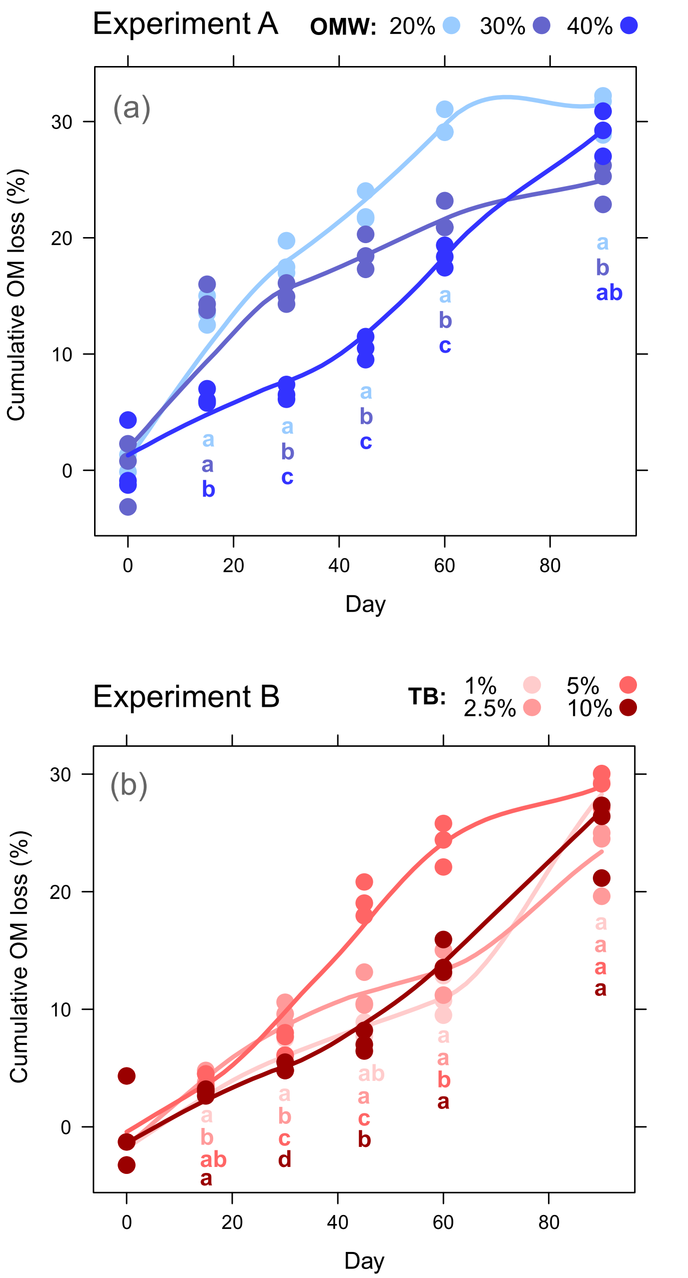

Fig. 4. Cumulative organic matter loss measured longitudinally in the experiments. Points represent semi-independent samples taken from the same compost pile (n=3). OM loss was evaluated based on OM contents and ash contents at each sampling (see methods) and added at each consecutive sampling for the calculation of cumulative OM loss. For each sampling date, different letters signify statistically significant differences as evaluated by Tukey's HSD.

mineralization of OM. High EC values in compost can cause problems with seed germination, and one solution can be mixing with other materials with low EC values (Álvarez-Alonso et al., 2024). Concerning nutrient contents, TN concentrations increased as a consequence of concentration with organic matter mineralization and mass loss (Bustamante et al., 2008). Otherwise, the concentrations of non-volatile elements increased as expected.

3.4. Characteristics of the final composts

The properties of the resulting composts from this experiment provide an idea of the degree of maturity, humification and stability of the composts, as well as their fertilizing capacity (Bernal et al., 2009). Observing final compost properties (Table 2), the pH values of

Table 2
Main characteristics of the mature composts (dry weight basis) grouped by Experiment (left-hand side Experiment A with OMW, and right-hand side Experiment B with TB).

	Experiment A				Experiment B				
	20 % OMW	30 % OMW	40 % OMW	*F-value / ANOVA*	1 % TB	2.5 % TB	5 % TB	10 % TB	*F-value / ANOVA*
pH	7.01 a	7.16 b	7.19 b	*14 ***	7.67 b	7.65 b	7.63 b	7.44 a	*16 ***
EC (dS m^{-1})	5.63c	5.27 b	5.10 a	*40 ****	4.20 b	4.20 b	4.23 b	3.73 a	*77 ****
OM (%)	63.72 b	64.75 b	62.22 a	*13 ***	64.36	64.36	62.59	63.76	*ns*
TOC (%)	33.63	33.27	31.53	*2.8 ns*	33.43	32.17	32.77	34	*ns*
TN (%)	2.38	2.16	2.12	*2.2 ns*	1.86	2.03	1.92	1.9	*ns*
TOC/TN	14.13 a	15.43 b	15.13 b	*8.1 **	18	15.9	17.07	17.97	*ns*
P (%)	2.77	2.6	2.61	*2.3 ns*	2.45	2.83	2.7	2.41	*ns*
K (g kg^{-1})	18.17	18.33	18.87	*0.8 ns*	18.73 a	20.97 b	21.10 b	21.10 b	*14 ***
PPH (mg kg^{-1})	558 a	616 b	664c	*349 ****	944 b	1004 d	990c	893 a	*45 ****
GI (%)	96	93	89	*0.5 ns*	85	94	88	92	*ns*
Ca (g kg^{-1})	5.17 b	4.60 a	5.17 b	*6.1 **	6.27c	5.20 a	5.90 b	5.90 b	*21 ****
Mg (g kg^{-1})	2.04 b	1.82 a	1.73 a	*11 ***	1.83	2.01	1.73	1.73	*ns*
S (g kg^{-1})	0.59 b	0.52 a	0.53 a	*6.5 **	0.53	0.58	0.57	0.57	*ns*
Na (g kg^{-1})	2.96	2.75	2.77	*3.1 ns*	2.61	3.08	2.91	2.91	*ns*
Fe (mg kg^{-1})	3700	3586	3574	*0.4 ns*	4719	4291	4157	4157	*ns*
Cu (mg kg^{-1})	185 b	133 a	133 a	*5.9 **	140	161	150	151	*ns*
Mn (mg kg^{-1})	697 b	622 ab	602 a	*5.2 **	625	696	662	662	*ns*
Zn (mg kg^{-1})	968 b	783 a	770 a	*16 ***	807 a	981 b	885 a	885 a	*13 ***

Values represent average values of the three semi-independent samples taken from each compost pile (a repeated-measures ANOVA was used). EC: electrical conductivity; OM: organic matter; TOC: total organic C; TN: total N; TOC/TN: total organic C/ total N; PPH: polyphenols; GI: germination index. *, **, ***: significant difference between treatments at $p < 0.01$, $p < 0.001$ and $p < 0.0001$, respectively. ns = no significant. Different letters within a column indicate significant differences between treatments ($p < 0.05$)

final composts were optimal, with pH values < 8 in the final stages (7.01–7.19 grouped by % OMW and 7.44–7.67 by % TB). These pH ranges would indicate that the compost is stable and should not impair plant growth based on this parameter alone (Bari Chowdhury et al., 2013; Table 2). In Experiment A, additions of more OMW slightly increased compost pH. This is likely due to the organic acids present in OMW. TB slightly reduced compost pH at 10 %, but not in other treatments. EC was also slightly reduced with increasing OMW concentrations, due to the reduction in the quantity of the pig slurry which has high ash contents (Table 2). TB also reduced EC in the 10 % treatment, which could be attributed to a lower mineralization of the organic matter in this treatment. An EC value > 4 dS m^{-1} is considered potentially inhibitory to plant growth (Luo et al., 2018) and additions of any product of these characteristics to soil should be limited for salt-sensitive plants, especially if EC exceeds > 5 dS m^{-1} (Albrecht, 2007). All composts obtained had values above 3.5 dS m^{-1}, owing to the high-nutrient feedstocks used (OMW and PSSF) which also have high ash contents. Minerals, which are abundant in OMW, increase EC, but since they are water soluble, they may be lost through leaching (Said-Pullicino et al., 2007; García-Randez et al., 2023).

TB addition did not have any significant effects on contents of organic matter, organic carbon, or N (Table 2). Specifically regarding N contents, this is relevant for nutrient conservation in composting, since increased aeration with TB addition could potentially cause greater N volatilization; however, it was seen that this was not the case, and the fertilizing potential of the material was not affected in this manner. Similarly, neither were C:N ratios impacted by TB. Optimum C:N is also very important parameter for successful composting and is a potential indicator of compost maturity (Akratos et al., 2017). As such, the compost heaps satisfied the thresholds established in literature for desired TOC:TN ratio (Cayuela et al., 2010).

Polyphenol contents (PPH, Table 2) were statistically different at different TB levels; however, these differences were of little consequence, whereas PPH contents were between 893 and 1004 mg kg^{-1}, and the differences between treatments were small. This is demonstrated by germination index data, whereas there were no significant differences between treatments for either experiment. According to the Spanish legislation (Real Decreto 503/2013), all the composts obtained had PPH values below the maximum concentration allowed (0.5 % or 5000 mg kg^{-1}). The highest values were found in composts made with higher % OMW, which is related to the high concentration of PPH in the raw material. None of the composts obtained showed a phytotoxic effect, with GI values between 85 % and 96 %, which are higher than those obtained by other authors for OMW composts (Altieri et al., 2010), whereas high GI values reflect the non-phytotoxic effect of mature composts. PPH contents decrease significantly during the thermophilic phase of composting due to their degradation (Bouhia et al., 2022).

Concerning the nonvolatile nutrient contents of the compost, the incorporation of increasing doses of OMW induced some changes, including lower contents of Mg, Cu, Mn and Zn, due to the lower concentrations of PSSF. According to the Spanish Fertilizer Law regarding the content of heavy metals in OMW composts, our composts are classified as "Type B" due to the presence of Cu and Zn in all of them. The values of Zn can be explained by its widespread use in pig farms to control diarrhea at weaning and to promote growth in piglets.

Table S5 shows the value (€ ton^{-1}) for each nutrient in the compost, based on the concentrations of these macronutrients in the final composts (Table 2). The composts obtained have relatively high economic values due to nutrient contents contained in manure, and agree with values reported by Ameziane et al. (2020) for composts produced with OMW and raw manure. Based on the current market prices, the P_2O_5 content is generally of the most valuable, ranging from 35 to 41 € ton $compost^{-1}$, followed by K_2O, and lastly N. The range of nutrient values between compost heaps was not large, ranging from 55 to 63 € ton compost^{-1}, which is higher than values reported in other studies (Pelegrín et al., 2018), and it must be taken into consideration that fertilizer prices have changed dramatically in recent years. These elevated values provide some impetus to economic returns from composting, supplementing or replacing fossil fuel-based or nonrenewable sources (Jara-Samaniego et al., 2017).

4. Conclusions

Industrial composting of OMW, PSSF and UPR was carried out in a large mechanical trench compost turner system in order to evaluate the effect of tennis balls as an inert structuring agent. Along the concentration gradient tested, it was found that 5 % (v/v) was the optimum mixture, as evidenced by improved exothermic parameters in this industrial-scale windrow composting process. Specifically, the use of TB increased operating temperatures of the compost piles and the mineralization of organic matter, effectively accelerating the process as compared to piles without artificial structuring agents. As such, this technology could reduce the number of turnings required as well as forced aeration (reducing energy costs). Furthermore, the results pointed towards an improved homogeneity and maintenance of the quality and characteristics of the final compost products. As such the study has shown that this type of management and reutilization of a relevant waste stream can produce a high-quality compost product with appropriate physico-chemical characteristics, ensuring maximum benefits for plant production. The study has shown that tennis balls may be used in the composting of organic wastes to reduce the need for bulking agents and improve the efficiency of industrial scale plants.

CRediT authorship contribution statement

Encarnación Martínez-Sabater: Validation, Resources, Investigation. **Javier Andreu-Rodriguez:** Validation, Resources, Methodology, Investigation. **José Antonio Saez Tobar:** Resources, Investigation, Formal analysis. **Maria Dolores Pérez-Murcia:** Visualization, Resources, Methodology, Data curation. **Juan Aviñó-Calero:** Writing – original draft, Validation, Resources, Methodology, Investigation. **Ernesto Santateresa:** Validation, Supervision, Resources, Methodology. **Luciano Orden:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Evan Alexander Netherton Marks:** Writing – original draft, Visualization, Formal analysis. **María Angeles Bustamante:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Raul Moral:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgments

This study forms part of the AGROALNEXT/2022/016 program and was supported by MCIN with funding from European Union NextGenerationEU (PRTR-C17.I1) and by Generalitat Valenciana. Grant EQC2018–004170-P was funded by MCIN/AEI/10.13039/501100011033 and by ERDF A way of making Europe. The study was also supported by a grant from the Generalitat Valenciana and the Agència Valenciana de la Innovació (INNTA3/2022/26).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2024.103799.

References

Akratos, C.S., Tekerlekopoulou, A.G., Vasiliadou, I.A., Vayenas, D.V., 2017. Cocomposting of olive mill waste for the production of soil amendments. in: Olive Mill Waste. Elsevier, pp. 161–182.

Albrecht, R., 2007. Co-composting of sewage treatment plant sludge and green waste: new methodology for monitoring organic matter transformations.

Alfano, G., Belli, C., Lustrato, G., Ranalli, G., 2008. Pile composting of two-phase centrifuged olive husk residues: technical solutions and quality of cured compost. Bioresour. Technol. 99, 4694–4701.

Altieri, R., Esposito, A., 2010. Evaluation of the fertilizing effect of olive mill waste compost in short-term crops. Int. Biodeterior. Biodegrad. 64, 124–128.

Álvarez-Alonso, C., Pérez-Murcia, M.D., Sánchez-Méndez, S., Martínez-Sabater, E., Irigoyen, I., López, M., Nogués, I., Paredes, C., Orden, L., García-Rández, A., Bustamante, M.Á., 2024. Municipal solid waste management in a decentralized composting scenario: assessment of the process reproducibility and quality of the obtained composts. Agronomy 14, 54.

Ameziane, H., Nounah, A., Khamar, M., Zouahri, A., 2020. Composting olive pomace: evolution of organic matter and compost quality. Agron. Res. 18.

Bari Chowdhury, Akm, Akratos, C.S., Vayenas, D.V., Pavlou, S., 2013. Olive mill waste composting: a review. Int. Biodeterior. Biodegrad. 85, 108–119.
Bernal, M.P., Alburquerque, J.A., Moral, R., 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. Bioresour. Technol. 100, 5444–5453. https://doi.org/10.1016/j.biortech.2008.11.027.
Bouhia, Y., Hafidi, M., Ouhdouch, Y., El Boukhari, M.E.M., El Fels, L., Zeroual, Y., Lyamlouli, K., 2022. Microbial community succession and organic pollutants removal during olive mill waste sludge and green waste co-composting. Front. Microbiol. 12, 814553.
Bustamante, M.A., Alburquerque, J.A., Restrepo, A.P., De la Fuente, C., Paredes, C., Moral, R., Bernal, M.P., 2012. Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. Biomass-.-. Bioenergy 43, 26–35.
Bustamante, M.A., Paredes, C., Marhuenda-Egea, F.C., Pérez-Espinosa, A., Bernal, M.P., Moral, R., 2008. Co-composting of distillery wastes with animal manures: carbon and nitrogen transformations in the evaluation of compost stability. Chemosphere 72, 551–557.
Bustamante, M.A., Paredes, C., Moral, R., Moreno-Caselles, J., Perez-Murcia, M.D., Perez-Espinosa, A., Bernal, M.P., 2007. Cocomposting of distillery and winery wastes with sewage sludge. Water Sci. Technol. 56, 187–192.
Casado, M., Sanz, C., Cáceres, R., Rufat, J., Vallverdú, X., Casadesús, J., Matamoros, V., Piña, B., 2023. Evolution of microbiome composition, antibiotic resistance gene loads, and nitrification during the on-farm composting of the solid fraction of pig slurry using two bulking agents. Environ. Res. 245, 117944.
Cayuela, M.L., Sánchez-Monedero, M.A., Roig, A., 2010. Two-phase olive mill waste composting: enhancement of the composting rate and compost quality by grape stalks addition. Biodegradation 21, 465–473.
Cheng, P., Jiang, L., Shan, R., Fang, Z., Ma, N., Deng, L., Lu, Y., Tan, X., Shen, W., Liu, R., 2022. An alternative to vermiculite: composting on tropical islands using coral sand to enhance nitrogen retention during ventilation. Fermentation 8, 552.
van der Wurff, A.W., Fuchs, J.G., Raviv, M., Termorshuizen, A., 2016. Handbook for composting and compost use in organic horticulture. BioGreenhouse COST Action FA 1105. https://doi.org/10.18174/375218.
Droussi, Z., D`Orazio, V., Provenzano, M.R., Hafidi, M., Ouatmane, A., 2009. Study of the biodegradation and transformation of olive mill residues during composting using FTIR spectroscopy and differential scanning calorimetry. J. Hazard. Mater. 164, 1281–1285.
Ekinci, K., Tosun, İ., Kumbul, B.S., Şevik, F., Sülük, K., Bıtrak, N.B., 2021. Effect of initial C/N ratio on composting of two-phase olive mill pomace, dairy manure, and straw. Environ. Prog. Sustain. Energy 40, e13517. https://doi.org/10.1002/ep.13517.
El Fels, L., Zamama, M., El Asli, A., Hafidi, M., 2014. Assessment of biotransformation of organic matter during co-composting of sewage sludge-lignocelullosic waste by chemical, FTIR analyses, and phytotoxicity tests. Int. Biodeterior. Biodegrad. 87, 128–137. https://doi.org/10.1016/j.ibiod.2013.09.024.
European Commission, 2022. Ensuring availability and affordability of fertilisers. COM 2022, 590 final/2.
García-Gómez, A., Roig, A., Bernal, M.P., 2003. Composting of the solid fraction of olive mill wastewater with olive leaves: organic matter degradation and biological activity. Bioresour. Technol. 86, 59–64.
García-Randez, A., Marks, E.A.N., Pérez-Murcia, M.D., Orden, L., Andreu-Rodriguez, J., Martínez Sabater, E., Cháfer, M.T., Moral, R., 2023. Is the direct soil application of two-phase olive mill waste (alperujo) compatible with soil quality protection? Agronomy 13. https://doi.org/10.3390/agronomy13102585.
Gea, T., Barrena, R., Artola, A., Sánchez, A., 2007. Optimal bulking agent particle size and usage for heat retention and disinfection in domestic wastewater sludge composting. Waste Manag 27, 1108–1116. https://doi.org/10.1016/j.wasman.2006.07.005.
Hachicha, R., Hachicha, S., Trabelsi, I., Woodward, S., Mechichi, T., 2009. Evolution of the fatty fraction during co-composting of olive oil industry wastes with animal manure: maturity assessment of the end product. Chemosphere 75, 1382–1386.
Hamid, N.J.A., Abdul Kadir, A., Amira Sarani, N., Ikhmal Haqeem Hassan, M., Nabila Huda Hashar, N., Amiza Hashim, A., Fatin Nabila Hissham, N., Qian Yi, L., Nuraiti Tengku Izhar, T., 2020. Overview on use of zeolites as bulking agent to optimize organic waste composting process. IOP Conf. Ser. Earth Environ. Sci. 616, 12050. https://doi.org/10.1088/1755-1315/616/1/012050.
Haug, R.T., 2018. The practical handbook of compost engineering. Routledge.
Jara-Samaniego, J., Pérez-Murcia, M.D., Bustamante, M.A., Pérez-Espinosa, A., Paredes, C., López, M., López-Lluch, D.B., Gavilanes-Terán, I., Moral, R., 2017. Composting as sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: suitability of the obtained composts for seedling production. J. Clean. Prod. 141, 1349–1358. https://doi.org/10.1016/j.jclepro.2016.09.178.
Jolanun, B., Towprayoon, S., 2010. Novel bulking agent from clay residue for food waste composting. Bioresour. Technol. 101, 4484–4490.
Luo, Y., Liang, J., Zeng, G., Chen, M., Mo, D., Li, G., Zhang, D., 2018. Seed germination test for toxicity evaluation of compost: Its roles, problems and prospects. Waste Manag 71, 109–114.
Marks, E.A.N., Kinigopoulou, V., Akrout, H., Azzaz, A.A., Doulgeris, C., Jellali, S., Rad, C., Sánchez Zulueta, P., Tziritis, E., El-Bassi, L., 2020. Potential for production of biochar-based fertilizers from olive mill waste in Mediterranean Basin countries: an initial assessment for Spain, Tunisia, and Greece. Sustainability 12, 6081.
Martínez-Sabater, E., Pérez-Murcia, M.D., Andreu-Rodríguez, F.J., Orden, L., Agulló, E., Sáez-Tovar, J., Martínez-Tome, J., Bustamante, M.Á., Moral, R., 2022. Enhancing sustainability in intensive dill cropping: comparative effects of biobased fertilizers vs. Inorganic commodities on greenhouse gas emissions, crop yield, and soil properties. Agronomy 12, 2124.
McGuckin, R.L., Eiteman, M.A., Das, K., 1999. Pressure drop through raw food waste compost containing synthetic bulking agents. J. Agric. Eng. Res. 72, 375–384.
Paredes, C., Medina, E., Moral, R., Pérez-Murcia, M., Moreno-Caselles, J., Ángeles, Bustamante, M., Cecilia, J., 2009. Caracterización de las diferentes fracciones de materia orgánica del sustrato agotado de hongos. Comun. En. Cienc. Del. Suelo Y. álisis Plantas 40, 150–161.
Paredes, C., Roig, A., Bernal, M.P., Sánchez-Monedero, M.A., Cegarra, J., 2000. Evolution of organic matter and nitrogen during co-composting of olive mill wastewater with solid organic wastes. Biol. Fertil. Soils 32, 222–227.
Pelegrín, M., Sáez, J.A., Andreu-Rodríguez, J., Pérez-Murcia, M.D., Martínez-Sabater, E., Marhuenda-Egea, F.C., Pérez-Espinosa, A., Bustamante, M.A., Agulló, E., Vico, A., others, 2018. Composting of invasive species Arundo donax with sewage and agri-food sludge: agronomic, economic and environmental aspect. Waste Manag 78, 730–740.
R Core Team, 2023. R: A language and environment for statistical computing.
Real Decreto 503/2013, 2013. BOE-A-2013-7540.
Real Decreto 999/2017, 2017. BOE-A-2017-14332.
Regni, L., Gigliotti, G., Nasini, L., Agrafioti, E., Galanakis, C.M., Proietti, P., 2017. Reuse of olive mill waste as soil amendment. in: Olive Mill Waste. Elsevier, pp. 97–117.
Sáez-Tovar, J.A., Pérez-Murcia, M.D., Vico, A., Pelegrín, M., Pérez-Espinosa, A., Bustamante, M.A., Andreu-Rodríguez, J., Martínez-Sabater, E., Marhuenda-Egea, F.C., 2021. Olive mill wastewater-evaporation ponds long term stored: integrated assessment of in situ bioremediation strategies based on composting and vermicomposting. Sci. Total Environ. 775, 145731.
Said-Pullicino, D., Erriquens, F.G., Gigliotti, G., 2007. Changes in the chemical characteristics of water-extractable organic matter during composting and their influence on compost stability and maturity. Bioresour. Technol. 98, 1822–1831.
Santos, A., Fangueiro, D., Moral, R., Bernal, M.P., 2018. Composts produced from pig slurry solids: nutrient efficiency and N-leaching risks in amended soils. Front. Sustain. Food Syst. 2 https://doi.org/10.3389/fsufs.2018.00008.
Tortosa, G., Alburquerque, J.A., Ait-Baddi, G., Cegarra, J., 2012. The production of commercial organic amendments and fertilisers by composting of two-phase olive mill waste ("alperujo"). J. Clean. Prod. 26, 48–55.
Tröster, M.F., 2023. Assessing the value of organic fetilizers from the perspective of EU farmers. Agriculture 13, 1057.
Vico, A., Pérez-Murcia, M.D., Bustamante, M.A., Agulló, E., Marhuenda-Egea, F.C., Sáez, J.A., Paredes, C., Pérez-Espinosa, A., Moral, R., 2018. Valorization of date palm (Phoenix dactylifera L.) pruning biomass by co-composting with urban and agri-food sludge. J. Environ. Manag. 226, 408–415.
Wang, X., Chen, T., Zheng, G., 2020. Perlite as the partial substitute for organic bulking agent during sewage sludge composting. Environ. Geochem. Health 42, 1517–1529.
Wang, K., Mao, H., Li, X., 2018. Functional characteristics and influence factors of microbial community in sewage sludge composting with inorganic bulking agent. Bioresour. Technol. 249, 527–535. https://doi.org/10.1016/j.biortech.2017.10.034.

Wang, X., Zheng, G., Chen, T., Nie, E., Wang, Y., Shi, X., Liu, J., 2019. Application of ceramsite and activated alumina balls as recyclable bulking agents for sludge composting. Chemosphere 218, 42–51.

Wu, Xiaoyan, Wang, J., Yu, Z., Amanze, C., Shen, L., Wu, Xueling, Li, J., Yu, R., Liu, Y., Zeng, W., 2022. Impact of bamboo sphere amendment on composting performance and microbial community succession in food waste composting. J. Environ. Manag. 303, 114144 https://doi.org/10.1016/j.jenvman.2021.114144.

Zahra, K., Farhan, M., Kanwal, A., Sharif, F., Hayyat, M.U., Shahzad, L., Ghafoor, G.Z., 2023. Investigating the role of bulking agents in compost maturity. Sci. Rep. 13, 16003.

Zhou, H.-B., Ma, C., Gao, D., Chen, T.-B., Zheng, G.-D., Chen, J., Pan, T.-H., 2014. Application of a recyclable plastic bulking agent for sewage sludge composting. Bioresour. Technol. 152, 329–336.