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Management of Green Waste Streams from Different Origins: Assessment of Different Composting Scenarios

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Abstract: The organic wastes of plant origin and, in particular, those coming from sources related to tourism activities, such as those generated from golf courses and touristic coasts, constitute an increasing concern due to the rise in their production and their unsuitable management. Thus, this work aimed to assess the use of different composting strategies to manage these specific green wastes, such as grass clippings and pruning waste from a golf course and marine plant debris, mainly from posidonia (*Posidonia oceanica* L.). To this end, two composting scenarios were established: the first only considered green wastes in the composition of the composting mixtures, and the second used sewage sludge as a co-composting agent. The temperature of the piles was monitored, and physicochemical and chemical parameters were also studied throughout the process. The results obtained showed that composting is a feasible method to manage and recycle this type of green waste, obtaining end products with suitable physicochemical and chemical characteristics. However, proportions of sea plant wastes in the composting mixture higher than 30% can compromise the fertilizing value of the final compost. Moreover, the use of an additional co-composting agent (sewage sludge) improved the characteristics of the end products obtained, provided that this co-composting agent had suitable initial characteristics.

Keywords: compost quality; golf course; grass clippings; marine plant wastes; pruning waste; sewage sludge

1. Introduction

Different green waste streams are produced in urban and periurban environments as a result of maintenance activities of public green areas, such as parks, gardens, and avenues, and street trees, or in private areas of increasing use, such as golf courses. In particular, the importance of golf courses has grown in recent years, especially in established areas associated with tourism activities, such as coastal areas. As an example, in 2018, there were 38,864 golf courses in 209 of the 294 countries of the world, which represents a worldwide diffusion rate of 84% of this sport. Most global golf course supplies are located in the USA (43%) and Europe (23%) [1]. At golf facilities (with one or more golf courses), turfgrass maintenance is reliant on repeated mowing, which together with the maintenance activities of the surrounding green area of the facility, generates large amounts of green wastes, mainly grass clippings and pruning waste, the production and typology of which depend on the season [2]. In addition, in coastal areas, wastes from different seagrasses and seaweeds can represent an environmental problem [3]. In particular, in the Mediterranean Basin, wastes from the marine plant posidonia (*Posidonia oceanica* (L.) Delile), the principal endemic Mediterranean seagrass, can represent an important environmental, economic, social, and hygienic concern in the coastal areas where they are deposited [4]. Posidonia wastes are mainly composed of fibers (residues of rhizomes and leaves decomposed), leaf litter, and balls of fibrous material (aegagropili) [4]. Thus, the management of all these types of green wastes is usually difficult and expensive, mainly due to their collection and transportation [5–7]. Moreover, waste streams from golf courses, especially from coastal areas, are often managed using unsustainable environmental options that imply an important waste of resources, such as incineration or landfill depositing [6,8]. Thus, these management options present a significant loss of nutrients, organic matter, and energy and can also directly and indirectly impact the environment, such as the emission of greenhouse gases. Therefore, composting can constitute a more sustainable strategy for the management and recycling of these waste streams, since it is an environmentally friendly and economically feasible technology not only for the management of organic wastes but also to obtain a stabilized, mature, deodorized, and sanitized product, free of pathogens and weeds and rich in humic substances, that is easy to store and is marketable as an organic amendment or fertilizer [9,10]. However, one of the main constraints associated with the composting of these wastes is their periodic production and their qualitative heterogeneity that varies depending on the season [5], as well as high salinity in the case of posidonia wastes [4]. However, this type of organic waste usually presents the advantage of having low concentrations of micropollutants, which allow obtaining composts that verify the quality requirements for use even in more restrictive agricultural sectors, such as organic farming [9]. Different studies have been conducted concerning the composting of green wastes, such as yard trimmings [6], grass clippings, palm and different tree prunings [5,11], and posidonia wastes [4,8]. However, little is known about the composting process development and quality of composts obtained when traditional green wastes are mixed with marine plant wastes. Therefore, this work aims to study the feasibility of composting to manage and recycle sea plant wastes and green wastes from a golf facility, as well as to evaluate the quality of the end products obtained, considering two different composting scenarios: (i) Experiment 1: only using green wastes; (ii) Experiment 2: mixing green wastes and a source of nitrogen (sewage sludge).

2. Materials and Methods

2.1. Composting Experiments

In order to optimize the process development and the characteristics of the final composts obtained, two composting experiments were conducted: (i) Experiment 1: optimization of the composting process of green wastes from a golf facility with sea plant wastes; (ii) Experiment 2: optimization of the co-composting process of the previous green wastes with a source of microorganisms and nitrogen (sewage sludge). The initial wastes used in the different composting scenarios were sea plant wastes (SPW), pruning wastes with grass clippings (PGW), and sewage sludge. SPW mainly constituted leaf litter, fibers, and balls of fibrous material of two Mediterranean seagrasses, mainly from posidonia (*Posidonia oceanica* (L.)) and, in a lesser proportion, from *Cymodocea nodosa*, another marine phanerogam endemic of the Mediterranean Sea. SPW was collected from two different sites of the Alicante coast (Valencian Community, Spain) (SPW1 and SPW3 from the Torrevieja coast; SPW2 and SPW4 from the Orihuela coast), avoiding the extraction of inorganic materials together with the plant wastes. PGW came from a golf facility located at Monforte del Cid (Alicante, Spain), and it was composed of grass clippings and mulberry (*Morus alba* L.) pruning, generated from mowing of the golf courses and maintenance activities of the facility, respectively. Sewage sludge (SS) came from a municipal wastewater treatment plant located at Orihuela (Alicante, Spain) after wastewater treatment by an aerobic biological process, stabilization by anaerobic digestion, and later dehydration with band filters. The principal characteristics of the initial wastes used in the composting heaps are summarized in Table 1. All sea plant wastes showed an alkaline pH and, in general, high electrical conductivity values, low contents of organic matter, total nitrogen, and phosphorous, and high contents of potassium, characteristics also reported by Cocozza et al. [4]. The pruning wastes also showed similar physicochemical properties to sea plant wastes, but the contents of organic matter were higher in these wastes, also having greater concentrations of the main macronutrients (NPK). On the other hand, sewage sludge showed an acidic pH, lower salinity than most green wastes considered, and the highest concentrations of N and P, with values within the usual ranges for sewage sludge samples, as reported by Sáez et al. [12].

Table 1. Main characteristics (dry weight basis) of the initial materials used in the co-composting scenarios.

Parameter	SPW1	SPW2	SPW3	SPW4	PGW	SS
Dry matter (%)	22.3 ± 1.3	38.2 ± 2.5	49.4 ± 4.5	30.3 ± 2.1	79.3 ± 0.2	18.9 ± 0.3
BD (kg L^{-1})	0.199 ± 0.020	0.404 ± 0.038	0.262 ± 0.001	0.221 ± 0.018	0.070 ± 0.001	0.889 ± 0.028
pH	8.5 ± 0.0	8.6 ± 0.0	8.6 ± 0.1	8.2 ± 0.1	8.2 ± 0.0	6.6 ± 0.1
EC (dS m^{-1})	10.3 ± 1.4	7.21 ± 0.71	2.37 ± 0.26	3.16 ± 0.01	3.30 ± 0.05	2.89 ± 0.02
OM (%)	14.3 ± 1.6	18.5 ± 0.6	11.2 ± 1.0	10.0 ± 1.1	64.9 ± 0.6	74.2 ± 0.0
TN (%)	0.33 ± 0.03	0.31 ± 0.00	0.30 ± 0.05	0.20 ± 0.0	1.69 ± 0.03	6.28 ± 0.15
TOC (%)	10.9 ± 0.5	11.3 ± 0.1	11.0 ± 0.0	10.7 ± 1.2	35.4 ± 4.8	41.3 ± 0.6
TOC/TN ratio	33.4 ± 5.0	36.9 ± 0.4	36.8 ± 6.0	52.1 ± 3.1	20.8 ± 2.5	6.57 ± 0.26
P (g kg^{-1})	0.29 ± 0.00	0.09 ± 0.00	0.51 ± 0.14	0.14 ± 0.0	4.36 ± 0.07	18.7 ± 0.6
K (g kg^{-1})	2.67 ± 0.22	1.54 ± 0.13	12.2 ± 0.4	13.5 ± 0.0	22.9 ± 1.4	2.62 ± 0.06
Na (g kg^{-1})	21.0 ± 0.46	23.8 ± 5.5	6.36 ± 0.10	10.8 ± 0.7	14.2 ± 0.35	3.01 ± 0.34

SPW: sea plant waste (SPW1 and SPW3 from the Torrevieja coast; SPW2 and SPW4 from the Orihuela coast); PGW: pruning waste with grass clippings; SS: sewage sludge. BD: bulk density; EC: electrical conductivity; OM: organic matter; TN: total nitrogen; TOC: total organic carbon. Data values reported as mean value ± standard error.

A total of five composting heaps (Table 2) were developed at the composting pilot plant (CompoLab) of the EPSO campus of the Miguel Hernández University, located in Orihuela (Alicante, Spain). All green wastes were homogenized and crushed to a <4 cm particle size before being used in the elaboration of the composting heaps. All composting mixtures were prepared as trapezoidal piles (5 m^3 each) and mechanically turned every week to favor the homogenization and the aeration of the heaps. Throughout the composting process, the temperature was monitored using various probes connected to data loggers (HOBO-Data Logger©). The moisture of the composting mixtures was kept in values no lower than 40% by incorporating water in each whirl of the piles. The end of the bio-oxidative phase was reached when the temperature in the composting heaps was close to the ambient temperature and did not increase after a whirl. After that, the composting piles were left to mature for around a month. During the composting process, four samples (beginning of the process, thermophilic stage, end of bio-oxidative stage, and end of maturity) were collected in all mixtures, using the methodology described by Bustamante et al. [13]. Each integrated sample was subdivided into two fractions: the first was dried at 105 °C for 24 h for the moisture determination, whereas the second fraction was dried at 45 °C, ground to a <0.5 mm particle size with an agate ball mill (Fritsch Pulverisette 3 SPARTAN), and stored for subsequent analyses.

Table 2. Proportions on a fresh weight basis (dry weight basis between brackets) of the raw materials used in the composting piles.

Composting Pile	SPW1	SPW2	SPW3	SPW4	PGW	SS
1	58.9 (28.8)				41.1 (71.2)	
2		75.1 (70.2)			24.9 (29.8)	
3					100 (100)	
4			22.4 (50.4)		5.6 (12.7)	72.0 (36.9)
5				14.6 (17.6])	6.2 (21.0)	79.2 (61.4)

SPW: sea plant waste (SPW1 and SPW3 from the Torrevieja coast; SPW2 and SPW4 from the Orihuela coast); PGW: pruning waste with grass clippings; SS: sewage sludge.

2.2. Analytical Methods

In all samples (initial wastes and composting samples), all determinations were carried out according to the methods detailed by Bustamante et al. [13]. Briefly, pH and electrical conductivity (EC) were determined in a 1:10 water/soluble extract ratio (*w*/*v*). Total organic matter (OM) was measured by mass loss on ignition for 24 h at 430 °C [14]. Total organic carbon (TOC) and total nitrogen (TN) were determined with an automatic elemental microanalyzer (EuroVector Elemental Analyser, Milano, Italy), whereas cation exchange capacity (CEC) was determined using $BaCl_2$-triethanolamine [15]. After acid digestion ($HNO_3/HClO_4$, 1:4 *v*/*v*) of the sample, P was colorimetrically measured as molybdovanadate phosphoric acid, while Na and K were measured using flame photometry (Jenway PFP7 Flame Photometer). Potential compost phytotoxicity was assessed with the germination index (GI) [16]. All analyses were conducted in triplicate.

2.3. Statistical Analyses

The quadratic exothermic index (EXI^2), determined as the quadratic sum of the daily difference between the temperature in the heap and that of the ambient during the bio-oxidative phase of composting [10], was used together with temperature to study the thermal profile of the composting heaps. Data were statistically analyzed using ANOVA followed by the Tukey B test ($p < 0.05$). Normality and homogeneity of the variances were analyzed with the Shapiro–Wilk and Levene tests, respectively, before ANOVA. The IBM SPSS Statistics v. 27.0 software package was used to conduct all statistical analyses.

3. Results and Discussion

3.1. Thermal Development in the Composting Scenarios

In both experiments, the temperature in the composting heaps quickly increased to thermophilic values (>40 °C), even reaching values higher than 60 °C in the first five days of the process (Figure 1). This thermal behavior has also been found in previous experiments in the composting of green wastes of different origins, especially yard trimmings [11,17,18] and agricultural wastes [19], as well as in studies of co-composting of green wastes with sewage sludge [10,20–22].

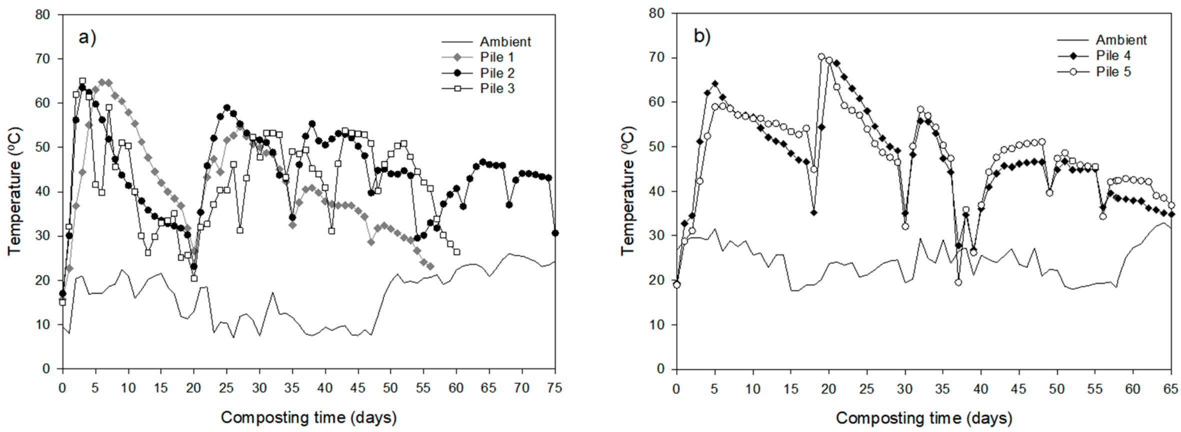

Figure 1. (**a**) Temperature evolution of the composting piles from Experiment 1 (Piles 1, 2, and 3, only constituting green wastes); (**b**) temperature evolution of the composting piles from Experiment 2 (Piles 4 and 5, constituting green wastes and sewage sludge).

In all mixtures, the duration of the thermophilic stage with temperature values $\geq$ 55 °C exceeded the period of two weeks established to favor the removal of non-spore-forming pathogens, assuring the suitable sanitization of the biomasses [23,24]. However, the duration and development of the bio-oxidative stage of composting were different in the piles of Experiment 1 (Piles 1, 2, and 3, only containing green wastes) and Experiment 2 (Piles 4 and 5, composed of green wastes and sewage sludge). This fact was not only reflected in the temperature evolution (Figure 1), which had a more stable profile in Piles 4 and 5, without interruptions at different times, than in those of Experiment 1 (Piles 1, 2, and 3) but also in the values of the parameters associated with the thermal behavior of the mixtures (Table 3). The mixtures of Experiment 2 reached the maximum temperature values during the process (Table 3), and in general, the duration of the bio-oxidative phase of composting was higher in these piles than in those of Experiment 1. The incorporation of sewage sludge as a source of nitrogen and microorganisms could have enhanced the development of the process, as it has been reported in different studies of co-composting of green wastes with sludge [10,25]. However, Pile 2 was the exception, since this mixture had the most intensive and longest bio-oxidative phase, also reflected in the parameter EXI^2 index, which showed the highest value, indicative of a more intensive process.

Table 3. Parameters associated with the exothermic profile of the co-composting processes.

	EXI^2 Index (°C^2)	Duration Bio-Oxidative Phase	Days with Temperature > 50 °C	Maximum Temperature Reached (°C)	Ratio EXI^2/Days in Bio-Oxidative Phase
Pile 1	211,169	56	29	65.1	3771
Pile 2	373,877	75	45	63.6	4985
Pile 3	259,973	60	26	65.1	4333
Pile 4	245,673	65	41	69.6	3780
Pile 5	268,368	65	38	70.7	4129

EXI^2: quadratic exothermic index (quadratic sum of the daily difference between the average temperature of the pile and the ambient temperature). Experiment 1: Piles 1, 2, and 3, constituting only green wastes; Experiment 2: Piles 4 and 5, constituting green wastes and sewage sludge.

3.2. Composting Process: Evolution of Physicochemical and Chemical Parameters

The evolution of the physicochemical and chemical parameters in the composting heaps corresponding to Experiments 1 and 2 was clearly different (Table 4). In the piles only composed of green wastes (Piles 1, 2, and 3), pH values tended to increase slightly during the first phases of the process, probably due to organic acid decomposition or ammonia release [11], showing a decrease and/or stabilization in the maturity phase. This behavior has also been reported in previous works composting green wastes [11,17,19]. On the contrary, the piles of green wastes and sewage sludge (Piles 4 and 5) showed a slight decrease, as also observed by Vico et al. [10] in a study of co-composting of palm wastes with different types of sludge. The final pH values of Piles 4 and 5 were within the suitable range for the use of compost in agriculture (pH = 6.0–8.5) [26], whereas the piles without sewage sludge (Piles 1, 2, and 3) had final pH values slightly higher than this interval, with values ranging from 8.6 to 9. Concerning the electrical conductivity (EC), the piles of Experiment 1 (Piles 1, 2, and 3) had the highest initial EC values, especially the mixtures containing marine plant debris, due to the higher salinity levels of this type of waste [4]. In these piles, this parameter did not have a clear pattern, though the general trend showed a decrease in relation to the initial values. This behavior was also reported by Zhang and Sun [18] in a study of composting of green wastes. However, in the piles of Experiment 2 (Piles 4 and 5), this parameter clearly increased during the process, mainly due to the release of inorganic compounds after organic matter mineralization [27], showing higher EC values at the maturity stage than the piles composed only of green wastes.

Regarding the solid organic matter fraction, OM and TOC decreased in all mixtures, indicating organic matter mineralization during composting [11]. The greatest reduction was observed in Pile 3, which showed the most intense and longest bio-oxidative stage, coinciding with the highest value observed for the EXI^2 index [10]. This composting mixture also showed the highest concentrations of both parameters at the initial phase of composting, probably due to the predominance of lignocellulosic wastes, resistant to biodegradation, which increased the length of the process [28]. In general, the patterns of TN in all heaps were opposite to those observed for TOC, increasing throughout the process, probably due to the concentration effect as a consequence of the mass reduction of the mixture [11]. The highest initial and final concentrations of TN were found in Piles 4 and 5, due to the presence of sewage sludge in these mixtures, and in Pile 3, probably due to the incorporation of marine plant debris in Piles 1 and 2, which produced a dilution effect as a consequence of the low NT contents usually found in this type of waste [3,4]. On the other hand, the TOC/TN ratio decreased in all mixtures during the process, observing a substantial decrease in the mixtures from Experiment 1 (Piles 1, 2, and 3), which also showed the highest initial TOC/TN, which is usually prevalent in composting mixtures only composed of green wastes [27]. This parameter is considered a maturity index, establishing limit values < 20 indicative of compost maturity [9]. However, as reported by Vico et al. [10] in a study of co-composting of palm wastes with sludge, initial values of TOC/TN lower, such as in Piles 4 and 5, or final values higher than this limit value, may indicate that this ratio is not suitable to be used as an absolute maturity index, though its evolution throughout composting can prove OM degradation.

Table 4. Physicochemical and chemical parameters in the initial and final composting samples (data expressed on a dry weight basis).

Composting Phase	pH	EC (dS/m)	OM (%)	TOC (%)	TN (%)	TOC/TN
Pile 1: 58.9% SPW1 + 41.1% PGW						
IS	8.4 ± 0.1	3.72 ± 0.63	28.1 ± 7.8	15.4 ± 3.8	0.31 ± 0.10	50.1 ± 3.5
TS	9.0 ± 0.1	3.59 ± 0.94	18.7 ± 1.7	11.4 ± 0.1	0.56 ± 0.19	21.5 ± 7.1
EBS	9.2 ± 0.0	2.29 ± 0.19	20.3 ± 5.9	13.0 ± 0.6	0.51 ± 0.14	25.5 ± 1.9
MS	9.0 ± 0.0	3.18 ± 0.32	18.5 ± 3.1	12.6 ± 0.4	0.60 ± 0.00	21.0 ± 0.6
LSD	*0.1*	*0.92*	*8.1*	*3.9*	*0.26*	*11.4*
Pile 2: 75.1% SPW2 + 24.9% PGW						
IS	8.2 ± 0.0	3.61 ± 0.16	42.5 ± 5.0	19.7 ± 1.0	0.53 ± 0.08	37.3 ± 3.6
TS	9.0 ± 0.0	3.22 ± 0.27	32.9 ± 3.6	20.2 ± 4.5	0.68 ± 0.00	29.7 ± 6.8
EBS	9.2 ± 0.0	2.96 ± 0.36	25.7 ± 3.1	14.2 ± 7.3	0.54 ± 0.39	26.7 ± 0.4
MS	8.8 ± 0.2	3.65 ± 0.40	24.5 ± 1.8	17.0 ± 1.2	0.91 ± 0.00	18.7 ± 1.4
LSD	*0.2*	*0.47*	*5.5*	*0.5*	*0.15*	*10.7*
Pile 3: 100% PGW						
IS	8.2 ± 0.0	3.30 ± 0.05	64.9 ± 0.6	35.4 ± 4.8	1.69 ± 0.03	20.8 ± 2.5
TS	8.9 ± 0.0	2.73 ± 0.01	53.5 ± 0.1	27.7 ± 1.5	1.89 ± 0.05	14.7 ± 1.2
EBS	8.6 ± 0.0	3.30 ± 0.05	54.1 ± 0.2	27.8 ± 0.2	1.73 ± 0.21	16.2 ± 2.0
MS	8.6 ± 0.3	3.27 ± 0.00	43.1 ± 1.4	25.7 ± 0.6	1.96 ± 0.16	13.1 ± 0.7
LSD	*0.1*	*0.07*	*1.5*	*4.7*	*0.25*	*3.2*
Pile 4: 22.4% SPW3 + 5.6% PGW + 72.0% SS						
IS	7.6 ± 0.0	2.72 ± 0.10	32.7 ± 4.7	19.3 ± 1.0	1.29 ± 0.17	15.1 ± 2.8
TS	7.3 ± 0.0	3.90 ± 0.04	32.8 ± 2.0	19.3 ± 0.7	1.56 ± 0.06	12.3 ± 1.2
EBS	7.4 ± 0.0	3.72 ± 0.08	31.4 ± 3.6	18.0 ± 1.1	1.36 ± 0.10	13.2 ± 0.2
MS	7.3 ± 0.0	3.71 ± 0.02	25.3 ± 2.3	18.7 ± 0.9	1.56 ± 0.16	12.0 ± 0.6
LSD	*0.1*	*0.12*	*5.5*	*0.1*	*0.36*	*2.8*
Pile 5: 14.6% SPW4 + 6.2% PGW + 79.2% SS						
IS	7.4 ± 0.1	2.84 ± 0.20	46.2 ± 3.5	25.7 ± 3.5	2.06 ± 0.47	12.6 ± 1.2
TS	7.1 ± 0.0	4.20 ± 0.02	42.3 ± 1.3	22.8 ± 0.8	2.13 ± 0.01	10.7 ± 0.4
EBS	7.4 ± 0.0	3.97 ± 0.02	37.1 ± 0.9	24.9 ± 2.6	2.10 ± 0.36	12.0 ± 0.8
MS	7.3 ± 0.0	4.10 ± 0.02	36.6 ± 3.1	22.3 ± 3.0	2.03 ± 0.31	11.0 ± 0.2
LSD	*0.1*	*0.2*	*3.6*	*2.9*	*0.07*	*1.9*

IS: beginning of the process; TS: thermophilic stage; EBS: end of bio-oxidative stage; MS: end of maturity. SPW: Sea plant waste (SPW1 and SPW3 from the Torrevieja coast; SPW2 and SPW4 from the Orihuela coast); PGW: pruning waste with grass clippings; SS: sewage sludge. EC: electrical conductivity; OM: total organic matter; TOC: total organic carbon; TN: total nitrogen. Data values reported as mean value ± standard error. LSD: least significant difference at $p < 0.05$.

3.3. Quality of the Final Composts

The main properties of the composts obtained in Experiments 1 and 2 are summarized in Table 5. The EC values in the final composts ranged from 3.18 dS m^{-1} (for Compost 1) to 4.10 dS m^{-1} (for Compost 5), these values being similar or even lower than those reported in previous works of co-composting of green wastes [10,28], verifying the threshold value of Composts 1 and 3 established for suitable seedling growth [29]. Concerning the TOC/TN ratio, all composts showed values lower than 20. This value is indicative of compost maturity [9], except for Compost 1, with a TOC/TN value slightly higher than this value, probably because this compost had the highest TOC/TN value at the beginning of the process (TOC/TN = 50.1). In the initial composting mixture, Composts 4 and 5 showed TOC/TN values < 20, but the previously commented decreasing trend of this parameter throughout the process shows the good development of the composting process also in these mixtures [10,21,30].

Table 5. Final agronomic characteristics (dry weight basis) of the mature composts.

Parameter	Compost 1	Compost 2	Compost 3	Compost 4	Compost 5
EC (dS m^{-1})	3.18 ± 0.32	3.65 ± 0.40	3.27 ± 0.00	3.72 ± 0.02	4.10 ± 0.02
TOC/TN ratio	21.0 ± 0.6	18.7 ± 1.4	13.1 ± 0.7	12.0 ± 0.6	11.0 ± 0.2
TN (g kg^{-1})	6.00 ± 0.00	9.10 ± 0.0	19.6 ± 0.16	15.6 ± 0.16	20.3 ± 0.31
P (g kg^{-1})	1.15 ± 0.04	2.36 ± 0.10	4.94 ± 0.22	6.23 ± 0.09	8.02 ± 0.56
K (g kg^{-1})	7.49 ± 0.33	10.8 ± 1.1	19.6 ± 0.4	4.12 ± 0.18	5.42 ± 0.23
Na (g kg^{-1})	6.76 ± 0.50	7.89 ± 0.77	16.9 ± 0.75	4.62 ± 0.39	4.62 ± 0.19
CEC (meq 100 g^{-1} OM)	49.8 ± 5.3	170 ± 5	171 ± 14	142 ± 12	125 ± 5
CEC/TOC (meq g^{-1})	0.54 ± 0.06	2.45 ± 0.08	2.35 ± 0.19	1.92 ± 0.16	2.05 ± 0.08
GI (%)	127 ± 4	63.5 ± 6.4	64.1 ± 3.0	98.1 ± 7.1	59.8 ± 1.1

Composts 1, 2, and 3, constituting only green wastes; Composts 4 and 5, constituting green wastes and sewage sludge. EC: electrical conductivity; TOC: total organic carbon; TN: total nitrogen; CEC: cation exchange capacity; GI: germination index. Data values reported as mean value ± standard error.

The composts obtained using marine plant debris and pruning waste (Composts 1 and 2) showed the lowest TN concentrations, these concentration being lower than those reported in previous experiments using green wastes [10,28] and similar to those reported in studies of composting using sea plant wastes [3,4]. Regarding the P and K concentrations, the values of P observed were lower in Composts 1 and 2, obtained from marine plant debris and pruning wastes, and similar to the rest of the composts, as well as those observed in other studies of composting using different green wastes mixed with sewage and agri-food sludge, such as date palm wastes [10], giant reed wastes [28], and agricultural pruning wastes [28]. Concerning the K concentrations, the composts obtained only using green wastes (Composts 1, 2, and 3) showed higher concentrations of this macroelement than the composts containing also sewage sludge in their composition, these concentrations being similar to those reported in previous studies of composting using high proportions of green wastes [10,28]. On the other hand, the concentrations of Na in the composts using marine plant debris were similar to the values reported in other experiments using these wastes [4] and higher than those observed in composting experiments using green wastes and sludge [21]. However, these values seemed not to have a negative influence on germination and seedling growth. This was observed in the values of the germination index (GI) (Table 5), which were higher in all composts than the threshold value of 50%, indicative of the absence of phytotoxicity and compost maturity [15]. Other maturity parameters, such as CEC and the CEC/TOC ratio [31,32], also indicated a suitable degree of maturity, since all composts verified the reference values established in the literature (CEC > 67 meq (100 g OM)$^{-1}$ and CEC/Corg > 1.9 meq g^{-1}, respectively) [9], except for Compost 1 for both parameters, probably because this compost also showed the lowest OM contents.

4. Conclusions

The results obtained show that the treatment of green wastes, together with sea plant wastes, constitutes a feasible and efficient method not only to manage these organic waste streams but also to add value to this type of waste, obtaining end products with good agricultural quality for use as organic fertilizers and/or organic amendments. However, the composting strategy based on the design of these mixtures must consider, on the one hand, a proportion in the composting mixture not higher than 30% (on a dry weight basis) of sea plant wastes to avoid a loss in the fertilizing value of the final compost. On the other hand, the incorporation of a ternary co-composting agent rich in organic matter and nutrients is necessary, such as sewage sludge, which enables not only the proper development of the process but also increases the organic matter and nutrient content in the final composts, improving their quality as organic fertilizers. However, further research concerning the potential limitations of sewage sludge as ternary co-composting agent in these mixtures due to the potential presence of microcontaminants, and regarding the potential use of alternative feedstocks (e.g., animal manures), should also be strongly strengthened to avoid potential negative side effects derived from compost use.

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References

1. R&A. *Golf around the World Report*; National Golf Foundation: Jupiter, FL, USA, 2019; Available online: https://www.thengfq.com/2019/02/ras-golf-around-the-world-report/ (accessed on 27 July 2021).
2. McCartney, D. Auditing non-hazardous wastes from golf course operations: Moving from a waste to a sustainability framework. *Resour. Conserv. Recy.* **2003**, *37*, 283–300. [CrossRef]
3. Han, W.; Clarke, W.; Pratt, S. Composting of waste algae: A review. *Waste Manag.* **2014**, *34*, 1148–1155. [CrossRef]
4. Cocozza, C.; Parente, A.; Zaccone, C.; Mininni, C.; Santamaria, P.; Miano, T. Comparative management of offshore posidonia residues: Composting vs. energy recovery. *Waste Manag.* **2011**, *31*, 78–84. [CrossRef]
5. Khalil, A.; Domeizel, M.; Prudent, P. Monitoring of green waste composting process based on redox potential. *Bioresour. Technol.* **2008**, *99*, 6037–6045. [CrossRef] [PubMed]
6. López, M.; Soliva, M.; Martínez-Farré, F.X.; Bonmatí, A.; Huerta-Pujol, O. An assessment of the characteristics of yard trimmings and recirculated yard trimmings used in biowaste composting. *Bioresour. Technol.* **2010**, *101*, 1399–1405. [CrossRef] [PubMed]
7. De Sanctis, M.; Di Iaconi, C. Evaluation of *Posidonia oceanica* residues as feedstock for anaerobic digestion. *Bioresour. Technol. Rep.* **2019**, *8*, 100317. [CrossRef]
8. Parente, A.; Montesano, F.F.; Lomoro, A.; Guido, M. Improvement of beached *Posidonia* residues performance to composting. *Environ. Eng. Manag. J.* **2013**, *12*, 81–84.
9. Bernal, M.P.; Alburquerque, J.A.; Moral, R. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour. Technol.* **2009**, *100*, 5444–5453. [CrossRef] [PubMed]

10. 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. Valorization of date palm (Phoenix dactylifera L.) pruning biomass by co-composting with urban and agri-food sludge. *J. Environ. Manag.* **2018**, *226*, 408–415. [CrossRef] [PubMed]
11. Bustamante, M.A.; Ceglie, F.G.; Aly, A.; Mihreteab, H.T.; Ciaccia, C.; Tittarelli, F. Phosphorus availability from rock phosphate: Combined effect of green waste composting and sulfur addition. *J. Environ. Manag.* **2016**, *182*, 557–563. [CrossRef] [PubMed]
12. Sáez, J.A.; Flores, P.; Bustamante, M.Á.; Sanchez-Hernandez, J.C.; Moral, R.; Pérez-Murcia, M.D. Nitrogen isotope fractionation during composting of sewage and agri-food sludge with pruning waste. *Agronomy* **2020**, *10*, 1954. [CrossRef]
13. Bustamante, M.A.; Alburquerque, J.A.; Restrepo, A.P.; de la Fuente, C.; Paredes, C.; Moral, R.; Bernal, M.P. Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. *Biomass Bioener.* **2012**, *43*, 26–35. [CrossRef]
14. Navarro, A.F.; Cegarra, J.; Roig, A.; Bernal, M.P. An automatic microanalysis method for the determination of organic carbon in wastes. *Commun. Soil Sci. Plant Anal.* **1991**, *22*, 2137–2144. [CrossRef]
15. Lax, A.; Roig, A.; Costa, F. A method for determining the cation-exchange capacity of organic materials. *Plant Soil* **1986**, *94*, 349–355. [CrossRef]
16. Zucconi, F.; Pera, A.; Forte, M.; de Bertoldi, M. Evaluating toxicity of immature compost. *BioCycle* **1981**, *22*, 54–57.
17. Brewer, L.J.; Sullivan, D.M. Maturity and stability evaluation of composted yard trimmings. *Compost Sci. Util.* **2003**, *11*, 96–112. [CrossRef]
18. Zhang, L.; Sun, X. Improving green waste composting by addition of sugarcane bagasse and exhausted grape marc. *Bioresour. Technol.* **2016**, *218*, 335–343. [CrossRef] [PubMed]
19. López-González, J.A.; López, M.J.; Vargas-García, M.C.; Suárez-Estrella, F.; Jurado, M.; Moreno, J. Tracking organic matter and microbiota dynamics during the stages of lignocellulosic waste composting. *Bioresour. Technol.* **2013**, *146*, 574–584. [CrossRef]
20. Doublet, J.; Francou, C.; Poitrenaud, M.; Houot, S. Influence of bulking agents on organic matter evolution during sewage sludge composting; consequences on compost organic matter stability and N availability. *Bioresour. Technol.* **2012**, *102*, 1298–1307. [CrossRef]
21. Himanen, M.; Hänninen, K. Composting of bio-waste, aerobic and anaerobic sludges-Effect of feedstock on the process and quality of compost. *Bioresour. Technol.* **2011**, *102*, 2842–2852. [CrossRef]
22. Morales, A.B.; Bustamante, M.A.; Marhuenda-Egea, F.C.; Moral, R.; Ros, M.; Pascual, J.A. Agri-food sludge management using different co-composting strategies: Study of the added value of the composts obtained. *J. Clean. Prod.* **2016**, *121*, 186–197. [CrossRef]
23. European Commission. *End-of-Waste Criteria for Biodegradable Waste Subjected to Biological Treatment (Compost & Digestate): Technical Proposals*; Publications Office of the European Union: Luxembourg, 2014.
24. Gavilanes-Terán, I.; Jara-Samaniego, J.; Idrovo-Novillo, J.; Bustamante, M.A.; Moral, R.; Paredes, C. Windrow composting as horticultural waste management strategy—A case study in Ecuador. *Waste Manag.* **2016**, *48*, 127–134. [CrossRef] [PubMed]
25. Yañez, R.; Alonso, J.L.; Díaz, M.J. Influence of bulking agent on sewage sludge composting process. *Bioresour. Technol.* **2009**, *100*, 5827–5833. [CrossRef]
26. Hogg, D.; Favoino, E.; Centemero, M.; Caimi, V.; Amlinger, F.; Devliegher, W.; Brinton, W.; Antler, S. *Comparison of Compost Standards within the EU, North America and Australia*; The Waste and Resources Programme (WRAP), Ed.; The Old Academy: Banbury, Oxon, UK, 2002.
27. Bustamante, M.A.; Paredes, C.; Marhuenda-Egea, F.C.; Perez-Espinosa, A.; Bernal, M.P.; Moral, R. Co-composting distillery wastes with animal manure: Carbon and nitrogen transformations and evaluation of compost stability. *Chemosphere* **2008**, *72*, 551–557. [CrossRef]
28. Reyes-Torres, M.; Oviedo-Ocaña, E.R.; Dominguez, I.; Komilis, D.; Sánchez, A. A systematic review on the composting of green waste: Feedstock quality and optimization strategies. *Waste Manag.* **2018**, *77*, 486–499. [CrossRef]
29. 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.; et al. composting of invasive species Arundo donax with sewage and agri-food sludge: Agronomic, economic and environmental aspects. *Waste Manag.* **2018**, *78*, 730–740. [CrossRef] [PubMed]
30. Lemaire, F.; Dartigues, A.; Rivière, L.M. Properties of substrate made with spent mushroom compost. *Acta Hort.* **1985**, *172*, 13–29. [CrossRef]
31. Bustamante, M.A.; Restrepo, A.P.; Alburquerque, J.A.; Perez-Murcia, M.D.; Paredes, C.; Moral, R.; Bernal, M.P. Recycling of anaerobic digestates by composting: Effect of the bulking agent used. *J. Clean. Prod.* **2013**, *47*, 61–69. [CrossRef]
32. Young, B.J.; Rizzo, P.F.; Riera, N.I.; Torre, V.D.; López, V.A.; Molina, C.D.; Fernández, F.E.; Crespo, D.C.; Barrena, R.; Komilis, D.; et al. Development of phytotoxicity indexes and their correlation with ecotoxicological, stability and physicochemical parameters during passive composting of poultry manure. *Waste Manag.* **2016**, *54*, 101–109. [CrossRef]