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Decentralized Composting of Organic Waste in a European Rural Region: A Case Study in Allariz (Galicia, Spain)

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Additional information is available at the end of the chapter

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Abstract

The inclusion of sustainability and circular economy principles, as well as the compliance of the European requirements in municipal waste management, involves improving the waste separation, recovery and valorization. The current municipal solid waste management system of Galicia (Northwestern Spain) that includes most of the municipalities involves the treatment of biowaste (mixed in the same container with the nonorganic rest fraction) in a single management facility. This biodegradable fraction, which accounts for 42% of the total amount of household waste, is treated by incineration for energy recovery. The local government of Allariz (Galicia) undertook a project to implement a management model decentralized for biowaste separation and treatment through composting. Municipality structure (type of housing, urban and rural areas, etc.) made it necessary to implement different composting systems: home composters, community composting islands and a dynamic composter. During the first year of start-up of the management model, the level of citizen acceptance was adequate, biowaste was correctly segregated and good quality compost for soil fertilizer was obtained. So, a reduction of around 8% of the mixed waste sent to the centralized treatment facility was observed. The biowaste recovery had also resulted in a recycling improvement of all remainder fractions.

Keywords: compost, organic fraction of municipal waste, circular economy, recycling, citizen participation

1. Introduction

The management and planning of the municipal solid waste produced by citizens in their dwellings is one of the main objectives to be addressed by the circular economy principles. The European Union, in its commitment to the environment and sustainable development, promotes among its members the implementation of concrete measures and actions in order to improve current conditions and establish a legal framework for the proper management of municipal solid waste. The European Parliament adopted the Directive 2008/98/EC on waste [1], laying down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use.

In densely populated and urbanized areas of the European continent, there are many alternatives for the management of this type of waste [2–4] but also in other continents, where the population density is much greater and the establishment of urgent measures becomes an essential work to avoid negative impacts on the environment or human health from household waste [5–7]. But it is also necessary to carry out actions in rural or semirural areas where the management of household waste must be adapted according to the needs of each area so that the objectives established by the regulations can be achieved in viable environmental and economic conditions. In Spain, 23% of the population lives in rural areas, according to the resident population, and the particularities of each zone make it difficult to manage municipal waste correctly [8].

The Spanish law 22/2011 on waste and contaminated soil [9], which transposes European Directive 2008/98/EC, sets the target that, before 2020, the amount of domestic and commercial waste destined for the preparing for reuse and the recycling for paper, metal, glass, plastic, biowaste or other fractions shall be increased to a minimum of overall 50% by weight. This legislation establishes a waste hierarchy with the following order from highest priority to lowest:

- **Prevention:** a set of measures taken at the design, production, distribution and consumption stages of a substance, material or product, to reduce the quantity of waste, the adverse impacts of the generated waste on the environment and human health and the content of harmful substances in materials and products.
- **Preparing for reuse:** include checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused without any other preprocessing.
- **Recycling:** any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations
- **Other recovery,** including energy recovery, when it occurs with a certain level of energy efficiency.
- **Disposal:** any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy

In order to achieve the targets established by the legislation, Spanish municipalities assume different management separate collection systems for household waste. These systems can be summarized in four models in municipalities with more than 50,000 inhabitants and in six models in smaller municipalities of 5000 to 50,000 inhabitants [10]. The Autonomous Community of Galicia, located in the northwest of Spain, has a total area of 29,574 km² and a population of 2,718,525 inhabitants in 2016. With a population density of 92.2 inhab/km², the most urbanized areas are mainly concentrated on the coast, while dispersed and rural population centers are established in the interior and the East of the Community. In Galicia, there are three different collection systems of municipal waste [11] that are summarized in **Figure 1** with the following characteristics:

- Model 1 of the Galician Society of the Environment S.A. (SOGAMA) to which are attached 295 municipalities and that covers 82.5% of the population of the community. Around 805,355 tonnes of waste were managed in the year 2015.
- Model 2 of the Treatment of Urban Waste of A Coruña to which are attached 10 municipalities representing around 14.3% of the population of Galicia. Around 174,318 tonnes of waste were managed in the year 2015.
- Model 3 of Sierra of Barbanza Environmental Complex to which nine municipalities belong, which represents around 3.1% of the Galician population. Around 32,220 tonnes of waste were managed during the year 2015.

All Galician municipalities are adhered to the models presented in **Figure 1** for municipal waste management, and there are no illegal landfills for the fractions considered in this study. The three management models implement containers in the public road for the municipal waste collection where the citizens deposit the waste generated in their homes in different fractions. The three models have independent containers for the separate collection of glass

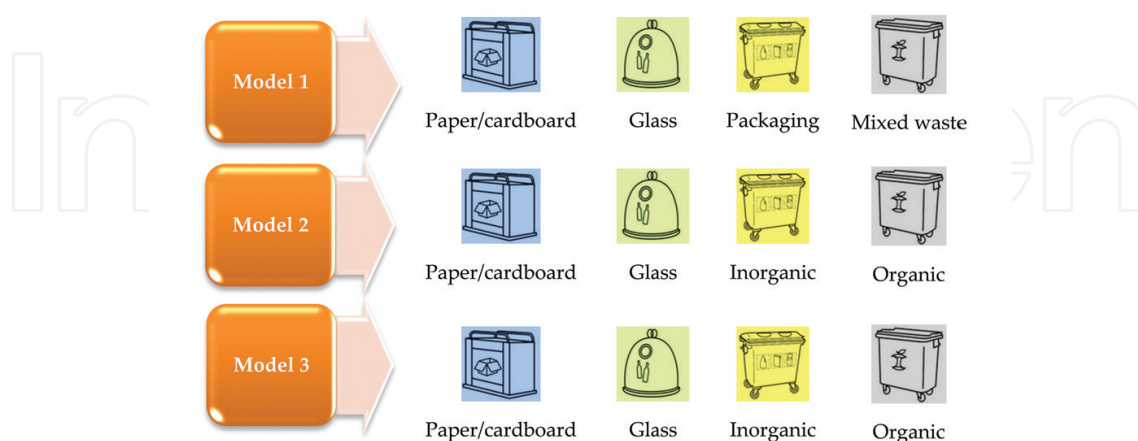


Figure 1. Models for the collection of household waste of the Autonomous Community of Galicia (source: prepared by the authors based on the information from Urban Waste Management Plan of Galicia [11]).

and paper-cardboard, but present substantial differences in the other two containers. In the model 1 (SOGAMA model), there is no differentiated collection of the organic fraction, while in the other two models, there is a differentiated collection of biowaste. The models 2 and 3 have a yellow container for the inorganic fraction where lightweight packaging and the rest of wastes that do not present differentiated separation are deposited and another container for the separate collection of the organic fraction. In the system 1, at the majority of citizens of the community disposal, there is a yellow container where the lightweight packaging (plastic, metal and liquid packaging board) is deposited and another container for the rest or mixed fraction, i.e., all wastes that are not subject to separate collection, in this case, biowaste along with sanitary textiles, ceramic waste, household cleaning waste, etc.

As indicated above, most municipalities of Galicia (82.5% of the population) are included under a centralized municipal waste collection system. So, waste can travel more than 150 km before proceeding to its management in the treatment plant. To SOGAMA's facility arrives the waste deposited in the yellow container and the mixed container (organic and nonrecyclable waste). The materials collected in the lightweight packaging container are classified according to its different typology, and later, they are sent to the recycling centers to be transformed into new products. The waste collected in the mixed container, once separated the materials that can be recycled (steel and aluminum fundamentally), is subjected to an energy recovery process, whereby they are incinerated to produce energy. The biodegradable fraction, which accounts for about 42% of the total amount of wastes generated in housing (**Figure 2**), is not collected in a differentiated way and is segregated together with the wastes deposited in the

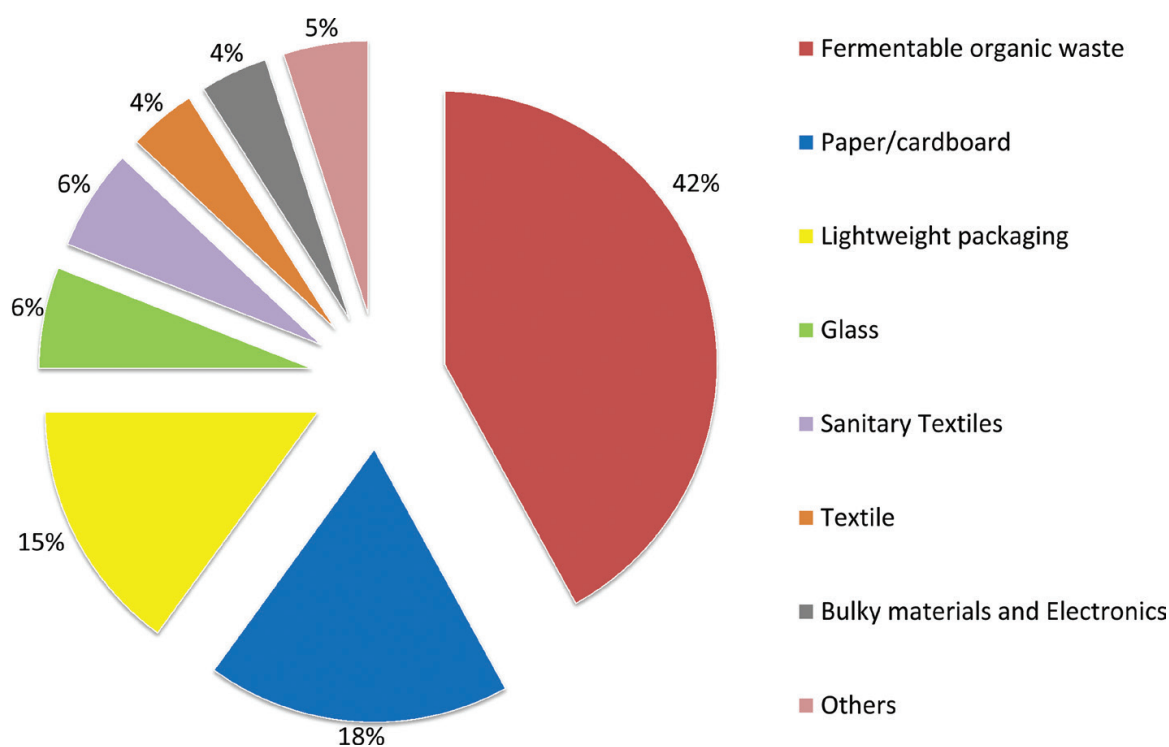


Figure 2. Composition of the household rubbish in Galicia [11].

mixed container. Therefore, the end-use of the biowaste, once it reaches the treatment plant, is the incineration for energy recovery; however, these biowastes have a low calorific value due to their high water content.

The definition of biowaste is described in Spanish law 22/2011 [9] and includes biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants. Both the implementation of sustainability and circular economy criteria in waste management, as well as ensure compliance with European requirements, mean improving the segregation of biowaste and its treatment. Composting is a simple, low-cost recovery technology that enables organic waste and by-products to be transformed into biologically stable materials called compost. The compost can be used as an amendment and/or soil fertilizer and as a substrate for plant growth, reducing the environmental impact of biowastes and making it possible to take advantage of the resources contained in them. Composting is defined as a controlled biooxidative process, which develops on heterogeneous organic substrates in solid state, due to the sequential activity of a great diversity of microorganisms present in the substrate. Under these assumptions, composting of the organic fraction of household waste is presented as an economically accessible and adequate option with the environmental requirements. For example, in India they have bet on the decentralization of composting for this type of waste in cities for several years ago [12]. For that, it is necessary to involve the population in waste separation and the implementation by local entities of composting systems. Finally, it is possible to close the cycle of organic matter by obtaining a product of good quality, compost, for local, community or individual use.

In this way, the start-up of new models of organic waste management in the municipalities through the use of composting is growing exponentially in the Galician community. Composting experiences are being currently carried out in San Sadurniño and municipalities of the province of Pontevedra included in the "Revitaliza" program [13].

2. Case study in Allariz

2.1. Study area

The municipality of Allariz is located in the province of Ourense belonging to the Autonomous Community of Galicia located in the northwest of Spain (**Figure 3**). Allariz has an area of 85.3 km² where a population of 5982 inhabitants distributed in 92 population centers and with a density of 70 inhab/km². According to the indicator of rurality established in Urban Waste Management Plan of Galicia [11] that takes into account, among others, data on population, population density, tourist and commercial level, the municipality of Allariz has a rural character. Allariz is located in the area of influence of the most populous municipality of the province, the urban municipality of Ourense, with approximately 100,000 inhabitants. The population structure of Allariz is distributed, from the interior to the exterior of the municipality, in the old town with housing of different heights, an area with new buildings of heights from three to four and, finally, a more rural area consisting of detached or semidetached houses with garden. In addition, there are also many shops in the town center and an industrial estate on the outskirts. The

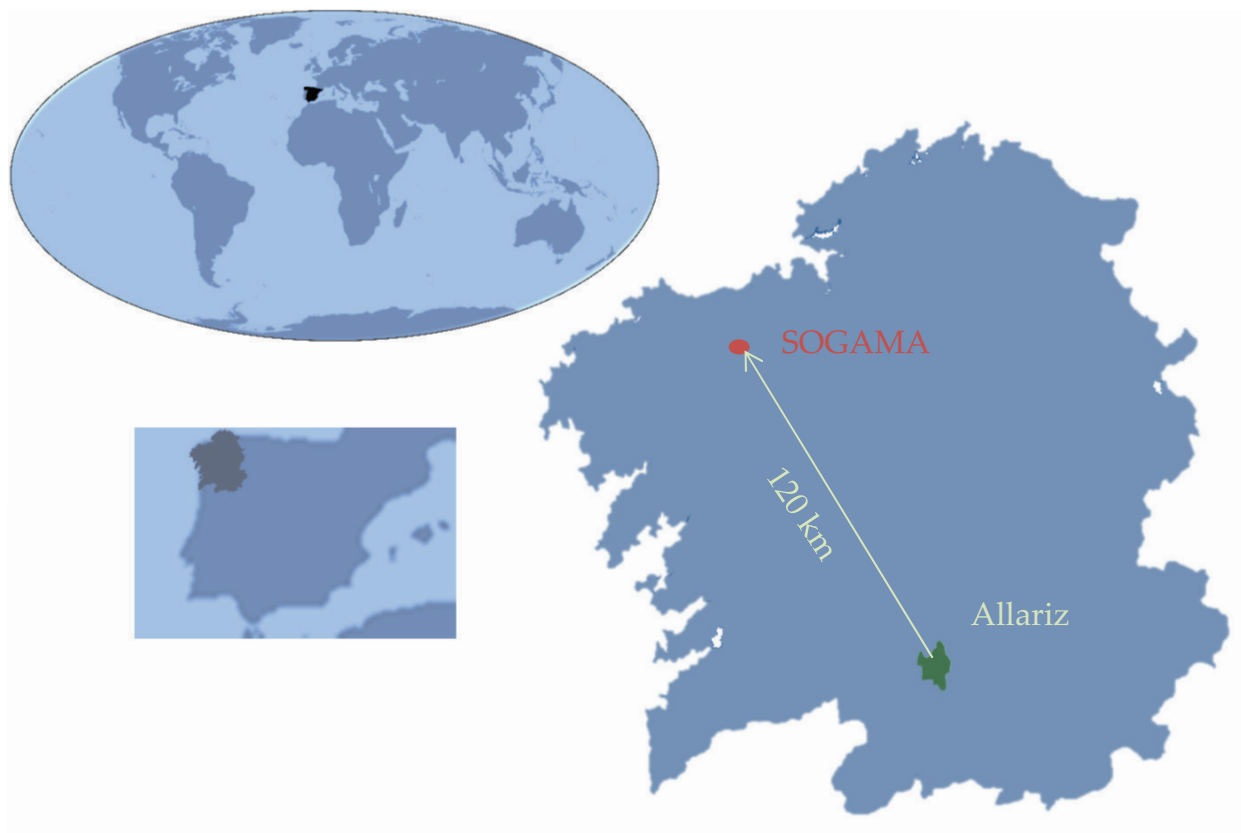


Figure 3. Location of the municipality of Allariz and the waste treatment plant of SOGAMA.

household waste of the mixed fraction and the packaging fraction must travel around 120 km away in a straight line (**Figure 3**).

At the end of 2014, Allariz set in motion to implement the separation, treatment and use of organic matter throughout the municipality. The following action lines were proposed:

- Promotion of single-family self-composting.
- Development and promotion of community composting.
- The specific collection of organic matter coming from big waste producers, such as catering establishments and food companies, for their joint composting.

These action lines aim to increase the recycling rate and minimize the percentage of wastes that are segregated together to be incinerated. Increasing the recovery of biowaste implies diverting them from incineration by reducing the emissions of greenhouse gases emitted during their combustion and their transport. Composting of biowaste produces compost for private or municipal use that allows closing the circle of organic matter by returning to the soil the nutrients extracted by plants and animals during their growth and development. This also leads to a greater use of waste in accordance with the hierarchy imposed by European regulations, and an efficient waste management model capable of contributing to sustainable development is consolidated.

Indirectly, it is also expected that by improving the household waste separation there will be an improvement in the existing separate waste collection of the different fractions: packaging, paperboard and glass. Thanks to increased citizens' environmental awareness can be reduced economic management costs, which arise as a result of the collection, transport and treatment of waste outside the municipality, in addition to environmental costs. The internalization of the organic fraction management in the municipality itself allows the strengthening of employment in a rural region.

Another objective of the plan is to recover the green waste that is generated in the houses with garden and during the maintenance of the green areas of the municipality. This green fraction consists mainly of pruning remains, grass clippings and leaves that can be crushed to be used as a structuring agent in the composting of biowaste.

2.2. Methodology

2.2.1. Composting process

Composting is a controlled biooxidative process, in which a heterogeneous organic substrate undergoes a thermophilic stage and a transient release of phytotoxins, obtaining as products: carbon dioxide, water, minerals and stabilized organic matter called compost [14]. Due to the high microbial activity during the composting process, the temperature increases and accelerates the degradation and mineralization of the organic matter. Changes in temperature throughout the process allow differentiating four phases [15]:

- Mesophilic phase: characterized by the increase of the temperature from values close to the ambient temperature until reaching approximately 45°C. During this phase, the mesophilic microorganisms begin to slowly degrade the organic matter.
- Thermophilic phase: at temperatures above 40°C, the mesophilic activity drops, and the degradation begins a thermophilic stage, reaching values of 60–70°C. The thermophilic phase is very important, since reaching temperatures of this magnitude produces pasteurization of the product, destroying the pathogenic microorganisms and seeds of invasive plant species, so this ensures the hygienization of the material produced. From the 80°C, excessive heat can cause the death of most microorganisms to stop the degradation activity, so the composting must be controlled so that these temperatures are not exceeded.
- Cooling phase: the mixture begins to cool because easily degradable materials have been consumed during the mesophilic phase and mainly in the thermophilic phase. As a consequence of this, a return to the mesophilic stage occurs and the temperature drops to near the values of the ambient temperature.
- Maturation phase: at this stage, complex secondary condensation and polymerization reactions occur, which results to the compost as final product. It is necessary that this phase has the duration such that the material acquires the maturity and the necessary stability of an organic amendment of agricultural application.

2.2.2. Composting systems

Thus, the implementation of the biowaste management model through composting was carried out at three levels:

- Individual composters for single-family houses. A total of 220 family composters were given voluntarily to the residents and with the only obligation to use the composter bin in order to treat the organic household waste to obtain compost. These individual composters have a volume of 300 L and, mainly, were delivered to homes away from community composters. The methodology used in these composters basically consists of alternating layers of biowaste with layers formed by leaf litter, crushed grass, chip or shredded pruning wastes that can be obtained in the garden of the participants themselves. In this system, composter users and those responsible for obtaining the compost are the family that generates the biowaste, and the municipality staff undertakes to carry out training and questioning by users.
- Community composters for residential areas and buildings of various heights. The municipality of Allariz implemented a total of 24 composting islands (areas for the placement of a group of composters) located on public land in urban and periurban areas with more than 130 composters. Each composter has 1000 L of capacity and is considered to accept the organic matter deposited by approximately 15 families. These modular composters are made of recycled plastic slats that enable the walls to be completely removable and have the advantage of work as independent or dependent modules of composting, making easier the movement and transfer of compost. Each island is constituted up of a number of modules that depend on the volume of population they serve. Bulking agent used in this system is shredded wood that comes from a biomass company located in the industrial estate of the municipality and the green waste provided by neighbors and municipal services. The work of the neighbors/participants focuses on separating correctly the organic fraction generated in their dwellings, getting a waste free of improper materials such as plastics, metals or glass, and transferring the biowaste to the nearest composting island. The town council distributed 10 L cubes to the neighbors to facilitate the transfer of biowaste. The organic fraction deposited in the composters, called the contribution composters, must be covered with the bulking agent, present in all the islands, to avoid the appearance of insects and odors. The other composters of the island, other than those of contribution, are used in the maturation of compost. The responsibility of the municipal staff is to carry out the works of mixing, irrigation, screening, turning and transferring between composters of the material, as well as to distribute the compost to the neighbors who have participated in this initiative.
- Dynamic composter for biowaste produced by big waste producers. This dynamic bioreactor Big Hanna model T120 consists of a rotating cylinder orientated horizontally with temperature sensors at different positions along the cylinder and a continuous aeration with fan. Biowaste is fed through a screw conveyor in the hopper situated in the front of the composter, rotation of the cylinder moves the material and the compost is emptied through the back side after about 8 weeks. The bioreactor can accept a load of 300–500 kg per week and has a capacity of about 3 m³. In this electric bioreactor, the periodic rotation of the cylinder itself produces the material mixture and helps the aeration of the material accelerating the decomposition of the organic matter. The municipal staff collects the organic matter generated

and separated by the catering establishments and food companies to be transferred to the bioreactor. The bioreactor is designed to use pellets as a control material for excess moisture produced during the process and is added together with the biowaste in the hopper by the municipal staff. After the composting cycle, the pellets become part of the final compost. The compost generated in the bioreactor is sieved by a 1-cm mesh and transferred to a composter until it reaches the parameters of maturity and stability enough to be applied to the soil with quality assurances.

The planning, distribution and start-up of the model were carried out along with information, training and awareness campaigns to the neighbors and the different parts involved in the model. The educational work of the citizens gave appropriate answers to the doubts and questions asked by the users. On the other hand, the choice of the message conditions the content, which must always be accurate and verified, and also transmitted with simplicity and clarity to achieve the objectives of the campaign. Knowing the municipality, its territory and its idiosyncrasy, helps in understanding the demands and terms of the message to be transmitted. **Figure 4** shows the poster that is present in the community composting islands of Allariz. With this poster, it is intended to draw the attention of neighbors, but also of tourists and visitors, increasing the initiative's visibility.

Therefore, the development of this management model was carried out jointly with the activities of dissemination and education through training and awareness talks to the citizens of Allariz, in both the rural area and the old town. Accordingly, it is worth noting the activities carried out for children in schools taking advantage of the cross-curricular thematic of waste management in school curricula. In addition, door-to-door visits were made to inform about the advantages of composting and 600 cubes of 10 L of capacity were delivered to the neighbors to transport their biowaste to the community composters and to the individual composter. For the composting of the biowaste produced by the big waste producers, 20 containers of 120 L of capacity were distributed and a schedule of door-to-door collection was established.



Figure 4. (a) Community composting island with an area of green waste contribution on the left and composters on the right. (b) Detail of one of the informative posters.

Training activities and follow-up work on the individual composters were carried out by the Association for the Ecological Defense of Galicia (ADEGA). The staff of the Ramón González Ferreiro Foundation, together with the municipal staff of Allariz, monitor daily (from Monday to Friday) the community composting islands, performing data collection works on temperature, moisture, type of material contributed, etc., and also place informative panels on these islands on the inappropriate uses that are detected. The implementation of corrective measures of problems encountered, such as excessive grass feed, presence of thick pruning remains or improper inputs, is essential for participants to learn in the most appropriate way and obtain good quality compost without causing odors, insect problems or other annoyances.

The Environmental Biotechnology group of the University of Vigo carried out the sampling and analysis of compost, both from the community composters and from the bioreactor for the biowaste of the big producers. In total, 29 samples of compost were analyzed and 5 characterizations of the bioreactor input material were performed.

Once the samples were analyzed and the data obtained were evaluated, the compost was distributed to the participating neighbors. These types of events are an important part of the training of citizens because the delivery of the final compost is valued as an award for participation and volunteer work. At this time of learning, citizens who do not have the opportunity to do compost in their own homes see as their work of separation and transfer of a substance, from which they are going to be undone because it has no value, is transformed into a product that can be used in flowerpots or urban gardens. The concept “from waste to compost” helps to a greater implication of the citizens in the model and greater awareness of environmental care with a change of mentality toward a perception of waste to resource, which leads to an improvement in the selective collection of all fractions and the quality of these fractions.

2.2.3. *Bulking agent*

The need to mix biowaste with a material that provides porosity, in order to facilitate the aerobic conditions for the composting process, becomes the key factor of the bulking agents. However, porosity is not the only intrinsic property required of a good bulking agent, but also, *inter alia*, its ability to capture and/or cede water according to the needs of the process [16]. The complexity and heterogeneity of the biowaste deposited by the neighbors involves a great variability in the moisture values. Thus, while the remains of fruit and vegetables are high in water, the bread, eggshell or fish remains have a lower content. The initial moisture content of biowaste is around 70–80% [17]. However, the continuous contribution of biowaste by citizens causes materials with different degree of degradation to be mixed inside the composter, causing variations in the density and humidity of the material. The physical, chemical and microbiological characteristics of the bulking agent are determinant, and all of them will influence, to a greater or lesser extent, the composting process. In this way, it is necessary to take into account the characteristics of the bulking agent, using the appropriate machinery, tools and handling, which provides the best conditions of this key factor.

The type of bulking varies depending on the composting system used. In the individual composters, biowaste is supplied by layers and is covered by green wastes from the dwelling of the participants: leaves, straw or shredded pruning. As for the bioreactor, it is designed to use pellet as a moisture control material. For community composters, mainly crushed wood is used as bulking. This material is represented mainly by a particle size of 1–2 cm with an average of 43% (**Figure 5**). This size stands out above the others because, on the one hand, it provides a greater porosity to the mixture without damaging the increase in temperature and, on the other hand, a considerable part of this fraction is recovered for the next composting cycle. The particle size of the bulking agent must be balanced. The thicker fractions have a higher percentage of recovery, so that when sifting the compost this fraction is recovered and can be recirculated for a new cycle of composting. However, particle sizes greater than 2 cm increase to a large extent the presence of macropores in the biowaste, which, if their percentage in the mixture is very high, can cause a decrease in temperature by an excess of aeration. The compost is usually sieved around 1 cm, so that bulking fractions smaller than this size are not recovered in the screening process and become part of the compost. In addition, an excess of small particles can fill the pores and complicate the aeration of the waste during the process.

To size the needs of the bulking agent, the particle size distribution provides very important information. In those moments in which there are difficulties in getting bulking agent, it is necessary to pay attention to the recovery rates of this one because this material degrades in the process and the finer particle sizes are not recovered, once it passes through the sieve, to recirculate and to use in another composting cycle.

On the other hand, it is convenient to deposit the bulking agent in a box protected from rain in order to control the moisture content of the compost by irrigation in all the three systems.

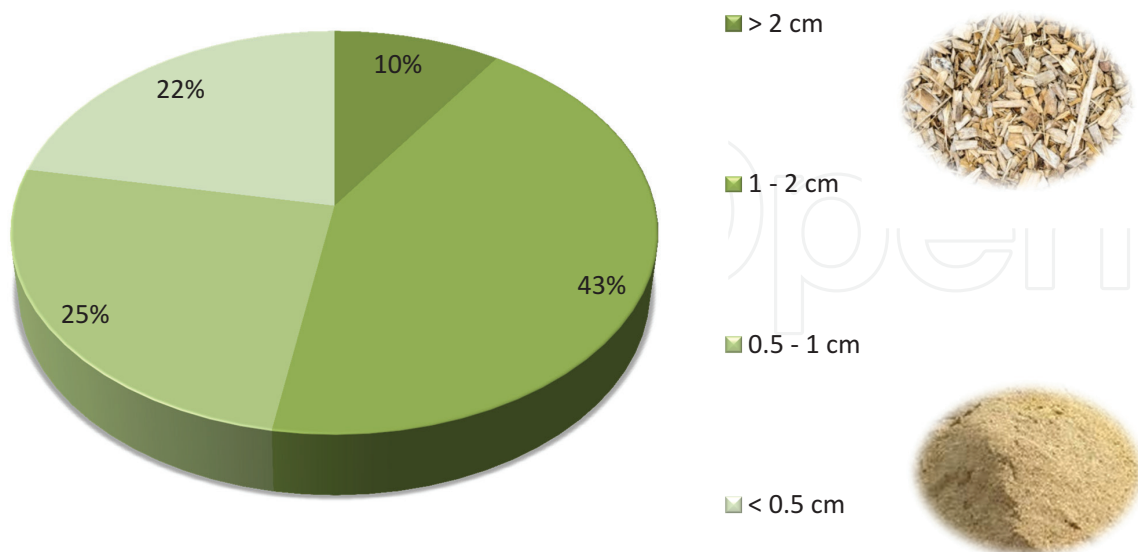


Figure 5. Particle size distribution of the bulking agent used in community composters (source: prepared by the authors based on the results of this study).

An excess of moisture during composting can produce bad smells due to the saturating the mixture. A pronounced decrease in moisture, as a consequence of the loss of water produced by the elevated temperatures inside the composter [18], must be compensated by irrigation in order not to stop the degradation of organic matter. In community composters, the green waste used for neighbors to cover biowaste has a greater effect the drier the bulking agent, reducing the odors released by them. During periods of time when municipal staff is not present to mix the bulking agent with biowaste, anaerobic episodes can occur due to the absence of porosity of the organic matter provided by the neighbors, in turn these materials may have several days in the cube or bag which may increase the presence of putrid odors resulting from anoxic decomposition. For this reason, a bulking agent capable of retaining these emissions, as long as the structure of the material is not corrected, can minimize odors and avoid possible annoyances to citizens

2.3. Results and discussion

2.3.1. Composting systems

In the three composting systems, periodic monitoring was carried out by members of the city council and collaborating entities in order to implement the changes in the management model and to control the composting process of biowaste. **Figure 6** shows a small summary of the versatility conditions presented by the three systems.

All the systems implemented in the decentralized model present several advantages depending on the needs of the user collective, being decisive variables such as the volume of waste production, the availability of an appropriate place for the development of the system, the necessary resources and, fundamentally, the economic cost that each system has.

The frequency with which the household waste is deposited varies in relation to the distance that the neighbors have to travel to deposit their wastes [19]. Thus, in the rural areas, the presence of individual composters is common due, among other factors, to the distance separating houses from containers. Other factors such as climatology, waste disposal schedule, reduction of biowaste and the need for a fertilizer for the orchard or garden are considered to be advantages of individual composting. At the level of the composting process, it should be noted that unlike individual composters, the modular system of community composters facilitates the emptying and transfer of the composted material, thanks to the simple manipulation of the plastic slats. At the same time, the use of this recycled plastic involves a reduction of up to 52% in environmental loads due to savings in raw materials, energy and emissions [17]. Another advantage that presents this modular system of composting is the activator effect that provides the proximity of the composters. This is because the proximity of a module with thermophilic temperatures facilitates the activation of the composting process in the nearest modules, reducing the effect caused by the low ambient temperatures that can occur at night or in colder seasons.

The effect created by the volume of material to be treated also has consequences in the process. The individual composters, with smaller volume, are more influenced by ambient temperatures than the material present in the community composters and, above all, the material of the biore-

	Individual composter	Community composter	Big Hanna bioreactor
			
Does the bio-waste leave the home?	No	Yes	Yes
Does the material reach thermophilic temperatures?	Lacks continuity	Yes	Yes
Is there a continuous contribution?	No	Yes	Yes
Is a collection schedule necessary?	No	No	Yes
Municipal management	No	Yes	Yes
Economic cost	Low	Medium	High
Level of physical effort	Low	High	Medium

Figure 6. Comparison of the three composting systems set up in the municipality of Allariz: individual composter, community composter and bioreactor for large producers.

actor that presents greater volume and isolation with the exterior. In addition to these reasons, the frequency of biowaste inputs to an individual composter depends to a large extent on the size of the family residing in the dwelling, i.e., small families of two or three members generate less volume of biowaste to feed the composter. Based on these premises, the individual composting lacks the intensity of the other two systems and, consequently, more time is necessary to produce compost. It is considered that the addition of meat and fish remains can accelerate the composting process [20].

The compost that is obtained in the bioreactor still lacks a state of maturity and stability required to be applied to the soil [21], in a system as a composter or through another system, to reach the conditions established by the legislation, reason being additional space is required for maturation [22]. In addition, the bioreactor system presents greater economic cost due to the high investment in the equipment purchase. To this must be added the cost for the collection and transfer of the organic waste, which is carried out in a determined schedule, and the cost of personnel for loading, unloading and control of the process.

2.3.2. Community composters

To evaluate the quality of compost generated in the community composting islands, these were analyzed before being delivered to the participants. A summary of the data of the 19 composts sampled in January 2017 are shown in **Table 1**, which also shows the variability of the samples on the general characteristics established by the legislation on fertilizer products [23] and other important parameters of stability and maturation [24, 25]:

- **Compacted bulk density.** Compost presented an important variability in this parameter and was betwefact that this parameter is affected mainly by the moisture and the distribution of the particles. As the organic matter degrades, the number of smaller particles increases, causing an increase in the bulk density. The higher the density, the lower the capacity to maintain adequate porosity values and higher compaction, although very low densities indicate numerous air spaces that can make water difficult for plants. The presence of particles of bulking agent in some composts caused the density decrease while the high moisture detected in several of them allowed higher densities.
- **Stones and others inert materials.** Both inert materials and stones are small-sized materials that remain at the end of the composting process and cannot be separated by refinement. 100% of the analyzed samples had a percentage less than 0.1% of inert materials greater than 2 mm. This is due, mainly, to the good separation of the wastes by the participants, which allows obtaining a very pure organic fraction and with a low presence of improper ones. In addition, the content of stones greater than 5 mm did not exceed 0.1%. The community composting system allows that once detected certain errors in the separation, these can be corrected through different mechanisms such as meetings with neighbors, information talks, e-mail messages or simply by direct contact with the participants.
- **pH.** At the beginning of the process, the biowaste deposited by the neighbors has a normally acidic pH due to its high water content and easily degradable organic matter. This measure is usually corrected until neutral and slightly alkaline values are reached in the final compost. With regard to the application of compost, considering that in Galicia most soils and water are acidic, it is advisable that organic amendments have a slightly basic pH to correct soil acidity and improve crop growth. All samples exceed pH 7, and one sample is above 8.
- **Electrical conductivity.** The evolution of this parameter is very important for final application of the compost to the soil since a high content can cause adverse effects on the germination and the growth of the plants. As the transformation of waste into compost progresses, salts

	Mean	S	Median	Percentile 2.5	Percentile 97.5
Inert materials > 2 mm (% sms)	<0.1	–	–	–	–
Stones > 5 mm (% sms)	<0.1	–	–	–	–
Bulk density compacted (g L ⁻¹)	396.70	104.02	376.52	254.64	577.50
Moisture (%)	57.67	13.15	61.15	33.82	75.12
Organic matter (%)	61.79	15.23	66.63	26.10	75.71
pH	7.66	0.26	7.70	7.17	8.04
Electrical conductivity (mS cm ⁻¹)	1.21	0.51	1.18	0.47	2.16
Total carbon (%)	29.20	8.31	34.05	11.10	36.12
Total nitrogen (%)	2.39	0.71	2.45	1.04	3.25
C/N ratio	12.25	1.28	12.00	10.14	13.90
N-NH ₄ ⁺ (mg kg ⁻¹)	163.3	389.8	77.1	28.3	1029.6
N-NO ₃ ⁻ + N-NO ₂ ⁻ (mg kg ⁻¹)	55.4	26.6	51.5	21.8	109.1
CaO (%)	6.88	3.24	6.40	2.00	13.68
K ₂ O (%)	1.73	0.68	1.81	0.67	2.67
MgO (%)	0.50	0.08	0.51	0.33	0.60
P ₂ O ₅ (%)	1.43	0.51	1.29	0.52	2.17
SO ₃ (%)	0.71	0.25	0.76	0.24	1.07
FeO (%)	0.41	0.20	0.35	0.20	0.83
Co (mg kg ⁻¹)	2.85	1.43	2.78	0.99	5.41
Mn (mg kg ⁻¹)	185.90	68.28	172.66	101.28	319.80
Mo (mg kg ⁻¹)	2.05	0.93	1.84	0.97	3.91
Germination index (%)	86.5	17.1	89.2	60.4	115.2
Maturation degree	IV–V	–	–	–	–
<i>Salmonella spp</i> (in 25 g)	Absence	–	–	–	–
<i>Escherichia coli</i> (ufc/g)	<1000	–	–	–	–

Table 1. Maturity and stability parameters in compost from community composters (source: prepared by the authors based on the results of this study).

and mineral components with different solubility are released. Irrigation during the process can reduce the content of these through the leachate. More than 60% of the samples had values higher than 1 dS m^{-1} , although only two samples exceeded values of 2 dS m^{-1} . Therefore, in this parameter, the use of compost does not present a risk to plant development.

- **Organic matter.** During the composting process, the intense microbial activity and high temperatures cause a reduction of the organic matter, in more or less proportion. Taking into account that compost is a product to be applied as an organic amendment, it is assessed that it must have a significant content in organic matter, above 40% [23], but that the organic matter is sufficiently stable. In this way, the analysis of parameters indicative of stability such as the self-heating test and the C/N ratio are performed. The self-heating test measures the heat released during microbial activity by classifying the material into five classes according to their maturity. All composts were classified according to their stability in classes IV and V indicative of mature compost. The values of the C/N ratio were all lower than 20 which are considered an adequate ratio for compost, although values below 12 are considered preferable [25], presenting 50% of the compost values lower than 12. According to the TMECC [24], the C/N ratio of compost is not an independent indicator of stability or maturity, so other indicators such as respirometry, pH, bulk density, organic matter reduction and self-heating must be considered.
- Another important value of maturity and stability is the germination index that is calculated by germination and root length of seeds growing in aqueous extracts of compost. Values higher than 80% are indicative of mature compost and the absence of phytotoxic compounds for plant growth being values below 50% indicative of immature compost [26, 27]. More than 60% of the samples reached values above 80%, which demonstrated a high degree of maturity, and none of the samples presented values below 50%.
- The content of pathogens was in accordance with the parameters proposed by the legislation and without exceeding the maximum levels of microorganisms. This is mainly due to the high temperature values reached during composting [20]. By means of the taking of temperatures, an evolution is detected according to the process of composting, reaching values that are around 60°C during the thermophilic phase. There are also sharp falls in temperature during the thermophilic phase due to occasional drops in the contribution of biowaste from the neighbors or sharp declines in the ambient temperature. Other factors that can affect the temperature are an excess of ventilation in the composters, although the composters that are closed can enter air of the outside, or also rainwater entries retained in the cap that enters the composter when the neighbors open it to deposit the waste. In addition, temperature oscillation is common throughout the maturation in community composters, which is due to the reactivation of the material by turning and homogenizing it. In this process, the material closest to the walls of the composter is usually wetter and less decomposed than the material inside the mass, and mixing these materials can trigger an increase in activity with the consequent increase in temperature. In addition, the increase of the ambient temperature or the increase of the solar exposition of the composters can reactivate the interior temperature of the material.

- Ammoniacal nitrogen. A single sample had higher ammonium values than those considered suitable for compost, 400 mg kg^{-1} [14], hence the high standard deviation indicated in the **Table 1**. The high ammonium content could be a consequence of problems of degradation of the organic matter during the composting process due to a lack of moisture in this sample.
- Total nutrient contents provide a measure of compost fertilization potential and, however, do not allow determining the bioavailability of these elements for the growth of plants and microorganisms living in the soil. Compost produced from biowaste presents a high proportion of reserve nutrients such as P, Mg, K and Ca, these macronutrients can reach values higher than other substrates, such as peat, and contain the amounts necessary for the growth of plants [28].

The Spanish legislation on compost, Royal Decree 506/2013 of 28 June on fertilizers [23], classifies compost into three categories according to the heavy metal content: classes A, B and C. **Figure 7** provides information on the content in heavy metals, indicating the frequency of samples corresponding to class A, B or C. All samples have a concentration below the class A threshold for cadmium, copper, lead and mercury with concentrations below 50% of the class A limit in copper, lead and mercury. For zinc, the concentrations detected in more than 70% of the samples meet the threshold of class A and the remaining ones are classified within class B. On the con-

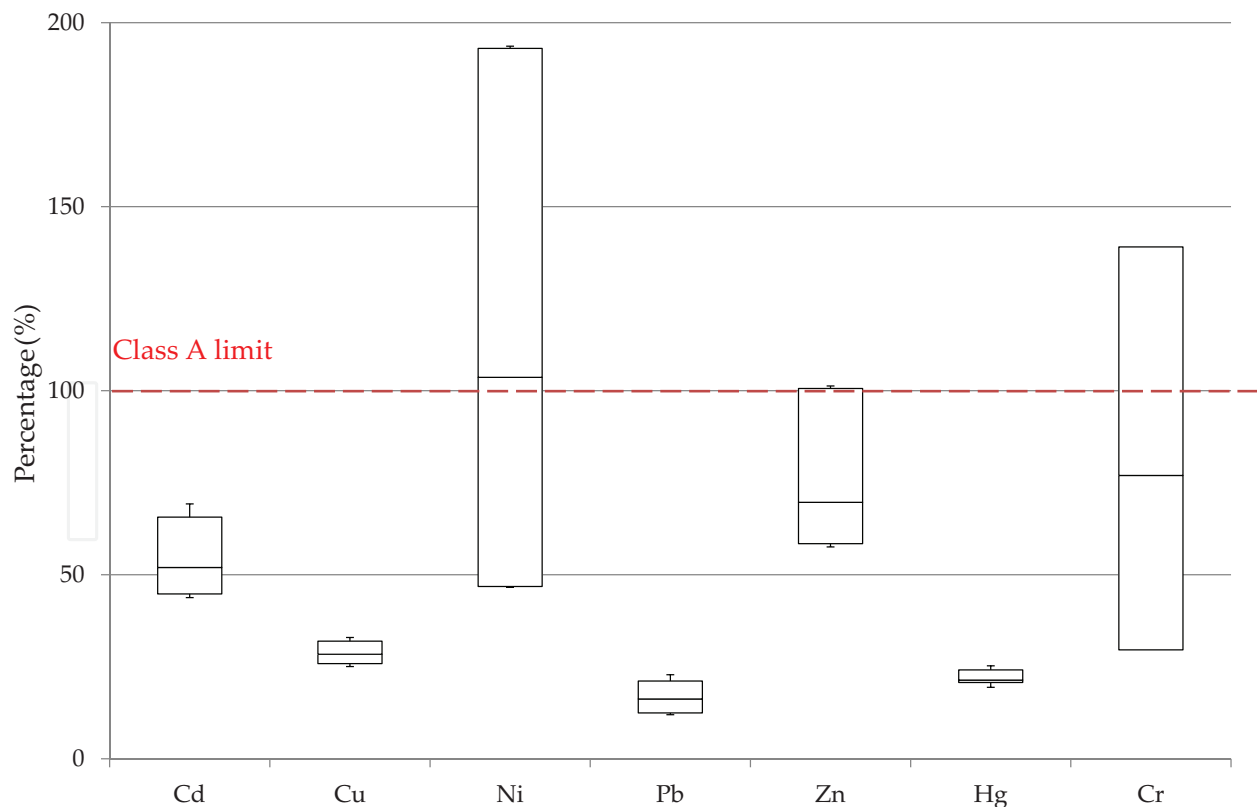


Figure 7. Boxplot with the heavy metals analyzed in the 19 compost samples generated in the community composters. Red line indicates the corresponding 100% with class A of compost.

trary, the samples show very high concentrations for chromium (37% of the samples are class B) and above all for nickel (53% of the samples are class B). The presence of these heavy metals in the final compost may have different sources, such as the presence of improper materials as elements outside the organic fraction of municipal waste selectively collected. On the other hand, Ansorena [17] concluded that the heavy metal content of the compost can be affected by the pollution of diverse exogenous sources and whose origin can be found in the auxiliary materials used, the environment, the process or the storage. The author shows as an example that in the composting plant of Lapatx (Guipuzkoa, Spain) high concentrations of nickel and chromium were detected and the analyses indicated that the material used as bulking agent contributed important amounts of these metals. Hence, more research is needed to find the source of nickel and chromium in the compost from community composters. Thus, compost obtained can be used without restriction for gardening and cultivation of fruit trees although its use should be valued for horticultural crops in compost of class B.

The compost sampled and analyzed are the first obtained after the start-up of the community composting system. In general, it is observed that the system allows the adequate management of the household biowaste, being necessary to determine the source of the contamination by heavy metals and to carry on with the continuous improvement of the system. In addition, as the population and municipal services assume more, experience and knowledge of the process will improve the system and quality of compost.

2.3.3. *Dynamic in-vessel composting*

Five characterizations of the input biowaste in the bioreactor were carried out, and nine samples of the output material of the bioreactor were analyzed. The material removed from the bioreactor during the first months of 2016 was sieved by a 1-cm mesh and matured in a composter taking samples at 2 months and 4 months of maturation. These values are represented in **Table 2**.

During the characterization of the input material of the bioreactor, it was observed that the percentage of improper ones is below 1% in fresh sample. The presence of plastic, metallic or glass wastes mixed with the input biowaste had a very low frequency, and their separation was carried out during the loading tasks in the bioreactor. This factor is important since the presence of improper ones causes pollutions in the organic material, so their absence makes possible that the levels of heavy metals classify the compost obtained by this system as fertilizer of class A, and therefore, in a compost without restriction of use. The low level of improper one indicates an adequate work of awareness of the big producer participants in the separation of biowaste. On the other hand, most biowastes introduced into the bioreactor, an average of 62%, were post-cooked wastes (leftover bread, pasta and vegetables), 26% were pre-cooked biowastes (peels, vegetables and fruits) and 12% were traces of paper napkins. The great presence of organic matter in a cooking process facilitates the biodegradation of the most resistant components.

During the composting process inside the bioreactor, there were high temperatures reaching 60°C because, as indicated in Ref. [29], the turnings significantly increase the duration of the thermophilic phase and, consequently, a greater degradation of the organic material. The turning of the material caused by the rotation of the drum facilitated the homogenization and the mixing

	T0	T1	T2
Inert materials > 2 mm (% sms)	<0.1	<0.1	<0.1
Stones > 5 mm (% sms)	<0.1	<0.1	<0.1
Bulk density compacted (g L ⁻¹)	385.72 ± 35.01	339.57 ± 32.1	468.22 ± 22.7
Moisture (%)	15.99 ± 0.8	31.20 ± 13.8	57.33 ± 10.7
Organic matter (%)	88.75 ± 2.2	84.53 ± 13.3	66.48 ± 9.1
pH	8.83 ± 0.5	8.24 ± 0.5	8.30 ± 0.5
Electrical conductivity (mS.cm ⁻¹)	4.59 ± 0.7	2.52 ± 0.4	1.17 ± 0.2
Total carbon (%)	42.65 ± 0.4	41.1 ± 2.2	31.72 ± 1.9
Total nitrogen (%)	2.02 ± 0.4	2.54 ± 0.4	2.16 ± 0.2
C/N ratio	21.5 ± 4.2	16.18 ± 1.1	14.69 ± 0.9
N-NH ₄ ⁺ (mg kg ⁻¹)	1686 ± 465	504.4 ± 2.7	68.2 ± 2.8
N-NO ₃ ⁻ + N-NO ₂ ⁻ (mg kg ⁻¹)	100.3 ± 2.5	94.6 ± 2.3	120 ± 5.6
CaO (%)	3.98 ± 0.85	5.33 ± 0.9	4.98 ± 0.3
K ₂ O (%)	1.09 ± 0.31	1.78 ± 0.6	0.97 ± 0.5
MgO (%)	0.32 ± 0.19	0.45 ± 0.2	0.38 ± 0.1
P ₂ O ₅ (%)	0.88 ± 0.46	1.43 ± 0.4	1.24 ± 0.3
Cd (mg kg ⁻¹)	0.50 ± 0.2	0.47 ± 0.1	0.48 ± 0.1
Cr (mg kg ⁻¹)	8.61 ± 3.5	12.5 ± 1.8	35.6 ± 3.2
Cu (mg kg ⁻¹)	20.07 ± 15.9	21.7 ± 4.7	19.2 ± 3.5
Ni (mg kg ⁻¹)	4.46 ± 2.3	6.69 ± 2.7	17.50 ± 4.2
Pb (mg kg ⁻¹)	4.26 ± 3.72	<4.0	<4.0
Zn (mg kg ⁻¹)	88.37 ± 70.05	113 ± 34	112 ± 29
Hg (mg kg ⁻¹)	0.09 ± 0.02	0.06 ± 0.03	0.07 ± 0.02
Germination index (%)	76.99 ± 16.2	77.2 ± 1.5	87.45 ± 2.0
Maturation degree	II	IV	V
<i>Salmonella spp</i> (in 25 g)	Absence	Absence	Absence
<i>Escherichia coli</i> (ufc/g)	<10	<10	<10

T0 material after 8 weeks in the bioreactor, T1 compost matured during 2 months, T2 compost matured during 4 months.

Table 2. Maturity and stability parameters in compost from Big Hanna composter (source: prepared by the authors based on the results of this study).

of the material, achieving the elevation of the temperatures until lowering the moisture to values below 30%. These low values can cause water stress in microorganisms by slowing down the process [30] and inhibiting the degradation of biowaste. In order to obtain compost with better conditions of maturity and stability, the compost of the bioreactor output was matured in plastic composters.

The compacted bulk density of the compost at the exit of the bioreactor is low which may be due to the presence of pellets which are mixed at the inlet with the biowaste. The pellet absorbs, on the one hand, the excess water present in the biowaste and, on the other, the metabolic water produced during the degradation of the material, losing its structural stability [31]. This reduces the presence of leachates and bad odors during the process but causes a decrease in compost density.

The quality of the compost obtained is the result of an optimal separation of the waste by the establishments adhered to the program, which allowed obtaining a very pure organic fraction with a low presence of improper ones and other materials like stones. Hundred percent of the analyzed samples had a percentage less than 0.1% of impurities greater than 2 mm, and no stones larger than 5 mm were found.

The reduction of organic matter during the process leads to an increase in the concentration of some heavy metals (**Table 2**); however, the quality of the biowaste and the lack of external pollutions allow all the samples analyzed to have a concentration below the threshold of class A established by the Spanish regulations for Cd, Cr, Cu, Ni, Pb, Zn and Hg.

As in community composters, the presence of high temperatures during the thermophilic phase reduces the content of pathogens to values below the levels allowed by state legislation for both *Salmonella spp* and *Escherichia coli* levels.

Thus, the compost is a product free of pathogens and seeds, as a consequence of the pasteurization to which the waste is submitted inside the bioreactor, but that is unstable and self-heating when adding water and oxygenates it by turnings. In this way, the maturation process of the compost allows to improve the parameters of pH, electrical conductivity, C/N ratio, ammoniacal nitrogen, germination index and self-heating test. In 2 months, turnings and the moistening of the compost allow its stabilization and, after 4 months, the mineralization of the organic matter is improved, reaching optimum quality parameters. Therefore, the Big Hanna compost must be matured with mixing and irrigation for at least 2 months to obtain compost that meets the criteria of stability and maturity. In addition, the performance of maturation in composters or similar systems avoids cross-contamination and protects the material from drying and excessive leaching by precipitation.

2.3.4. Other waste fractions

The complete implementation of the decentralized model of Allariz (door-to-door collection of large producers, individual composting and community composting) was carried out during the spring of 2016. **Figure 8** and **9** shows the corresponding monthly data of the fractions of waste collected by the municipality according to the SOGAMA model implemented: glass fraction, paper-cardboard fraction, lightweight packaging fraction and mixed or rest

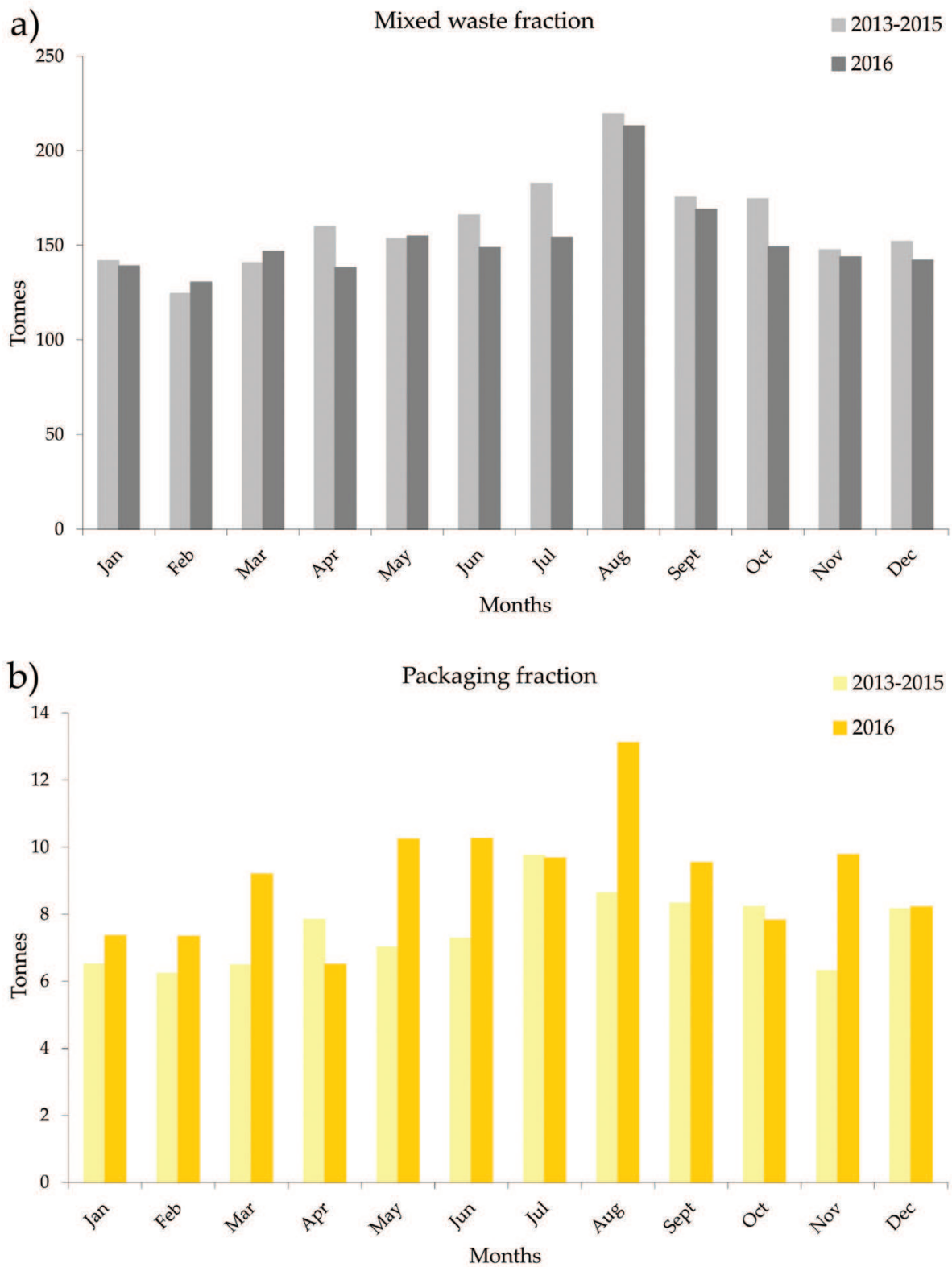


Figure 8. Different fractions collected in the municipality of Allariz: (a) average monthly production of the years 2013–2015 vs monthly production of the year 2016 of the mixed fraction, (b) average monthly production of the years 2013–2015 vs monthly production of the year 2016 of the lightweight packaging fraction.

fraction. It is noteworthy that the results show how Allariz is a rural municipality in which the presence of tourists and neighbors with second dwelling increases during the summer months, especially the month of August. The amount of waste collected during the summer period can be up to 40% higher than that collected in the months of lower production.

During the period beginning in the spring of 2016 until the end of the year, a reduction in the mixed fraction tonnes sent to SOGAMA by 7.3% over the average monthly tonnes delivered during the years 2013–2015 was observed (**Figure 8a**). The collection rate of mixed waste in the year 2016 was 0.838 kg/inhab/day. The reduction in the mixed fraction collected was accompanied by:

- An increase of 20.1% in the collection of the lightweight packaging fraction with respect to the years 2013–2015 (**Figure 8b**). The collection rate of lightweight packaging fraction in the year 2016 was 0.050 kg/inhab/day.
- An increase of 8.5% in the paper-cardboard fraction with respect to the years 2014–2015 (**Figure 9b**) (there was no selective collection of this fraction in containers in 2013). The collection rate of paper-cardboard fraction in the year 2016 was 0.045 kg/inhab/day.
- An increase in the collection of the glass fraction around 11.8% compared to 2015 (**Figure 9a**) (no data of years 2013 and 2014 are available). The collection rate of glass fraction in the year 2016 was 0.087 kg/inhab/day.

The collection of total waste during the year 2015 presented a rate of 1.038 kg/inhab/day, while the waste collection of 2016 corresponded with 1.019 kg/inhab/day. Therefore, the reduction in the rate of collected waste, namely the reduction in the mixed fraction, is due to two causes:

- The deviation of the organic fraction toward the three implemented composting systems. The neighbors and the big producers segregate the biowaste to destine them to composting and do not introduce them in the mixed fraction container. In the same way, the green waste generated by the neighbors (grass clippings, pruning and leaves) is deposited in the areas of contribution of the community composting islands for their use as bulking agent, so they are not introduced into the rest container.
- Improvement of recycling of other fractions that are segregated incorrectly in the mixed fraction by citizenship. Thus, it has been observed that the lightweight packaging fraction deposited erroneously in the mixed container was reduced.

Thus, a smaller amount of waste from the mixed fraction leaves the municipality, which supposes the reduction of the costs of transport and the costs of treatment, as well as the reduction of the annoyances caused to the neighbors of the municipality by odors coming from the mixed container and of the neighboring municipalities by the passage of trucks loaded with organic wastes in phase of decomposition. When fewer tonnes of wastes are delivered to incinerate and more tonnes of waste separated correctly, there is a reduction in the total cost of the collection service [32].

It should be taken into account that the improvement of recovery and recycling data corresponds to the implementation of the decentralized model in which it is estimated to participate in around 20% of the population of the municipality. Therefore, the participation of a greater

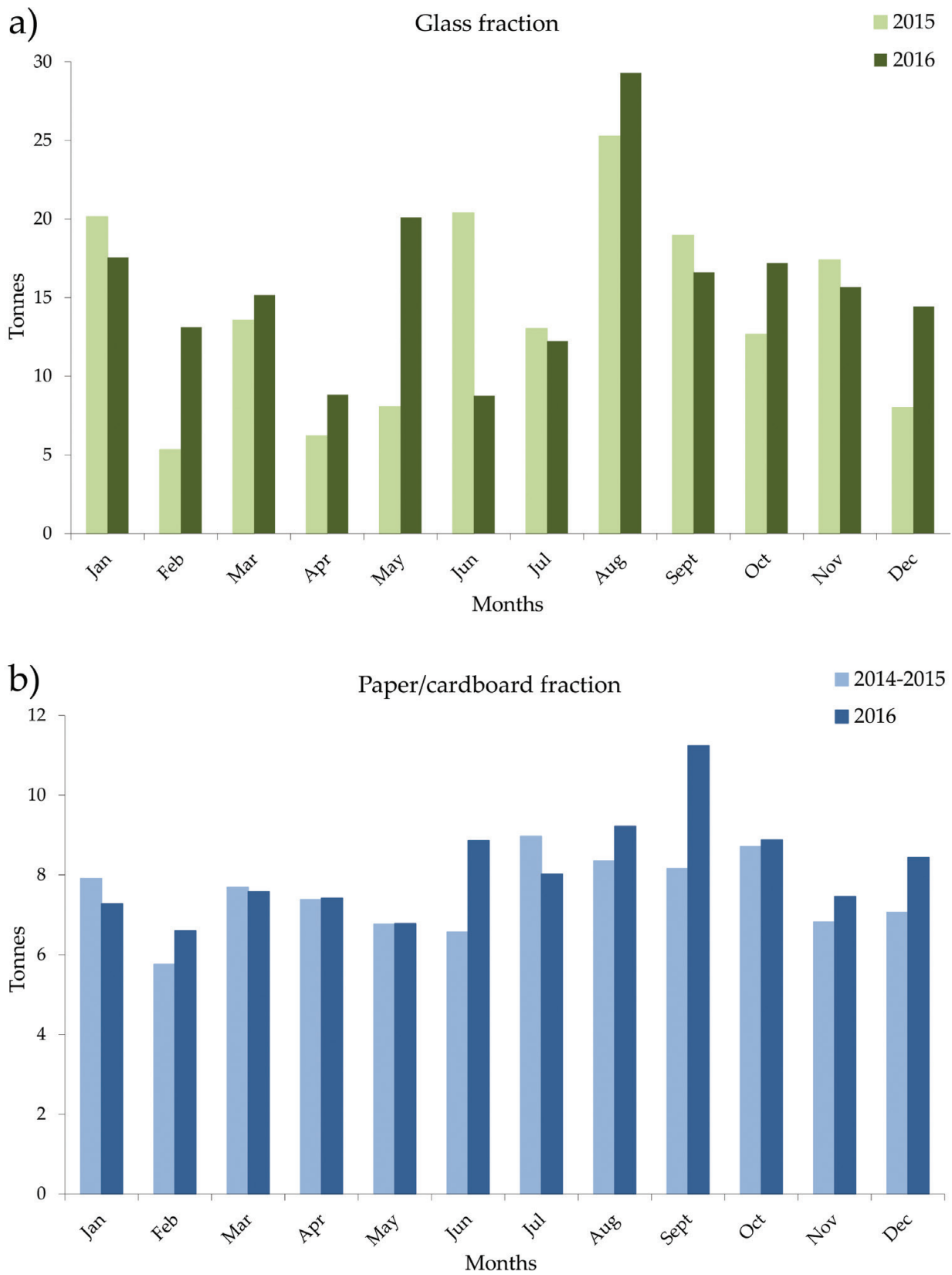


Figure 9. Different fractions collected in the municipality of Allariz: (a) monthly production of the year 2015 vs. monthly production of the year 2016 of the glass fraction, (b) average monthly production of the years 2014–2015 vs monthly production of the year 2016 of the paper-cardboard fraction.

number of inhabitants in the different systems of composting will enable the improvement of the recycling data.

3. Conclusions

Through the promotion of decentralized composting, carried out in the municipality of Allariz, the organic fraction of municipal waste is valued by obtaining high-quality compost and closes the circle of organic matter by applying it to the soil. This, in addition to increasing the environmental awareness of citizens, achieves the diversion of biowaste from the energy recovery, reducing the emissions of greenhouse gases emitted by the sector during the incineration and the landfill. In this way, a greater waste exploitation is achieved in accordance with the hierarchy imposed by European regulations, consolidating an efficient waste management model capable of contributing to sustainable development. On the other hand, the saving of economic resources is reinvested in the locality and it is possible to strengthen the employment in a rural region and to minimize the dependence of the services provided by supramunicipal organisms.

Currently, in Galicia, it is very common to burn pruning and gardening remains produced in the houses. By means of composting, a recovery of these wastes is achieved due to the need to add a low-density material, with capacity to retain water and to contribute to the porosity, to the mixture of household biowaste.

Another indirect result of the establishment of decentralized biowaste composting is the increase in the percentage of separate collection of the other municipal waste fractions. It is because, thanks to direct contact with the citizens, channels of information and learning are established, which improve the separation of the different fractions of both organic and inorganic wastes. Therefore, the reduction in the mixed fraction is not only a result of the removal of the biowaste therefrom but also of the improvement in the separation of the other fractions.

Due to its presence in our society, the management of organic matter, both biowaste and green waste, is the cornerstone of good municipal waste management. This makes European legislation more and more demanding and aims to achieve more rigorous objectives. The economy of the future depends on the degree of sustainability applied to the management of these vital resources.

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