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Research article

Efficiency of biological and mechanical-biological treatment plants for MSW: The case of Spain

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A R T I C L E I N F O

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A B S T R A C T

Biological and mechanical biological treatment plants combine mechanical and biological treatments to recover the greatest possible amount of materials from municipal solid waste (MSW) and biostabilize the organic fraction to be landfilled or applied in land. These plants handle a high percentage of the MSW generated in Europe. This work presents an exhaustive analysis of the existing plants in Spain which evaluates their typology as well as their performance. In Spain, 137 plants, which receive 13 Mt/year of waste, provide the country with total coverage. Twenty-two types of plants have been identified and grouped into six categories. There are four categories that receive mixed MSW: 1) sorting plants; 2) recovery and composting plants; 3) biodrying and recovery plants; and 4) recovery, biomethanation and composting plants and two that receive separately collected biowaste: 5) composting plants, and 6) biomethanation and composting plants. In plants that receive mixed waste, around 5% of the total input is recovered as recyclable materials (662,182 t/year), of which 29% corresponds to plastics, 27% to metals, and 27% to paper and cardboard. In addition, biostabilized material and/or biogas, and rejects (45–77% of the input) are obtained. In the biowaste plants, high-quality compost (more than 105,000 t/year), a higher biogas yield (43.60 Nm^3/t·year) and a lower proportion of rejects (around 29%) are obtained.

1. Introduction

The biological treatment (BT) and mechanical biological treatment (MBT) plants of municipal solid waste (MSW) includes different technologies for treatment. It consists of a combination of mechanical processes (crushing, densification, magnetic separation, separation by size or by density, etc.) and biological treatments (through aerobic or anaerobic degradation) [1,2]. In these facilities, the materials present in the MSW are processed to recover those that are recyclable, to convert them into marketable raw materials, and biostabilize the biodegradable organic matter [3]. In fact, the number and capacity of plants in Europe has increased significantly in the last two decades, as a result of the legal obligation to limit the disposal of biodegradable organic matter (biowaste) in landfills and to increase recycling and energy recovery from waste [4–6].

BT and MBT plants can be classified according to the different technologies used, the degree of automation or the process used for the biodegradation of the biowaste. The configuration of the facilities also depends on the input flows and the products to be extracted.

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The composition of the input material depends on the collection systems, i.e., whether it is mixed collected waste or there are separate monomaterial or multimaterial streams, while the recovered products depend on the market priorities at that time [3].

Therefore, depending on the type of plant, the quantities and qualities of the materials recovered will be different, as will the amount and characteristics of the rejects generated [2,7]. The rejects are made up of materials that cannot be recycled or cannot be separated due to limitations of the technologies installed (for example, small-sized elements) or to other reasons. Thus, part of the rejects is due to the inefficiency of the plant and another part can be attributed to the non-circular production and management system (products designed without taking into account the end of their useful life).

Most of the materials present in the rejects are combustible and have a high energy content [2,3,8], especially when the original MSW has a high calorific power [9]. Therefore, from a technical perspective, they can be used energetically through incineration, co-incineration, gasification or pyrolysis [10]. Hence, an alternative for their recovery is to transform them into a solid recovered fuel (SRF) [11–14]. Furthermore, incineration with energy recovery allows minimizing the use of fossil fuels without a significant impact on human health compared to other activities (road traffic, space heating, industrial activity) [15].

Since BT and MBT plants began to spread, different studies have been carried out on their efficiencies and their environmental and economic impacts in various European countries. Some studies have focused on improving the quality of the SRF [7,16,17]. Other studies were aimed at optimizing the different flows of material recovery operations [18,19] or at increasing the recovery of specific materials [20]. There are plants in which the minimum environmental impact is prioritized [21] and others in which energy saving and energy efficiency systems are applied to the equipment [22]. However, most studies have focused on environmental and economic aspects, rather than on the technical performance of the processes [3].

In 2017, Europe had 570 plants with a capacity of approximately 55 million tons [23,24]. In most of these facilities a combination of mechanical processes is used. Bulky waste (mattresses, furniture, etc.) that could block the sorting line is initially removed. Next, the tearing of bags is carried out by means of bag breakers or trommels. The trommels also have the function of separating, by size, the biowaste fraction (also called the fine fraction or wet fraction) from the rest of the materials (coarse fraction or dry fraction) that will be separated based on their composition (paper, cardboard, glass, metals, plastics, etc.) manually or by means of different mechanical equipments: magnetic separators, eddy currents, optical devices, infrared spectrum, ballistic, disk and/or pneumatic separators. The separate collected biowaste is processed aerobically or anaerobically using different technologies that generate compost as a product. This compost is refined with the use of vibrating tables, trommels and electromagnets to remove fine materials such as glass, stones, plastics, and metals [2,25]. In EU the most prominent country in terms of composting is Austria with 32% of the MSW, while Germany is noted for its recycling (49%) [26,27]. Nevertheless, there are countries, such as Poland, which compost only 11% of the generated MSW [28].

In this work, an exhaustive analysis of the BT and MBT plants operating in Spain is carried out to identify and characterize the different typologies, their mass balance and their efficiency in materials and energy recovery. With this objective, a series of useful indicators for the assessment of this sort of plants is proposed. The results have been analyzed and compared with other data published.

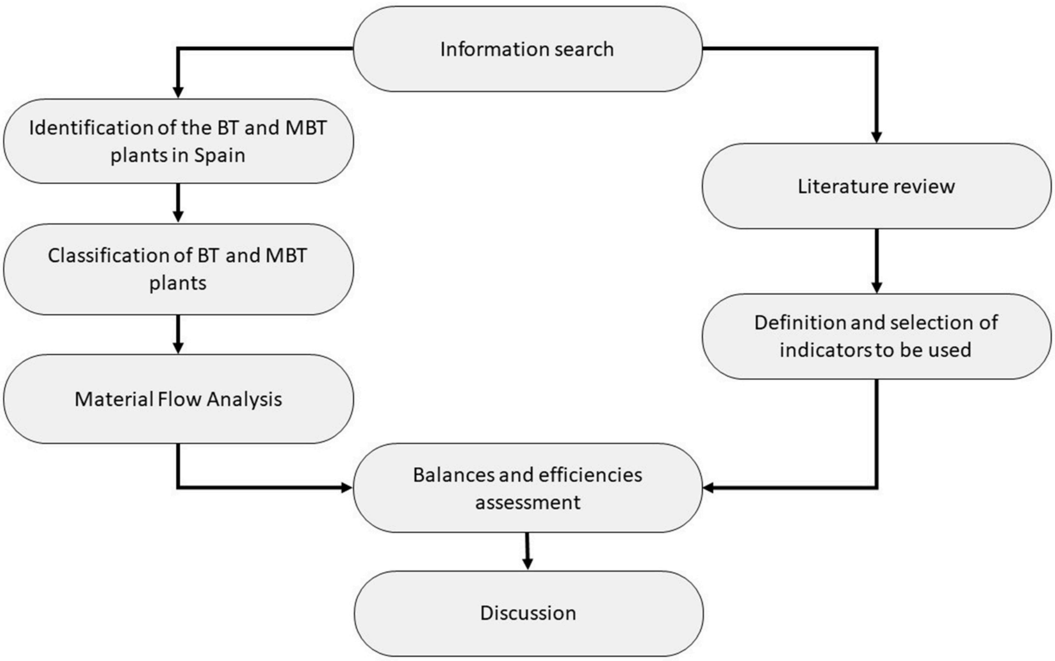

Fig. 1. Description of the work methodology.

2. Methodology

Fig. 1 defines the work methodology that has been followed to conduct this study.

In accordance with Fig. 1, on the one hand, a literature review about BT and MBT plants around the world has been done, and then the possible indicators to be used, have been defined and selected. On the other hand, an exhaustive search for information on the plants in Spain was carried out. In order to do this, the information published by public bodies at the national, regional and municipal levels was analyzed. This information was provided by public and private organizations (consortiums) that own and manage MSW plants. The most recent year for which information could be collected from all plants was 2016 and therefore the data analyzed corresponds to that year. The data gathered follow the standards of the statistical office of the European Union. When necessary this information has been supplemented with data reported in scientific and technical journals. The MSW treatment plants that currently exist in the 17 regions of Spain were identified, analyzed and classified based on their characteristics and the treatment processes carried out in them. Once the different types of facilities had been defined, a model of each of them was made in order to study their treatment processes and the input and output flows of materials. This makes it possible to identify and quantify the streams of recyclable materials and rejects generated, to establish the efficiency of each type of plant.

To express the performance of the plants, the following indicators were defined:

- Global efficiency in the recovery of recyclable materials (GE_{RM}): relationship between the quantity of recyclable materials recovered in the plant and the total amount of waste entering the plant, expressed as a percentage by weight. Recovered material include the possible impurities separated together with the recyclable material.
- Global efficiency in the recovery of biowaste (GE_{BW}): relationship between the quantity of raw biowaste recovered in the plant and the total amount of waste entering the plant, expressed as a percentage by weight.
- Biogas production efficiency (PE_{BGAS}): relationship between the volume of biogas generated in the biomethanation process and the total input of waste to the plant, expressed as Nm^3 of biogas/t MSW.
- Global efficiency of biostabilized materials production (GE_{BIOST}): relationship between the quantity of biostabilized materials produced in the plant and the total amount of waste entering the plant, expressed as a percentage by weight.
- Global efficiency of compost production (GE_{COMP}): relationship between the quantity of compost produced in the plant and the total amount of waste entering the plant, expressed as a percentage by weight.
- Losses (L): relationship between the quantity of material lost in the treatment (gaseous and liquid emissions) and the total amount of waste entering the plant, expressed as a percentage by weight.
- Rejects (Rejects): relationship between the quantity of material not recovered in the plant and the total amount of waste entering the plant, expressed as a percentage by weight.

The recovered materials are generally sent to transformation or recycling plants where they are conditioned to be used as raw materials. Regarding the quality of the different separated materials, there is not available specific data for each plant. However, the Extended Producer Responsibility Collective System (EPRCS) for packaging in Spain [29] forces to a minimum quality for the recovered materials; i.e. the impurities in the recovered ferric materials and aluminum should be less than 20% in wet weight basis and less than 3% in paper-cardboard, etc. As a result, in this work it is assumed that the quality of plants products meets these limits.

3. Results and discussion

3.1. *Classification of the plants*

The existing BT and MBT plants in Spain were classified according to several criteria: type of MSW treated in the plant, stages of the treatment process, technologies and processes of mechanical treatment, and technologies and processes of the biological treatment.

3.1.1. *Type of MSW treated in the plant*

Depending on the incoming waste, two types of facilities can be distinguished:

- MBT plants that treat mixed MSW: in these plants, the mechanical treatment for the recovery of recyclable materials is more complex, since the incoming waste is very heterogeneous and contains a large amount of both recyclable and non-recyclable materials. This heterogeneity has a significant impact on the characteristics of the MBT outputs which can be quite variable [2]. Furthermore, a significant variability in the composition of the input MSW between MBT plants around the world. On the other hand, a wide variety of different equipment and processes are used for material recovery.
- BT plants that treat separately collected organic fraction: in these plants the incoming material is mainly made up of biowaste, with a small amount of other waste. The mechanical treatment in these plants consists in conditioning the material for subsequent biological treatment. The material is cleaned and some materials (mainly ferrous metals and plastics) are recovered. In the case of composting plants, the addition of pruning or garden waste as structuring material is necessary.

3.1.2. *Stages of the treatment process*

Depending on the treatment process, facilities can be classified into four types:

- Mechanical treatment plants (or sorting plants) (SP): in these plants, the mechanical classification of the non-biodegradable fraction of the mixed MSW is carried out. The different recyclable materials are separated in order to recover them. The unrecovered material (reject) is destined for energy recovery or disposal. The SP can appear as a treatment prior to energy recovery [14].
- Mechanical biological treatment plants of mixed MSW (recovery and composting plants (RCP) or recovery, biomethanation and composting plants (RBCP)): These plants have a first mechanical stage for the recovery of recyclable materials and the separation of biowaste, which goes on to the biological stage for biostabilization. The biostabilization can be carried out in two ways: through composting (aerobic treatment) or through biomethanation (anaerobic treatment) and subsequent composting of the digestate. The biological stage also includes different refining processes of the biostabilized material [2,7,30]. They are the most widely established facilities for the treatment of mixed MSW in Spain and Europe [3,4,23,31], the main objective of which is to ensure a reduction of biodegradable waste to be disposed of in landfill in order to meet the targets of the Landfill Directive 1999/31/EC and Directive 2018/850 [2,32].
- Biodrying and recovery plants for mixed MSW (BRP): The process begins by biodrying the waste as it is received. Secondly, by means of a mechanical treatment, recyclable materials are separated from the biowaste, which is subsequently led to the composting process [33]. According to Psaltis and Komilis [34], typical industrial biodrying in MBT is a technique of autothermal drying shredded municipal waste for a period of 7–15 days. This technology has expanded in many EU countries, such as Poland where biodrying installations have a total capacity of at least 500,000 t/year and constitute a significant part of the national municipal waste management system [35].

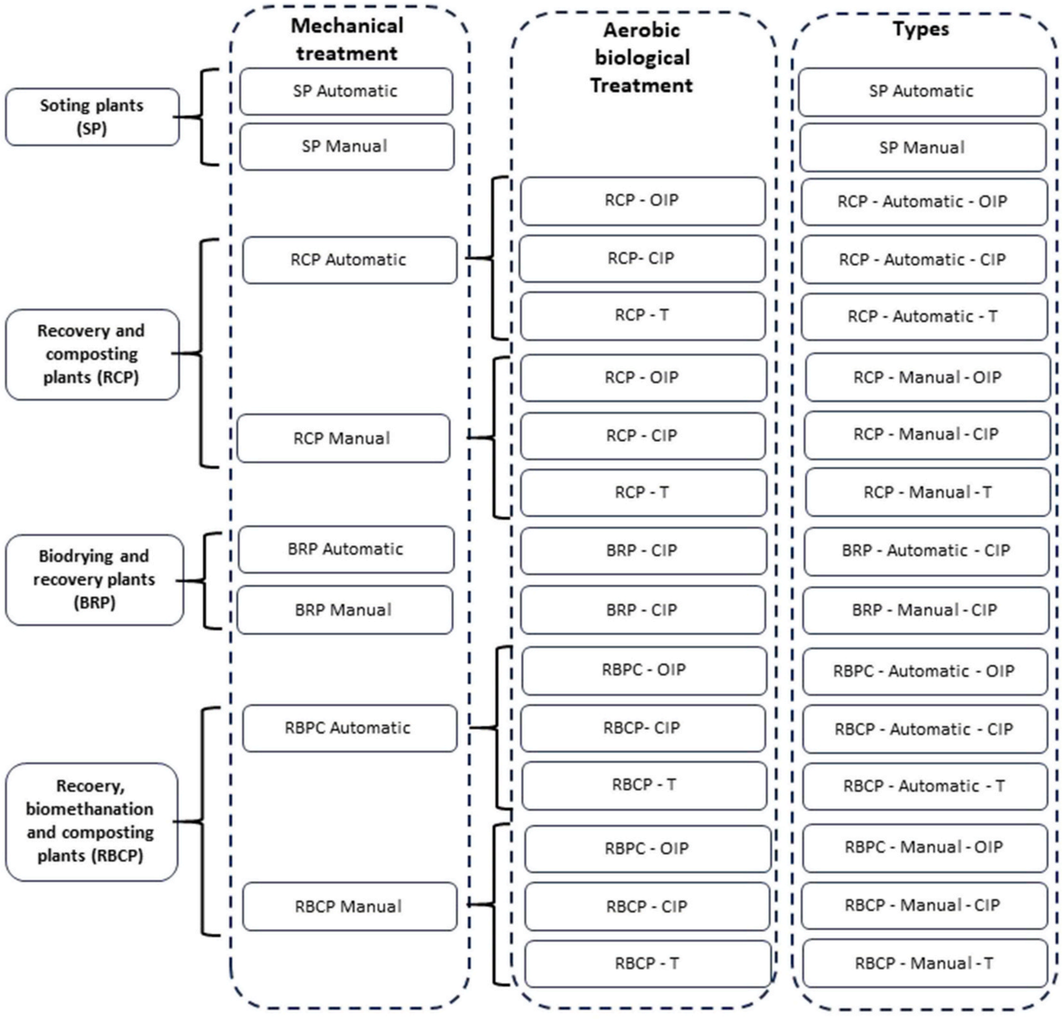

Fig. 2. Alternative types of the MBT plants that receive mixed waste (SP: sorting plants; RCP: recovery and composting plants; BRP: biodrying and recovery plants; RBCP: recovery, biomethanation, and composting plants; BWCP: biowaste composting plants; BWBCP: biowaste biomethanation and composting plants; OIP: open industrial plant; CIP: closed industrial plant; T: tunnel).

- Biological treatment plants for selectively collected biowaste (Biowaste composting plant (BWCP) and biowaste biomethanation and composting plant (BWBCP)): The biological stage is the most important one in these plants, which can be carried out through composting or through biomethanation and digestate composting. The compost refining process is also included [31,36]. In BWCP a better quality of organic waste implies a decrease of the non-compostable materials, reducing the environmental impacts [37]. Some works have even studied the suitability of treating only biowaste in MBT plants, demonstrating the high quality of the compost obtained [38].

3.1.3. *The technologies and processes of mechanical treatment*

The plants can be classified according to their level of automation, which can be fully automated or a combination of mechanical, automatic, and manual methods.

The automatic plants separate the MSW stream automatically into the different recyclable materials. Automatic systems include loaders, bridge cranes and grabs, conveyor belts, bag openers, trommels, ballistic separators, grinders, pneumatic suction, electromagnets, eddy currents, optical separators, compacting presses, densimetric tables, etc.

In the manual plants, the waste stream passes through a cabin where a series of operators classify the different materials, depositing them in hoppers. In addition, in some cases mechanical equipment is also involved, such as bag openers, trommels, ballistic separators, electromagnets, eddy currents or pneumatic separators for suctioning plastic film.

3.1.4. *Biological treatment processes and technologies*

Plants can carry out the biological treatment of MSW aerobically (composting or biodrying) or anaerobically (biomethanation). The technologies and processes used in each case are different:

- Composting: it can be carried out in fermentation rows, open industrial plants (OIP) or closed industrial plants (CIP) and closed reactors (channel, tunnel (T), rotating horizontal cylindrical reactor or vertical reactor). The composting process is done either to produce an organic fertilizer (in the case of separate biowaste collection), or to reduce the amount of biodegradable waste in landfills, since the resulting material is biostabilized.
- Biodrying: it takes place in a closed reactor. This process is useful to partially stabilize the biowaste, to reduce its weight and volume and for the resulting material to serve as fuel.
- Biomethanation: it takes place in a closed reactor. This process produces biogas and a digestate that can be used as organic fertilizer.

According to Spanish and UE legislation, compost is a fertilizer obtained from the fermentation of separately collected biowaste. However, the product obtained from the fermentation of the biowaste mixed with other waste is called biostabilized material [39], which has limitations to its use as a fertilizer [40].

3.1.5. *Classification of plants*

Thus, considering all the possible alternatives, the existing MBT plants in Spain, which receive mixed MSW, can be classified into 16 different types (Fig. 2).

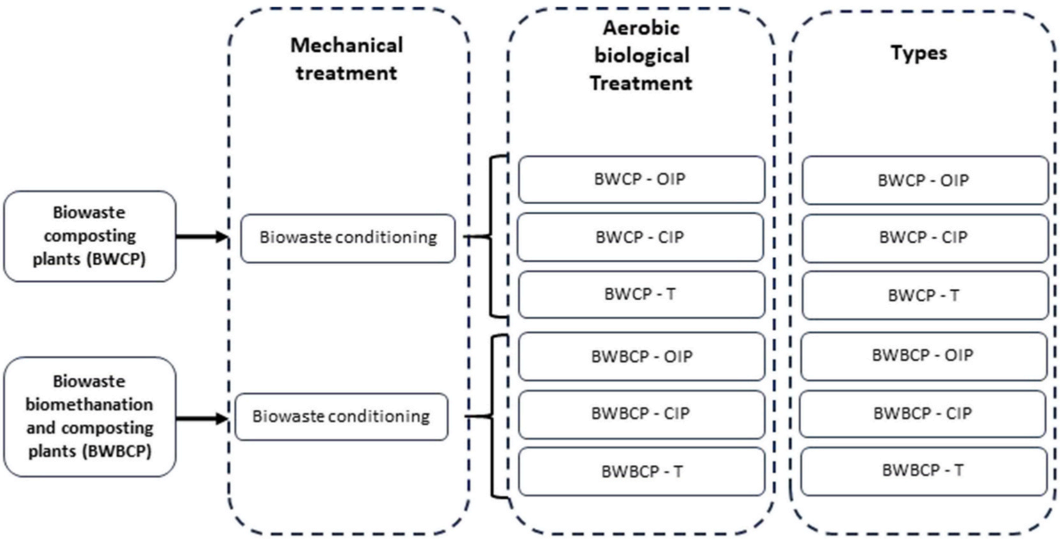

Fig. 3. Alternative types of the BT plants that receive separately collected biowaste (BWCP: biowaste composting plants; BWBCP: biowaste biomethanation and composting plants; OIP: open industrial plant; CIP: closed industrial plant; T: tunnel).

At a first level, the MBT plants are classified into four types: SP, RCP, BRP, and RBCP. In the case of mechanical treatment: automatic (AUTO) and manual (MANU) plants were identified. In the biological treatment of composting, the processes in an open industrial plant (OIP), in a closed industrial plant (CIP), and in tunnels (T) were considered; the fermentation row process is no longer applied in Spain at municipal level.

BT plants can be classified into two main categories, and considering the alternatives for the biological treatment of biowaste/digestate, 6 types of plants are finally obtained (Fig. 3).

3.2. BT and MBT plants in Spain

Table 1 shows a summary of the 137 B T and MBT plants operating in Spain at the end of 2016 (the full list and details is shown as a Supplementary Information). The plants with the greatest presence for the treatment of mixed MSW were the RCP, followed by the RBCP, with 67 and 22 plants, respectively. Regarding the treatment of separately collected biowaste, the predominant type was BWCP, with 34 facilities of this type. A great variability in the treatment capacity was observed among the different types of plants that treat mixed waste. This is because in Spain there are large (more than 5 million inhabitants) and small regions (less than 1 million inhab) and there is no transfer of waste from one to another. On the other hand, the plants that receive separately collected biowaste are generally smaller, since they receive only part of the urban waste.

The process of recovering recyclable materials in mixed MSW is done manually in most of the plants. However, the automatic process is also quite widespread, existing in 3 SP, 31 RCP, and 7 RBCP, that is, in 43% of the plants.

Regarding the biological process, when it comes to composting biowaste from mixed MSW (RCP and BRP), the most used system is closed industrial plants (28 plants) followed by tunnels (24 plants). In the case of BWCP, the majority includes the composting of the organic fraction of MSW in an open industrial plant (18 plants), followed by tunnels (12 plants). The composting of the digestate obtained in biomethanation (RBCP and BWBCP), however, is performed mainly in tunnels (18 plants) and never in an open industrial plant, since strong odors are generated in the process. At a global level in Spain, tunnel composting is the most used, while open industrial plant composting is the least common.

3.3. Identification of inlet and outlet streams in BT and MBT plants

Table 2 shows a summary of the waste that enters the plants and the output streams, for both the mechanical and the biological stages.

Material inputs are mainly mixed MSW and biowaste. Biowaste usually includes any biodegradable waste, such as food waste, kitchen waste, pruning waste, gardening waste, etc. In the RBCP and BWBCP, the digestate is mixed with shredded pruning or green waste for composting. Similarly, in the BWCP, the biowaste, once conditioned, is mixed with shredded pruning or green waste for composting. In most Spanish plants, food scraps from MSW are mixed with pruning and gardening waste to balance the Carbon content of the substrate, it also act as a bulking agent. The fermentation process takes place in tunnels (i.e. Ecopark 1 in Barcelona, treatment plant of Valencia, treatment plant of Castellón, environmental facility in Códoba, etc.), OIP (i.e. treatment plant in Málaga, environmental facility in Alcalá del Río (Seville), Meruelo recovery and recycling center (Cantabria), Cartagena waste treatment facility, etc.) or CIP (i.e. Alcalá de Guadaíra waste treatment facility (Seville), Toledo Ecopark, CTR of Terrasa (Barcelone), waste treatment plant od Manises (Valencia), etc.). At European level, in other countries such as Attica (Greece) a mixture of food waste with green waste was made and fermented in tunnels [36]. However, in a plant in Crete (Greece) the primary composting occurs in the continuous flow aerobic composting tank for five weeks [41]. In other plants (north-eastern Poland) closed modules are combined with covered and uncovered aerated piles [38]. In Rome (Italy) stabilization bioreactors operating in parallel with forced aerated conditions for four weeks are used [42]. On the other hand, in a plant of France, 3 day-retention-step in a Biologic Reactor Stabilizator (BRS®, also called rotary drum reactor), in order to pre-compost the input waste is applied, following mechanical sorting operation and anaerobic digestion of the sorted fraction [21]. In a plant in an Italian province, the whole mass of residual waste is biodried aerobically in

Table 1
Types of plants in Spain (SP: sorting plants; RCP: recovery and composting plants; BRP: biodrying and recovery plants; RBCP: recovery, biomethanation, and composting plants; BWCP: biowaste composting plants; BWBCP: biowaste biomethanation and composting plants; OIP: open industrial plant; CIP: closed industrial plant; T: tunnel).

Type of MSW	Type of plant	Number of facilities	Average quantity of waste treated by type of facility (quantity range) (kt/year)	Type of mechanical stage		Type of biological stage		
				AUT	MANU	OIP	CIP	T
Mixed MSW	SP	5	180.9 (17.1–360.7)	3	2			
	RCP	67	119.5 (40.5–223.6)	31	36	16	27	24
	BRP	1	62.0	0	1	0	1	0
	RBCP	22	143.1 (66.7–249.0)	7	15	0	8	13
Biowaste[a]	BWCP	34	25.1 (0.3–115.8)			18	4	12
	BWBCP	8	29.4 (5.3–55.8)			0	1	5
TOTAL in Spain		**137**		**41**	**54**	**34**	**41**	**54**

[a] In these plants, the municipal biowaste is mixed with other types of biodegradable organic waste such as that from pruning, gardening, etc.

Table 2
Type of plants and number of material streams leaving the plants (n: number of output streams of recyclable materials) (SP: sorting plants; RCP: recovery and composting plants; BRP: biodrying and recovery plants; RBCP: recovery, biomethanation, and composting plants; BWCP: biowaste composting plants; BWBCP: biowaste biomethanation and composting plants; OIP: open industrial plant; CIP: closed industrial plant; T: tunnel).

Type of MSW entering	Type of MBT plant	Types of mechanical stage	Types of biological stage	Number of streams of materials		Number of streams of rejects	
				Mechanical stage	Biological stage	Mechanical stage	Biological stage
Mixed MSW	SP	MANU/AUTO	–	n	–	2	–
Mixed MSW	RCP	MANU/AUTO	OIP/CIP/T	n	1	1	2
	BRP	MANU/AUTO	CIP	n	1	1	2
Mixed MSW and pruning	RBCP	MANU/AUTO	OIP/CIP/T	n	2	1	2
Biowaste and pruning	BWCP	MANU	OIP/CIP/T	n	1	1	2
	BWBCP	MANU	OIP/CIP/T	n	2	1	2

windrows with forced aeration from underneath the floor [43].

The number of output streams of recyclable materials (n) in the mechanical stage depends on the legislation and/or market needs. According to Ecoembes [29], the most commonly separated streams are, in this order, HDPE (high-density polyethylene); PET (polyethylene terephthalate); LDPE (low density polyethylene, generally in film form); plastic mix; aluminum metal containers; steel packages; and cartons. In the biological stage, the outputs are compost, biostabilized material, and biogas. These outputs are the most widely obtained in plants around the world.

Finally, other output currents are rejects, which can also be classified according to the stage that generates them. In the mechanical stage, fine rejects are produced (only in the SP and normally with a size of less than 80 mm) and other coarse ones, with a size greater than 80 mm [43]. In other countries, the size of the coarse and fine fractions may change from plant to plant, i.e. at the Mertesdorf (Germany) plant, waste with a size greater than 40 mm is called the coarse fraction, while the fine fraction is less than 3.5 mm in size [44]. Coarse rejects have a lower ash content and higher calorific power, since they are made of non-biogenic material such as plastics, especially film types, textiles, rubber, wood, and multi-material waste.

In Spain, in the biological stage, a thick reject (between 30 and 80 mm) is generated in the refining of the material after the fermentation phase, with high moisture content. A fine reject with less moisture (with a size between 8 and 30 mm) is also generated from the refining of the compost/biostabilized material, which has a higher ash content [7,45].

This material, having considerably different properties than coarse rejects was also studied in other countries by Samolada and Zabaniotou [17] and named as refuse derived fuel (RDF). As Bourtaslas and Themelis [3] observed, RDF mainly consists of non-recycled paper and plastics.

3.4. Efficiency of BT and MBT plants in Spain

In 2016, 21.8 Mt of MSW were generated in Spain [46], of which 18 Mt were collected mixed and 3.8 Mt selectively. The generalized collection scheme divides MSW into four selective collection streams: biowaste, paper-cardboard, glass and light packaging (metals, plastics, and cartons). The amount of MSW that was treated in the BT and MBT plants was 13 Mt: 12.3 Mt mixed MSW, 0.55 Mt biowaste, and 0.16 Mt other biodegradable waste (pruning and sludge).

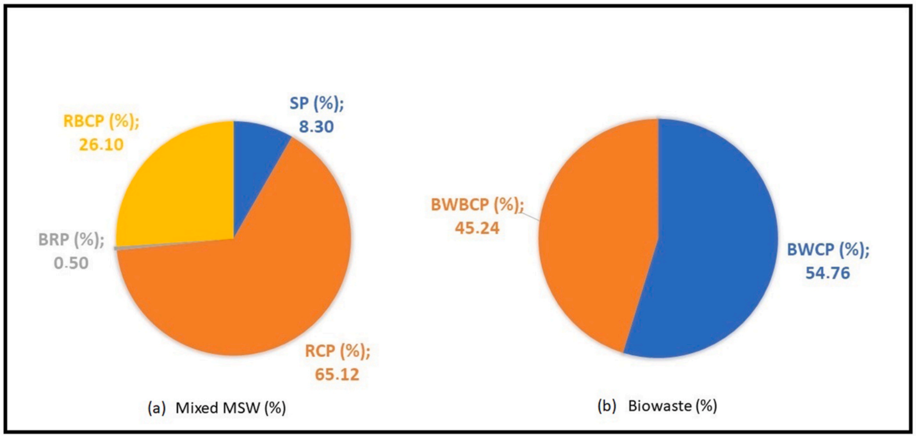

Fig. 4. Distribution of the mixed MSW (%) and biowaste (%) treated in plants in Spain (SP: sorting plants; RCP: recovery and composting plants; BRP: biodrying and recovery plants; RBCP: recovery, biomethanation, and composting plants; BWCP: biowaste composting plants; BWBCP: biowaste biomethanation and composting plants).

Regarding mixed MSW, 8.30% was treated in SP, 65.12% in RCP, 0.5% in BRP, and 26.10% in RBCP (Fig. 4a). Therefore, at the national level, most of the MBT for mixed MSW is carried out in RCP.

Regarding biowaste, 54.76% was treated in BWCP and 45.24% in BWBCP (Fig. 4b). This distribution is similar to the one in Germany, where 59% of the biowaste is treated in BWCP and 41% in BWBCP. In Italy, the BWCP is significantly predominant (treating 88% of the biowaste), while in countries, such as France, United Kingdom and Poland, the anaerobic digestion of biowaste is no relevant so far [47]. In Spain there are differences by region: four of them treat 100% of the biowaste in BWCP, while in three the majority of this stream is treated in BWBCP.

Table 3 shows the percentage of materials recovered in each type of facility. It can be seen that the main materials recovered are plastics, metals, and paper/cardboard. Glass appears in a low proportion due to the existence of an important and widespread system of selective collection since 1984. In SP, glass presents a higher percentage than in the others because it suffers less breakage in the treatment process, and can be better recovered. The "Others" fraction is made up of bulky waste (tires, furniture, electrical appliances, etc.) that arrive at the MBT plants and are not recovered. In the only biodrying plant that exists in the country, the glass is not recovered and there is no data on the cartons recovered. Small amounts of metals and plastics are recovered at BWCP and BWBCP plants, but quantitative data are not available. Finally, and globally, the total recyclable materials recovered in mixed MSW MBT plants reached 662,182 t/year, 29.44% corresponding to plastics, 27.23% to metals, 27.31% to paper/cardboard and the rest to other materials.

As stated in the methodology, the data obtained does not consider the quality of the materials extracted from the MBT plants since this information is not publicly available. However, it can be assumed that the quality of each of the separated materials fulfill the requirements set in terms of impurities content for its recovery.

The production of biostabilized material in the MBT plants for mixed MSW was 727,504 t, with the greatest amount being produced in RCPs. On the other hand, the production of compost in the biowaste treatment facilities was 105,232 t, which was mostly produced in BWCPs. In addition, the biomethanation process generated 68 million Nm^3 of biogas in RBCPs and 2.5 million Nm^3 in BWBCPs.

Reject generation at the MBT plants stood at 8.9 Mt, that is, 68.46% of the waste entering the plants, above most of the data reported in different countries. In the Bangkok plant (Thailand) the reject represents 43% [48], 69,1% in the Anno Liosia plant (Greece) [49]; in the Isfahan plant (Iran), 28,6% [50]); 30% in the Phitsanulok plant, Thailand; 50% in the Rayong plant, Thailand or 60% in the Nashik plant, India [51]; 63,1% in the Ravenna plant (Italy) [52]); 33% in the Goa Plant (India) [53]; 15–58% in 7 Italian MBT plants studied by Gadaleta et al. [54].

Despite technological advances in recent years, there is still great variability in the generation of rejects. This great variation in the amount of rejects and therefore also in the amount of materials recovered from one plant to another is due, in part, to the composition of the waste received. Table 4 shows that in Spain the plants that receive mixed MSW obtain a much higher rate of rejects than the plants that receive biowaste. In addition, the widespread MSW collection model in the country involves the selective collection of four fractions of recyclable materials (paper-cardboard, glass, metals, plastics, and cartons), As a result, the mixed MSW that reach the MBT plants includes smaller fractions of recyclable material than in the areas where all the MSW is collected mixed.

Regarding the generation of rejects, the BWCP and BWBCP produced the lowest percentage of rejects, with values around 29%. While in those plants where mixed MSW was treated, the generation of rejects increased considerably to values between 45% (BRP) and 77% (SP). This occurs because when mixed MSW is treated, the treatment process is more complicated, since the number of materials to be separated is greater and the amount of non-recyclable materials is also greater, which increases the percentage of rejects. De Araujo Morais et al. [55] also deduced this in a similar study. The BRP has an intermediate value (45.67%), which indicates that biodrying decreases the weight of the rejects obtained, since the residue is previously dried.

The data in the table also shows the influence of the plant technology: a lower rate of rejects is obtained in the biodrying plant studied, due to the loss of moisture from the waste (the percentages of recovered materials are not higher than in other plants). On the other hand, part of the Spanish plants are obsolete and in need of refurbishment. Some of the plants work above their design capacity and in other plants there is a lack of workers and/or equipment. If all this was improved, the plants efficiency could increase and the quantity of rejects decrease.

Given that the rejects can exceed 50% of the incoming waste to the system [3], the key room for improvement in all the technological solutions for the plants is the possibility of use of the rejects [56]. In Spain the main destination for the rejects is landfill disposal (84.45%), which represented 56.20% of the waste disposed of. The rest is recovered energetically (15.54%), accounting for 57.50% of the material entering the Spanish incinerators.

Table 4 shows the values obtained for the treatment efficiency indicators at a national level for the different types of BT and MBT plant.

Regarding the global efficiency of the recovered materials (GE_{MR}), the values obtained for all types of plants are similar, at around 5%. This contrasts with the values obtained by Bourtsalas and Temelis [3], who obtained an average GE_{MR} of 20% in 6 plants in Greece and Cyprus. In their study on MBT plants in Poland, Połomka and Jędrczak [56] who report a GE_{MR} of 14% in MBT plants in Poland,

Table 3
Percentage of materials recovered in the MBT plants.

Type of plant	Metal (%)	Plastic (%)	Glass (%)	Paper/cardboard (%)	Cartons (%)	Others (%)
SP	37.25	21.04	13.21	21.17	2.00	5.33
RCP	26.04	29.05	4.42	27.10	4.43	8.96
BRP	28.62	58.66	–	7.39	na	5.33
RBCP	27.05	32.95	3.32	30.11	3.81	2.76

Table 4
BT and MBT plants efficiency indicators.

Type of MBT plant	GE_{MR} (%)	GE_{BW} (%)	PE_{BGAS} (Nm^3/t)	$GE_{BIOST/COMP}$ (%)	Reject (%)	Losses (%)	Total (%)
SP	**5.47**	**16.5**	–	–	**77.10**	**0.93**	**100**
RCP	**5.54**	–	–	**7.75**	**67.66**	**19.05**	**100**
BRP	**4.76**	–	–	**4.97**	**45.67**	**44.60**	**100**
RBCP	**4.93**	**-**	**21.93**	**6.61**	**70.64**	**-**	**-**
BWCP	–	–	–	**12.64**	**28.09**	**59.27**	**100**
BWBCP	–	**-**	**43.60**	**9.18**	**30.54**	**-**	**-**

GE_{MR}: global efficiency of the recovered materials; GE_{BW}: global efficiency of the recovered biowaste; PE_{BGAS}: biogas production efficiency; $GE_{BIOST/COMP}$: global efficiency of biostabilized/compost.

and Gadaleta et al. [54], who obtained values between 1 and 31% in 7 MBT plants in Italy. The main reason for this variability is the different composition of the waste received, which in Spain includes less amount of recoverable materials due to the selective collection streams mentioned above. It should be noted that there is an SP in which biowaste is only separated from the mixed waste stream to compost it in other plants. The separated biowaste fraction represents 16.5% of all the waste entering the SP.

If the global efficiency of the biological stages ($RG_{BIOST/COMP}$) is analyzed, the plants where the separately collected biowaste is treated stand out above the rest. These plants have a higher efficiency since the separately collected biowaste contains a lower quantity of non-desirable materials than the biowaste from mixed MSW. In relation to the plants that treat mixed MSW, the RCP are the ones that obtain higher efficiency in the production of biostabilized material (7.75%). While in those that treat the separately collected biowaste, the highest efficiency for the production of compost occurred in the BWCP (12.64%). Regarding the production of biogas, it is observed that the performance of the BWBCP is twice that obtained in the RBCP, due to the fact that the biodegradable fraction in the input waste is significantly higher in the BWBCP. Furthermore, in RBCP the biowaste has been in contact with other types of waste, some of which have substances and products that act as biomethanation inhibitors, such as ammonia, sulfur, light metal ions, heavy metals, and organic compounds [57].

Lastly, losses are caused during the treatment process by moisture loss (in liquid or vapor form) or by gaseous emissions in the aerobic decomposition of the biowaste. It can be seen that the SP have very few losses, since only a separation of materials is carried out, and these are in the form of steam. The greatest losses occur in the plants that carry out composting. Of these, BWCP stand out above the rest, due to the fact that they receive biowaste with high moisture content. BRP also has significant losses due to the initial biodrying and composting process. In the plants that incorporate the biomethanation stage, it has not been possible to calculate the losses since they did not provide details about the gas composition.

4. Conclusions

In this work, a detailed analysis of the existing BT and MBT plants in Spain and their performance has been carried out.

BT and MBT plants for mixed MSW can be classified into six main categories. The number of plants of each type existing at the national level and the technologies they use have been presented, along with their material balances and performance indicators for the latest data available.

At the end of 2016, Spain had 137 MBT plants, with a high degree of coverage, since all regions have at least one facility of this type in their territory. The most used facilities for the MBT of mixed MSW are the RCP and the RBCP, with 67 and 22 plants, respectively. Regarding the treatment of the selectively collected biowaste, the predominant type of plant is the BWCP with 34 facilities.

The recovery of recyclable materials is carried out manually in most of the plants (54 facilities). The closed industrial plant (CIP) is the most widely used system for composting the organic fraction present in the mixed MSW (28 facilities) and open industrial plants (OIP) are the most common for composting the selectively collected biowaste (18 facilities). Globally, however, tunnels (T) are the most common composting technology (54 facilities). The composting of the digestate obtained in the biomethanation process is mainly carried out in tunnels.

The efficiency in the recovery of materials, GE_{MR}, was similar (around 5%) in all the plants receiving mixed MSW. This is a low value when compared to published results from other plants around the world, partially due to the selective collection of recyclable materials, which represents 17.4% of the MSW generated in Spain. Nonetheless, the indicator values obtained in different contexts are not directly comparable, since they are strongly influenced by the composition of the input waste, which can vary significantly from one place to another. In fact, the plants that treat the selectively collected biowaste in Spain present better efficiencies (GE_{COMP} and GE_{BGAS}) than the others.

The generation of rejects presents high values in the plants that process mixed MSW, due, on the one hand, to the heterogeneity of the incoming material, and, on the other hand, to the need of improvement of the design and/or operation of the facilities.

In the case of the BWCP and BWBCP, where the incoming material is much more homogeneous and with low amounts of waste, the percentage of rejects decreases considerably to values around 29%. However, the percentage could go down if selective collection and the treatment process were further improved.

Finally, the information and reported indicators analyzed in this paper could be useful as a reference for the monitoring of other facilities and further research to improve the recovery of materials from MSW. With this scope, it would be convenient to deepen the analysis and include parameters that consider the rate of impurities in the recovered materials, the quality of the final products and the composition of the waste entering the plant.

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Data availability statement

The raw data analyzed in this research are not available in a single repository. They have been obtained from a large number of public and private organizations sources. They have been included in the Supplementary material of this article.

CRediT authorship contribution statement

N. Edo-Alcón: Methodology, Data curation, Conceptualization. **A. Gallardo:** Validation, Supervision, Data curation, Conceptualization. **F.J. Colomer-Mendoza:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **A. Lobo:** Visualization, Validation, Supervision.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e26353.

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