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Strategies for the Sustainable Management of the Organic Fraction of Municipal Waste

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Abstract: The organic fraction of municipal waste, OFMW, management is one of the main concerns for urban waste managers in developed countries. Composting this biodegradable urban waste and using the compost in agricultural activities is a quickly growing method and is a viable option to manage urban waste in both the developed and the developing world. This research presents the example of the management proposal for Cartagena city in Spain, in which the technical and environment feasibility has been studied. This work aimed to evaluate the composting of a mixture of different residues, namely organic waste, pruning, and *Posidonia oceanica* (L.) Delile, which was collected from the beaches of the municipality while cleaning. Mixtures 1, M1 (composed of 20% OFMW and 40% pruning and seaweed) and 3, M3 (composed of 30% OFMW and 70% pruning) proved to be the best to reach the ideal compost (1.23-0.08-1.28 NPK and 2.22-0.33-3.45 NPK, respectively). An extreme mixture, M2, was evaluated (50% PO; 50% pruning) but poor results were obtained due to a non-optimal initial C/N by not containing OFMW. At the same time, the volumes by urban nucleus and the viability of different composting strategies have been studied, proposing that 180,000 inhabitants use the centralized composting plant and almost 31,000 inhabitants use self-composting and community composting. Considering the carbon footprint of this management, the value was 50% lower than the total management in a centralized plant. Moreover, the final use of compost is optimum with self-composting and community composting because it is nearest to agricultural consumptions, also reducing the transport of the final product.

Keywords: municipal waste management; *Posidonia oceanica* (L.) Delile; carbon footprint; pruning of municipal gardens

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1. Introduction

One of the main problems of municipalities today is the management of the organic fraction of municipal waste, OFMW. the directives established a deadline for the collection and separation of biodegradable municipal waste in 2020, but it is still not possible to achieve that target. The European Union, through Directive 2018/851 [1], modified, among many other aspects, these deadlines, given the low level of compliance of the municipalities, setting December 2023 as the deadline. In a more detailed way, article 22 of this law on bio-waste, Directive 2018/851 [1], states that:

> *"Bio-waste either be separated and recycled at source, or be collected separately and not mixed with other types of waste" and also propose to "encourage the recycling, including composting and digestion, of bio-waste in a way that ensures a high level of environmental protection and generates an output that meets relevant high quality standards", "encourage home composting" and "encourage the use of materials produced from bio-waste".*

This, coupled with milestones such as limiting municipal waste to a maximum of 10% of landfillable municipal waste by 2035, as well as recycling at least 55% of municipal waste by 2025 and 60% by 2030, make the issue of municipal waste management a priority. Following the specifications given by the regulations and the recommendations issued by the Ministry of Ecological Transition, the main way to manage biowaste is through composting. Composting is an aerobic decomposition of biodegradable waste under controlled conditions and its transformation into humus by the action of micro and macro-organisms, which can be used as a fertilizer in agriculture. Compostable waste refers to a biodegradable waste (also known as green waste or organic waste). In principle, all organic waste of a biological origin is compostable. This includes food leftovers from households, restaurants, canteens, and bars; green waste from gardens and parks; and dirty paper.

When we focus on the management of the organic fraction of municipal waste for composting and subsequent use, we can see that there are many wastes managed by municipalities that could be used in the composting process, providing the necessary N and C fractions. Many studies have used *Posidonia oceanica* (L.) Delile in composting [2], whilst others have also used a mixture of seaweed and fish waste [3,4], seaweed with pruning waste [5], pruning and domestic waste [6], and different mixtures of agricultural and municipal waste [7], to achieve efficient waste management and a circular economy of the municipalities [8]. The characterization of the available raw materials, their seasonality, and volume are, therefore, important factors to consider when defining the management strategy of each municipality. Although these residues can also be destined for use as ruminants feed, some works highlight possible metabolic consequences [9] in high quantities and so a pretreatment is necessary, which, therefore, increases the cost of use.

Regarding [10,11], there are different composting systems, with their main objective being to transform waste into a stable and sanitary safe material. Two general types of systems exist: closed and open. In closed systems the waste is processed in reactors. They can be simple or more complex, combining mechanical agitation and forced aeration. They are generally metallic structures, cylindrical or rectangular in shape, where parameters such as aeration, temperature, etc. are kept controlled. These systems enable the initial stages of fermentation to be accelerated. When these stages are finished, the material is removed from the reactor and stored for maturation in the open air or in open warehouses. In general, they are industrial systems with high costs. One of the main advantages of these systems is that they considerably reduce composting surfaces and achieve better control of fermentation parameters and odors, as well as being faster. Open systems are more traditional and are applied in rural areas and where there is abundant land. They are low cost and utilize relatively simple technology. These can be from:

- Piles or turned rows
- Static piles with forced aeration
- Combined systems

In these systems, the waste is placed in a pile or row, with a height between 1 m and 3 m, and 4–5 m wide. Temperature and humidity must be controlled, and they require turning to allow oxygen to reach the central point of the composting mass.

Municipalities typically adopt open systems in piles or turned rows, which can be different depending on the waste collected and composting place:

- Centralized composting: biodegradable waste is collected at home by the municipality staff and taken to a central composting plant; the compost can be used in municipal gardens, public land improvement or educational activities.
- Community composting: biodegradable waste is collected at home or brought by citizens and processed centrally, as with in-plant composting. However, the difference is that community composting programs generally cover a smaller geographic area than centralized ones and are at the local community level. The final product is used by the citizens participating in the program, thus, closing the cycle of waste generation and recycling.

- Home composting: citizens compost the biodegradable waste they have generated and use the compost thus produced themselves. This may require the purchase of a composting unit, but it is not essential, since many citizens may use home-made units.

These distinctions are very marked by the economic and environmental costs associated with collection. If we take into account that biodegradable waste cannot be stored for a long time considering the odors and sanitary problems that it can cause, we end up facing an issue previously observed in other municipalities [8]. However, the periodic collection of small volumes makes management very costly from the economic and environmental point of view. In this sense, to minimize emissions and be as neutral as possible in terms of CO_2 emissions, the minimization of transport is a requirement to be taken into account and should be one of the points to be considered [12–15].

Many municipalities in Spain must define the management of their OFMW before 2023 and study the possible solutions to be adopted. Cartagena municipality can be an example and can present one of the Mediterranean coastal municipalities with dispersed urban centers and tourist and agricultural development. Regarding its current management, it should be noted that in 2005 the municipality of Cartagena, in compliance with Directive 2018/851/EC [1], started a waste treatment line at the El Gorguel plant (37°34′46.7′′ N; 0°53′34.4′′ W), where the mixed biowaste is separated and cleaned for subsequent composting. With respect to selective collection, the municipality has containers for glass, plastic, paper, cardboard, and pruning in some residential neighborhoods. Biodegradable waste is not collected separately, but arrives at the treatment plant in the green container called "rejection", where it is mixed:

- Organic household waste already separated at home.
- Non-separated waste.
- Any non-bulky waste that has no designated disposal zone.

This mixture means that the biowaste is contaminated by different materials such as batteries, medicines, etc.

In this regard, the compost obtained at the El Gorguel plant has been studied by Conesa [16] and Peñalver [17] in lines of work of the Chair of Municipal Infrastructures of Cartagena city with the UPCT, from which the following conclusions were drawn:

- The analyses carried out in October 2015 and May 2016 showed similar characteristics for the final compost, so the material obtained is stable in composition over time.
- In terms of characterization, the analyses showed pH values around 7.5 and a high electrical conductivity of 8–9 dS m^{-1}, mainly conditioned by high levels of Cl^- in the 1:5 extract (>1200 mg L^{-1}). Soluble organic carbon concentrations were high (>20,000 mg kg^{-1}), as is to be expected for an organic residue.
- The content of some heavy metals (Cu, Pb, and Zn) exceeded the limit established for the most unfavorable case (Class C), in accordance with Annex V of Royal Decree 506/2013 of June 28, on fertilizer products.

Therefore, we can state that the current management is not sustainable since the biowaste is not collected separately, thus, the compost obtained does not meet the specifications to be used as fertilizer due to the contamination of the "rejection" container with improper waste.

This work presents a proposal for an OFMW management strategy for Cartagena municipality. For this purpose, (i) the existing waste was identified, characterized and composted with different compositions and volumes, in order to determine the ideal composition suitable for composting; (ii) tests of mixtures were carried out, evaluating their feasibility; (iii) a management strategy was defined by zones according to the geographic distribution of the population centers, evaluating the carbon footprint compared to the current management; (iv) finally, a proposal was made for seasonal management and possible destinations for the compost generated.

2. Materials and Methods

2.1. Definition of the Case Study

Cartagena municipality has a population of 216,108 inhabitants (INE, 2020) spread over a municipal area of 558.08 km^2; the population in the 2020 census reached a value of 257,522 inhabitants. The 558.3 km^2 of its municipal area is structured into neighborhoods, localities, and scattered hamlets that are administered under Councils, thereby constituting a municipality with a highly scattered population, as shown in Figure 1, which makes collection management rather difficult.

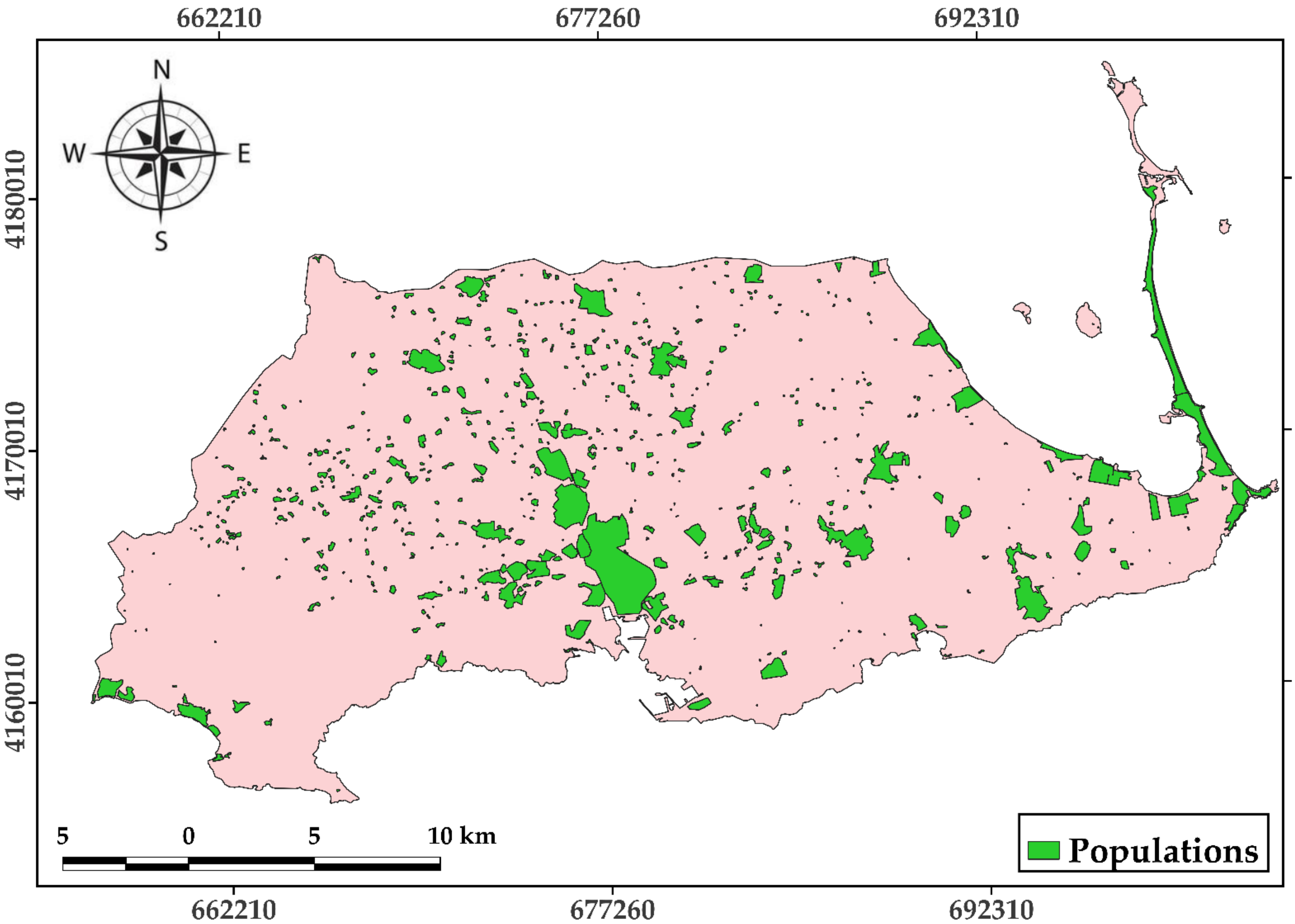

Figure 1. Population centers in the Municipality of Cartagena (own elaboration).

2.2. Study of Raw Material Mixtures and Composting Process

A pilot composting experience was carried out for four months, from 4 November 2019 to 27 February 2020, at the Tomás Ferro Experimental Station of the Polytechnic University of Cartagena, using the composting area set aside on the farm for this purpose. After studying the bio-waste volumes managed by the municipality, it was suggested as a starting strategy to consider three feedstocks for blending:

- Biodegradable material from the hospitality industry and private houses: for this test, the biodegradable material was obtained from the dining room of the University Residence of the UPCT, as a representative of the materials obtained in the municipality. The waste was collected daily and taken to the experimental station. The waste was transported in bags, which were removed to avoid fermentation. The waste was crushed prior to composting, leaving a medium consistency. A total of 9550 t of stabilized biodegradable material from household and hotel waste is separated annually at the Cartagena triage plant.

- The pruning waste was provided by the Cartagena City Council's Parks and Gardens Service. The pruning residue taken was a representative sample that contained grass, tree pruning and shrubs in the municipality. The pruning was shredded and deposited in an aerated place, in an extended layer to avoid fermentation. The Cartagena City Council's Parks and Gardens Service registers an annual volume of biodegradable material of 2280 t. If plant raw material is needed, there is a central pruning and biowaste agricultural plant near to El Gorguel.
- *Posidonia oceanica* (L.) Delile: is commonly known as Neptune grass or Mediterranean tapeweed; it was collected from the beaches of the municipality while cleaning. It was transported to the experimental station and spread in thin layers to avoid fermentation after being shredded into straw consistency, then sifted to remove as much as possible. The council collects 2090 t of *Posidonia oceanica* (L.) Delile from the beaches of the municipality annually.

At the Experimental Station, three compost piles of 3.00 × 1.50 × 1.60 m were formed with these wastes in the shape of a triangular prism. Prior to the establishment of the compost heaps or piles, a characterization of the raw materials was carried out. This information is needed for the definition of the mixtures, since composting requires certain values for its activation. Initially, in the raw materials and in the mixtures during the test, pH, %C (Total organic matter method by calcination. Organic carbon = total organic matter 1.724), and N [18] were analyzed in order to determine compliance with the royal decree 506/2013 of June 28 [18], on fertilizer products. At the end of the trial, N, P, K, Ca, and Mg [18], Cr, Ni, Cu, Zn, Cd, Pb [18], Escherichia coli [19], and Salmonella [20] underwent the same analysis. The samples analyzed from the piles were mixed from three randomly selected areas each time.

The piles were watered to maintain 55–60% moisture and flipped when they reached temperatures of around 60 °C, which corresponded to approximately one watering and one flipping per week per pile. Compost is known to be "ready or done" when the temperature drops to room temperature, in addition to the appearance of black soil with a loose consistency, no garbage odor, and a damp forest soil smell. Likewise, during the fermentation process, the C/N ratio should decrease to values between 12 and 18 [10].

If the final obtained material after fermentation has a high C/N value, it indicates that it has not undergone complete decomposition, and if the ratio is very low, it may be due to excessive mineralization, although this depends on the characteristics of the input material, hence, the importance of identifying the volumes of each raw material to comprise the piles.

2.3. Strategy Definition and C Footprint Quantification

Based on the results and the location, a management strategy by zones was proposed and the carbon footprint was quantified following the UNE-ISO 14064 methodology [21], both for the new management and the current management, taking into account scope 1 emissions, considering the consumption of transport fuels.

Likewise, the compost product to be obtained was calculated and a possible use of the product was proposed, depending on the location of the final compost.

2.4. Statistical Analysis

A principal components analysis (PCA) was performed with pH, CE, C, and N in all samples to study the structure of dependence and correlation established among the variables in the three different mixtures. A one-way ANOVA followed by a Tukey's test ($p < 0.05$) was performed to assess differences among PCA factor scores. Statistical analyses were performed with the software IBM SPSS for Windows, Version 22.

3. Results and Discussions

3.1. Raw Materials

The characterization of the input materials is presented in (Table 1). The C/N values of each material demonstrate that it was very heterogeneous both in composition and moisture, a fact that justifies the search for the ideal mixture to ensure good composting:

Table 1. Characterization of raw materials.

Samples	pH	CE (mS cm^{-1})	C (%)	N (%)	Humidity%	Ratio C/N
Posidonia Oceanica	7.87	40.47	16.33	0.31	86.26	51.91
Pruning	6.13	6.42	48.13	3.96	37.13	12.14
Biodegradable municipal waste (OFMW)	5.38	11.00	39.91	1.33	70.13	29.95

Based on this characterization, a series of theoretical mixtures was defined, which helped us to determine the volumes of input material. A C/N ratio of 20–35 is considered adequate for the success of composting, since the microorganisms consume approximately 30 parts of carbon for each part of nitrogen; we looked for mixtures that met these values, and that exceeded them, to see how they would behave over time. The mixtures chosen, volumes used, and weights are presented in Table 2:

Table 2. Mixtures chosen for the experimental test for each pile.

Mixture	C/N	V_{total} (m^3)	V_{PO} (m^3)	$V_{pruning}$ (m^3)	V_{OFMW} (m^3)	$Weight_{PO}$ (kg)	$Weight_{pruning}$ (kg)	$Weight_{OFMW}$ (kg)
40% PO *, 40% pruning, 20% OFMW *	22.34	3.6	1.4	1.4	0.7	302	216	468
50% PO *, 50% pruning, 0% OFMW *	40.87	3.6	1.8	1.8	0	378	270	0
0% PO *, 70% pruning, 30% OFMW *	21.25	3.6	0	2.5	1.1	0	378	702

* PO *Posidonia Oceanica*; OFMW: organic fraction of municipal waste.

As can be seen from the C/N ratio, mixtures 1 and 3 would be the most appropriate, to propose extreme mixtures, such as 2, to evaluate the effect on the composting process.

Figure 2 shows the analyses carried out for the follow-up of the trial during the four months:

As we can see, the evolution of the compost analysis varied throughout the test because of the flipping and the humidity provided by the rains, stabilizing at the end of the test (Figure 2). We can see that both mixtures 1 and 3 reached the compost value with the quality required by [18], with the indicator of more mature compost being the closer these C/N values are to 10. Thus, we can say that in mixture 3 maturity was reached earlier (Figure 2c). As we can see in Figure 2c, mixture 2 did not reach mature compost values, due to a poor initial C/N ratio and a high EC (Figure 2e) because of the saline fraction provided by *Posidonia oceanica* (L.) Delile, without pretreatment, since Luzi et al. [22] found numerous benefits of the composting process with the addition of nanocrystals extracted from *Posidonia oceanica* (L.) Delile. As we can see, mixture 2 had a poor N mix with high values of C/N (Figure 2b,c). The pH and EC of the mixtures (Figure 2d,e) were similar at the end of the experiment, although mixture 2 had higher values during the time, owing to the salinity of the *Posidonia oceanica* (L.) Delile.

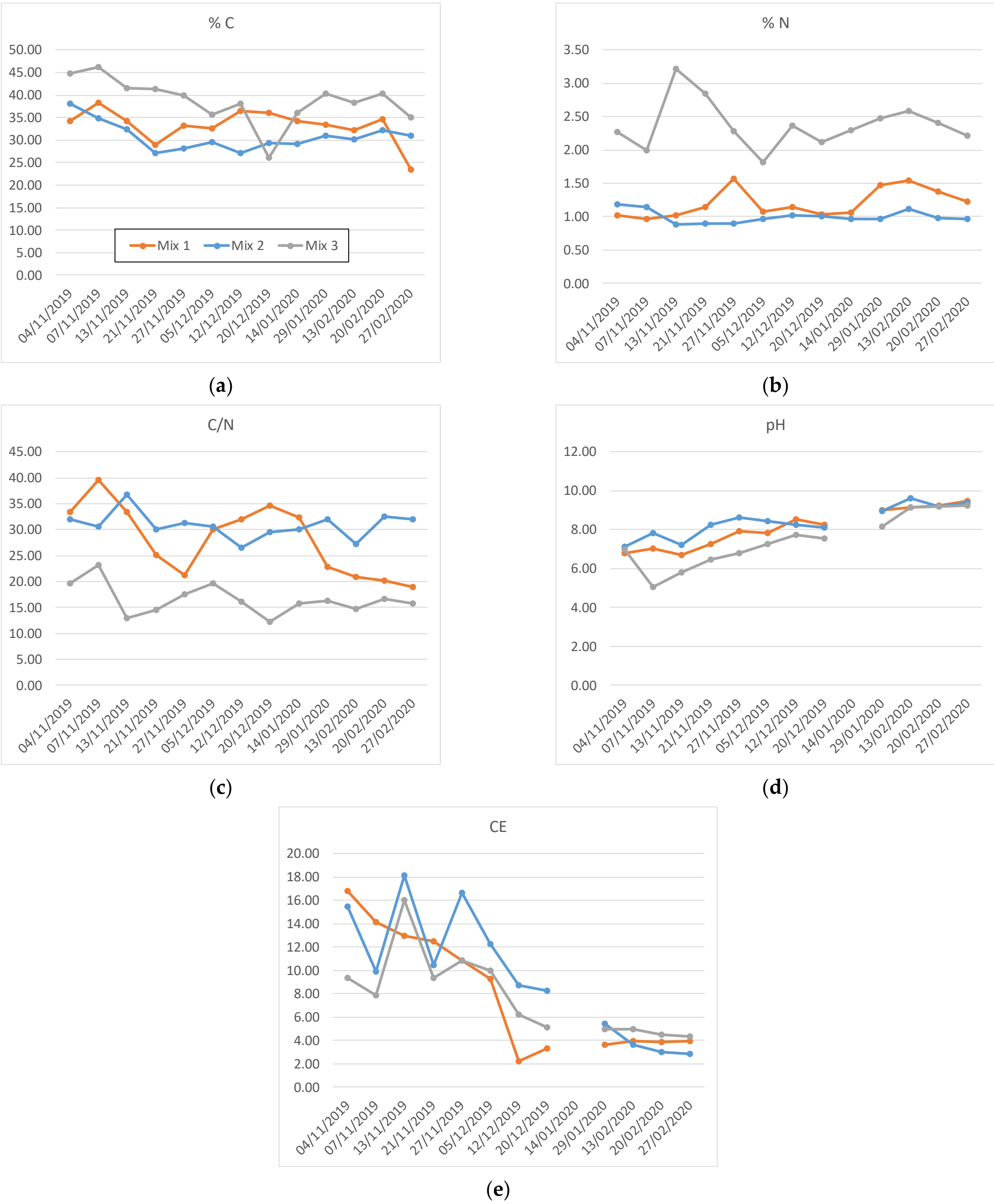

Figure 2. Trial progress; analytical data. (**a**) %C; (**b**) %N; (**c**) C/N; (**d**) pH; (**e**) EC.

Table 3 shows the Matrix of PCA obtained with N, C, EC, and pH in all mixtures.

PC1, which explained 51.1% of the variation, significantly separated all mixtures ($p < 0.01$). This PC1 was related to C and N (Table 3), indicating that all mixtures were separated from the beginning of the composting process up to the final compost by C and N contents. PC2, which explained 35.7% of the variation, significantly separated the different sampling dates related to changes in pH and EC. Thus, pH and EC were the properties that significantly changed over time, with overall increases in pH and decreases in EC. The PCA performed (Figure 3) showed that 86.8% of the total variation could be explained by the first two PCs. The content of C decreased during the composting process, as previously reported [23], but decreases were in the same proportion in all mixtures, maintaining the separation of all mixtures throughout the whole process based on C and N. A well-matured compost should present a C/N ratio of <20, and so mixture 2 would indicate a poor maturity compost [24].

Table 3. Matrix of PCA obtained with N, C, EC, and pH in all mixtures.

	PC1 (51.1%)	**PC2 (35.7%)**
N	0.911	−0.044
C	0.906	0.139
EC	−0.152	0.942
pH	−0.480	−0.850

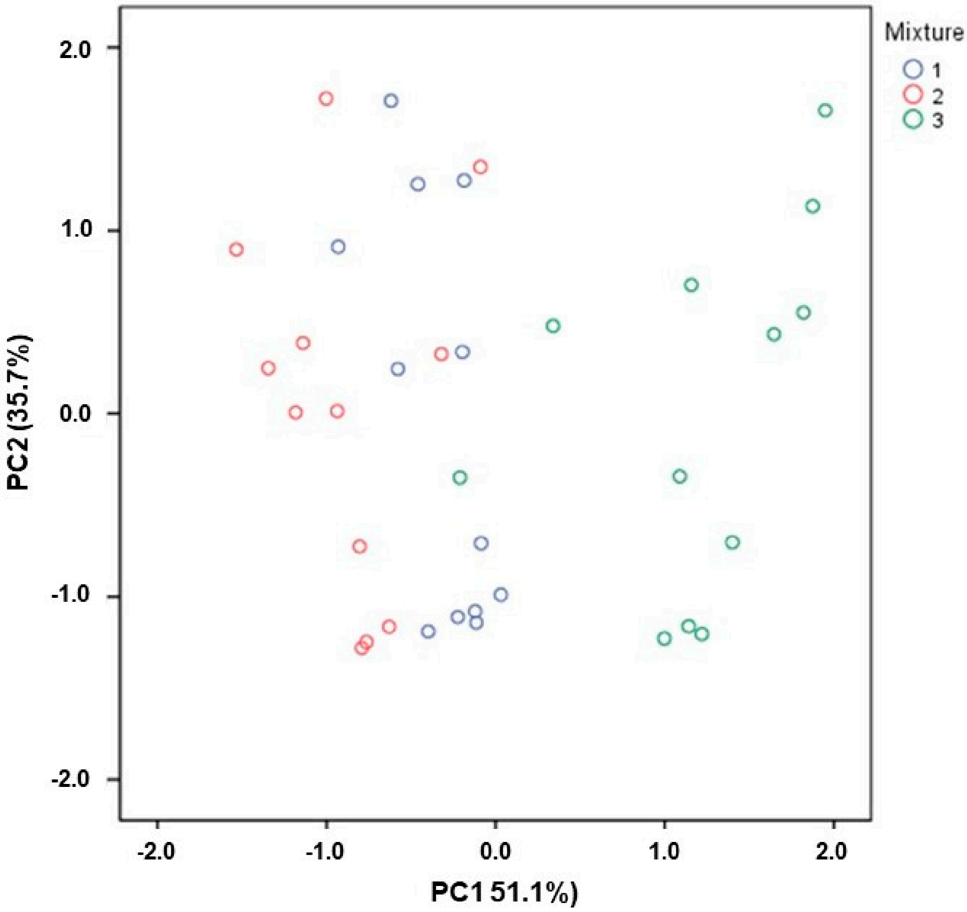

Figure 3. PCA factor scores of variations in C, N, pH, and EC in the three mixtures studied.

At the end of the test, the quality parameters required by [18] (Table 4) were analyzed; these refer to metals and microorganisms, with optimum quality values being obtained in all cases which were well below the limits of the legislation, as several authors have also found and collected in the review [25].

The nutrients were also analyzed to establish the richness of the compost obtained and its value for possible uses. Table 5 shows that mixture 3 had a higher nutritional power in terms of NPK values, which were similar to the values found in the bibliography [26].

Table 4. Metal and microorganism content values at the end of the test and limits.

Mixture	Cr mg kg^{-1}	Ni mg kg^{-1}	Cu mg kg^{-1}	Zn mg kg^{-1}	Cd mg kg^{-1}	Pb mg kg^{-1}	*Escherichia coli*	*Salmonella*
1	19.52	14.65	16.95	70.83	0.46	31.18	<1000	absence
2	17.48	12.32	14.08	66.02	0.29	24.31	<1000	absence
3	17.19	10.31	21.33	98.33	0.52	32.06	<1000	absence
EU 2019/1009	70.00	50.00	300.00	800.00	1.50	120.00	<1000	absence

Table 5. Nutrient values at the end of the test.

Mixture	PO_4^{3-}%	P_2O_5%	K^+%	K_2O%	Ca%	Mg%	NPK
1	0.11	0.08	1.06	1.28	0.20	0.11	1.23 *-0.08-1.28
2	0.08	0.06	0.71	0.86	0.21	0.13	0.97 *-0.06-0.86
3	0.44	0.33	5.74	3.45	0.54	0.11	2.22 *-0.33-3.45

* Data from Figure 2.

3.2. Biowaste Management Strategy

3.2.1. Definition of Management Alternatives

In accordance with the guidelines given by the Ministry [10], the management methods to be adopted in the municipality of Cartagena according to population centers, as shown in Figures 3 and 4, should be:

- Centralized composting (Figure 4): for city waste also including hospitality establishments and markets. This management is proposed for areas of higher demography and will go to the composting plant at El Gorguel.
- Community composting (Figure 4): for residential neighborhoods with low-rise houses or buildings with private and/or communal green areas.
- Home composting: for isolated hamlets and isolated rural areas with a low population (Figure 5).

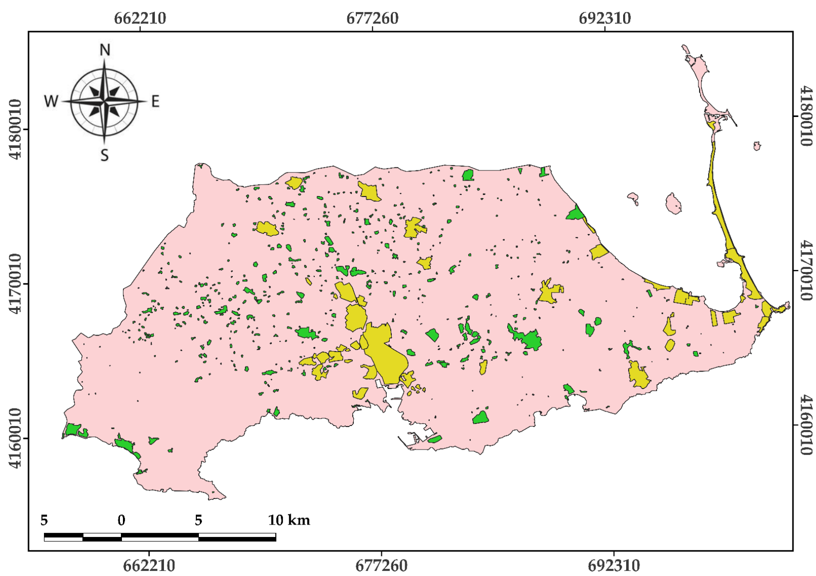

Figure 4. Differentiation of the population centers for which community (■) and centralized (■) composting with collection is proposed (own elaboration).

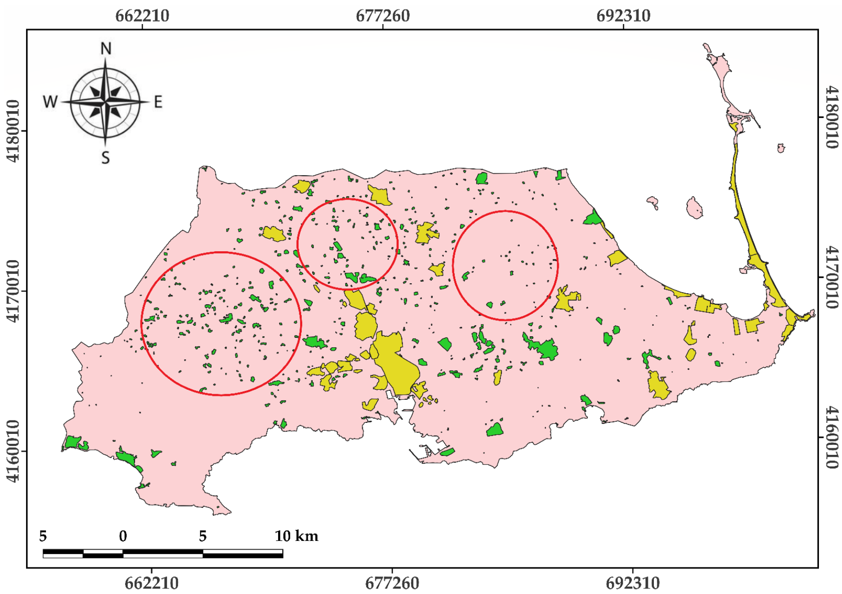

Figure 5. Small population centers for which self-composting could be proposed (own elaboration).

3.2.2. Home Composting or Self-Composting

According to the study on waste management models in isolated rural environments [11] published by the Ministry of the Environment, Rural and Marine Affairs, self-composting should be promoted in dispersed rural areas, since, as mentioned above, centralized collection would be very costly from an economic and environmental point of view, given their dispersion. The characteristics of these environments in terms of the availability of space, the high generation of vegetable waste, whether it be their own or nearby, and the possible use of the resulting compost to close the organic matter cycle and reduce the use of fertilizers and chemical fertilizers, make it the ideal strategy for these areas [12–15].

As can be seen in Figure 4, the western part of the municipality presents ideal conditions for self-composting, as they are small villages with a rural tradition, which have surrounding land that can absorb the compost generated. The decision as to whether these nuclei can undertake this management will be defined after public consultation through the channels of neighborhood associations and local associations. Similarly, small population centers in the eastern and central areas can also be consulted. Figure 5 shows the proposed consultation areas.

In terms of management, farmers have traditionally collected organic waste to transform it into compost for their soils. Waste composting is nothing more than imitating the fermentation process that normally occurs on a forest floor but accelerated and in a direct way. There are two main systems for self-composting: in piles and in composters:

- Windrow composting: this is the traditional method of composting. The biowaste is piled directly onto the soil, usually in heaps. This method allows large volumes of organic matter to be treated, while at the same time achieving high temperatures (up to 65–70 °C), which allow the compost to be sanitized.
- Composting in composters: in this case, the composting process takes place inside closed containers. These bins or composters can be made of different materials (wood, plastic, grids, blocks, etc.) and can even be homemade from drums, pallets, etc., or a commercial model can be purchased. Unlike pile composting, such containers protect the compost from rain, prevent access by animals, require slightly less space and are more aesthetically pleasing than piles, and can be placed in a wide variety of locations, such as gardens, allotments, or patios.

3.2.3. Community Composting

Community composting is a system of the centralized treatment of organic waste (bio-waste) of a collective or community, which has a degree of participation and direct involvement in the process. It differs from home composting in the collective nature of participation. Community composting is presented as a very appropriate alternative to replace the collection system with the destination of the management plant. It offers an economic and environmental benefit by reducing the number of containers and the transport of biowaste to the plant, and in many cases a social benefit, as the neighbors are involved in a joint project to manage their waste and improve their neighborhood or district.

For their implementation, composters are in the so-called community composting areas, which can be in unused spaces (plot of land, wasteland, the "outskirts" of the locality), but always close to the homes of the neighbors, for easy access. In these areas the neighbors bring their organic waste, or it is collected, and all the necessary elements for the composting process can be found there. For the future success of the proposal, it is advisable that they are managed by an experienced person, normally a person or service contracted by the municipality. It would be interesting to also include the shredding of plant waste provided by citizens or by the municipality from garden pruning.

Most community composting initiatives have a strong educational and awareness-raising component, involving schools and local associations, but we must not forget that their purpose is the reduction and transformation of organic waste.

In the municipality of Cartagena, the areas proposed for community composting would be those marked in Figure 4, subtracting the small nuclei that carry out self-composting (Figure 5), which will be known after the neighborhood consultation; these solutions present several economic and environmental performance factors [27].

3.3. Environmental Balance of the Alternatives

This section aims to evaluate the management options from an environmental point of view, assessing the carbon footprint. For this purpose, we have considered the in-plant management of all the bio-waste, with the current management as Alternative 1. We have also considered the mixed proposal with in-plant management, self-composting, and community composting, proposed in this study as Alternative 2. For this purpose, we have made several simplifications:

1. The volume of the net organic fraction of municipal waste collected per inhabitant of 128 g inhabitant^{-1} day^{-1} [28].
2. The density of the organic fraction of municipal waste 0.60 t m^{-3} [28].
3. m^3 collection trucks are adopted.
4. Euro V trucks with a diesel fuel consumption of 30 L 100 km^{-1}
5. In Alternative 2, five preferential transport routes have been defined for collection to landfill in the option of coexistence with local composting (Canteras, Albujón and surroundings, Center, Mar Menor, Manga and Cabo de Palos, with an average transport route of 45 km each, round trip). Many works establish optimal routes by GIS [29,30] and with the integration of tools such as the 'internet of things' (IoT), 'artificial intelligence' (AI), 'cloud computing', and 'intelligent transportation systems' [31].
6. In Alternative 2, 50% of the residents have community composting and a radius of no more than 0.50 km will be proposed for the composter sited in community composting. Further, it is supposed that over 95% will be done walking. So, 764 residents live in 305 houses (2.50 habitants/house); considering 2 trips/ week and 52 weeks per year, they will have a carbon footprint of 8 t CO_2 eq.
7. In Alternative 1, although the volume of management in local composting is 1/6 of that managed in the plant (Table 6), with respect to transport, three more routes with 50% more kilometers each are considered, given the high number of small population centers.

Table 6. Comparison of alternatives of OFMW transport from an environmental point of view.

Alternatives	Residents [1]	V $_{OFMW\ net}$ (kg day^{-1})	V $_{OFMW\ year}$ (t year^{-1})	Collection (km day^{-1})	Carbon Footprint [2] t $_{CO2\ eq}$
A1. Central plant	210,106	26,893.57	9816.15	855	67.37
A2. Central Plant	179,548	22,982.14	8388.48	450	35.46
Local composting	30,558	3911.42	1427.67	0.05	8.00

[1] inhabitants with this management alternative; [2] Calculated considering 2.61 kg of CO_2 L^{-1} diesel fuel consumed: 0.5 kg of CO_2 km^{-1}.

Table 6 shows the comparative data in terms of the volume of OFMW to be managed and the carbon footprint of the two proposed alternatives:

As we can see, and as expected, Alternative 2 has a lower environmental impact, being almost 35% lower, as it has fewer vehicle journeys, and always bearing in mind that it has been considered as scope 1 in the impact assessment, the same as other authors' results [15]. Similarly, it should be considered that in Alternative 2, by using prunings from neighborhood gardens in the nearby composting areas, there will also be a reduction in CO_2 emissions that are avoided by this transport.

3.4. End Uses

In terms of the end uses of compost, with respect to areas of use and the seasonality of raw materials, we see it as appropriate to opt for:

- Mixture 1 with 20% OFMW and 40% pruning and seaweed, respectively, could be a recommended mixture from May to September in and around the coastal area, in order to avoid the transport of seaweed.
- Mixture 3, where there is no seaweed and a mixture of residue and pruning: a ratio of 30–70% could be a suitable combination for the inland west of the municipality and on the coast from October to April.

As for compost, it provides innumerable benefits for soil and crops and is basically due to the contribution of organic matter and nutrients, as well as to the physical characteristics of the material itself. These include, according to [10]:

- The recovery and supply of organic matter and nutrients contained in the amendment, providing slow-release macro and micronutrients necessary for crop development and increasing soil organic matter.
- Increased CO_2 fixation (sequestration of part of the organic carbon in the soil). Improved soil structure, leading to improved water infiltration, as well as improved conditions for crop development and the working conditions of the substrate.
- Increase in the cation exchange capacity of the soil, due to the action of the clay–humic complex, increasing its fertility.
- Improved nutrient uptake capacity and water retention capacity of the soil.
- Others: increased soil resilience, the prevention of erosion and desertification, with increased biodiversity and biological activity (development of beneficial soil microorganisms), the substitution of other fertilizers or amendments and peat.

For all these reasons, the main sectors demanding or potentially demanding compost, which can be found in the municipality of Cartagena, are as follows:

- Agricultural sector: conventional agriculture and organic farming. The use of compost for crop fertilization is widespread and has innumerable benefits; it is especially recommended in areas that are classified as sensitive, such as the agricultural areas of Campo de Cartagena surrounding the Mar Menor (Zone 1 of Decree Law 2/2019 of 26 December on the Integral Protection of the Mar Menor) and the areas of Marina de

Cope and Puntas de Calnegre [32]. Similarly, there are numerous rural or agricultural areas in the municipality that can receive the compost produced, given their activity.
- Landscaping and gardening sector, public council and private (companies and domestic).
- The recovery of poor and degraded soils. In the Cartagena area, because of its extensive industrial activity over decades, there are numerous enclaves in need of organic material to form and improve soils for subsequent use.
- Any action requiring topsoil supply, road margins, slope stabilization, landfill rehabilitation, etc.

It should be noted that in agricultural use, the benefits of composting are already being seen in comparison to manure or sewage sludge, as compost is a stable organic material that does not contain pathogens or unwanted plant seeds, and where most of the organic pollutants have been degraded during the composting process itself. Moreover, due to its greater stability, it contributes to a greater extent to the improvement of soil structure, and therefore water retention, and nutrient retention.

Although we know that these initiatives are difficult to implement both in the community composting and self-composting phases, as well as in the management of subsequent use, and as identified by [33], an effort must be made in the information and help support phase to initiate the processes. To help in this transition and optimization of processes and transport, there are numerous works and tools, such as the one carried out in the H2020 project DECISIVE (A Decentralized Management Scheme for Innovative Valorization of Urban Biowaste), explained in [34].

4. Conclusions

In the example of the city of Cartagena, which may be similar to that of many other Mediterranean coastal towns, in addition to OFMW, two other plant residues are identified, the management of which poses a problem for the city council: the pruning of the gardens and *Posidonia oceanica* (L.) Delile, from the beaches in the municipality. From the study of three mixtures of these raw materials, it is concluded that mixtures 1 (20% OFMW and 40% pruning and algae) and 3 (30% OFMW and 70% pruning) obtain good quality values within what is admissible in the regulations, RD 824/2005. In both cases, good nutritional values of NPK are obtained, being 1.23/0.08/1.28 for mixture 1 and 2.22/0.33/3.45 for mixture 3. From mixture 2 (50% PO, 50% pruning), good C/N ratio parameters are not obtained.

Regarding the management of collection and composting, a separation of the organic fraction of the garbage in the homes for the municipality of Cartagena is proposed, as is:

i. A collection of the same through a special biowaste container located in the points where there are the rest containers, with a centralized composting plant. This solution is proposed for the largest population centers, covering a total of 179,548 inhabitants.
ii. For the rest of the population, a total of 30,558 inhabitants, distributed in smaller population centers and scattered hamlets, self-composting and community composting are proposed for the largest nuclei.

Considering the transportation savings that the proposed biowaste management entails, compared to current practices, it has been verified that the carbon footprint in scope 1 is reduced by 35%, from 67.37 t CO_2 eq per year to 43.46 t CO_2 eq.

Taking into account the seasonality of the raw materials, it has been proposed to use mixture 1 from May to September in the coastal area and surroundings to avoid the transport of *Posidonia oceanica* (L.) Delile, and mixture 3, in which there is no Posidonia, for the interior west of the municipality and on the coast from October to April.

The use of this compost is recommended for municipal and local parks and gardens and for the recovery of degraded soils; there are numerous enclaves of the municipality that require the establishment of topsoil.

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