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Assessment of biowaste composting process for industrial support tool development through macro data approach

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ABSTRACT

This study aims to assess composting efficiency and quality of compost through the study of the parameters of the Catalan Waste Agency (ARC) data-base by developing indicators useful for industrial sector. The study includes 17 composting plants for an 8-years period (2010–2017), the quantities of materials treated and generated in these plants: biowaste, yard trimmings, refuse and compost, as well as chemical characterization of compost: total organic matter, organic nitrogen, pH, electrical conductivity, self-heating test, pollutants and ammonium. Plant were sorted into 4 size classes depending on size capacity and into 4 technologies employed during thermophilic phase.Different indicators were developed related to improper fraction content, yard trimmings ratio, mass losses, compost production, refuse generation and plant saturation. The main results indicate that improper fraction is 10%, process losses 68%, refuse generated 25% and saturation 79%. Differences were observed in size and technology; for instance, smaller plants presented lower improper content, refuse and saturation and higher losses while plants with turned windrows during decomposition presented higher improper, yard trimmings ratio and plants with vessel technology showed lower losses and higher saturation. Also, the compost quality is higher if the plant saturation and improper fraction are below 90% and 7%, respectively. The indicators were useful to assess the process and were related to the compost quality obtained.

1. Introduction

Biodegradable waste is the main part of municipal waste in terms of weight and can present a significant risk to the environment if not treated properly. Different regulations (Directive 1999/31/EC or Directive 2008/98/EC) promote the diversion of biodegradable waste from landfill to reduce impacts (leachates, gasses) and to recover resources (organic matter and nutrients) to circular economy framework. This waste is transformed through biological treatments, such as composting or anaerobic digestion, to obtain compost or digestate. Separate collection (SC) of municipal solid waste (MSW) contributes to recover and recycle materials in the best conditions. Because of this, awareness campaigns and implication of local administration play an important role to meet this goal. In Catalonia SC of MSW is promoted since 1993 through Llei 6/93, on waste (currently repealed by Decret Legislatiu 1/2009, de 21 de juliol, pel qual s'aprova el Text refós de la Llei reguladora dels residus), and SC of biowaste is mandatory for all Catalan municipalities since coming into force of Decret Legislatiu 1/2009. In Catalonia, the Catalan Waste Agency (ARC in Catalan acronym) is the organism that compiles the information on waste generation and management as well as on the treatment facilities.

In Catalonia, the quantities of separately collected MSW have increased progressively since 2000 until 2010, when values got stuck around 40% of the MSW generated (ARC, 2019). In 2017, a total of 3,8 million ton of MSW were collected, of which 1,54 million ton were separately collected. Biowaste separately collected accounts for the 378,942 ton, the 9.8% of the total municipal waste and the 24.7% of the municipal waste selectively collected. This biowaste is transported to composting plants or combined cycle plants (anaerobic digestion + composting) to be treated. The quality of the biowaste is affected by its content of improper fraction (e.g. plastic, glass, etc), which should have been previously diverted and deposited into specific containers. The percentage of this fraction depends on collection system and area. Door-to-door collection and rural areas have been found to present the lowest values (6,06% and 8,74% of the biowaste, respectively). Nevertheless, the proportion ranges from below 1% to over 20% in the worst cases (ARC, 2019). Individual involvement of citizens is crucial but also, in order to improve quality, different tools other than collection system, such as identification of waste producer, penalization (as Pay as you throw – PAYT) or compensatory actions are used and have proved effective.

The quality of the product obtained in composting plants depends both on the quality of the biowaste input and the handling of the

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process. The former is mainly related to pollutants and nutrients content and the latter to compost stability and maturity. Campos-Rodrigues et al. (2019) analysed in detail the effect of the improper materials of the biowaste in the increase of pollutants (heavy metals) in compost. The assessment of the quality of compost usually requires physical, chemical and biological analysis. However, the process performance assessment has not been receiving the same attention. According to general definitions of composting, the efficiency of the process should consider the capacity of treating large amount of material, by reducing weight and volume and obtaining a product of high quality (physical, chemical and biological). For Zhang and Matsuto (2010), the type of waste, the amount of material and the operation conditions can influence the process and its costs. There are different methods that allow monitoring the composting process but that requires periodical sampling that cannot be considered in the current operations of the plants (moisture, temperature, gases), because not all facilities have Programmable Logic Controller (PLC) installed for process monitoring, and frequent expenses that cannot be afforded. Unfortunately, there is not a great amount of bibliography focused on measuring the efficiency of the composting process, some bibliography only focuses on the evolution of organic matter or chemical parameters to determine the efficiency of plants (Adani et al., 1997; Biasioli et al., 2009; Colón et al., 2017; Young et al., 2016), or work with modelling processes (Rafiee et al., 2017).

The study of the mass balance of the plants can provide useful information on the efficiency of the process, which, according to Bartl (2014), can be measured by three criteria: (1) how much material is lost, (2) what is the quality of the product and, (3) what is the energy and water demand. When analysing mass balance of composting plants, most of the research is focused on particular processes. One of the more recent studies is Abad et al. (2019), which considers the 3 criteria of Bartl (2014), and thoroughly analyses the process and economical aspects of combined anaerobic digestion and composting plant of 45,000 t/year of treatment capacity for biowaste. Also, mass balances of home composting have been specifically studied (Andersen et al., 2011; Vázquez and Soto, 2017) as well as nutrient balance during the composting of different wastes (Koyama et al., 2018). A specific study on plant performance is Zhang and Matsuto (2010) which analysed the process of 77 plants classified by type of waste treated. To summarise, most of the studies assess the biological process, but not the real performance of the facilities in its whole to widely assess the efficiency.

According to this overview, the aim of this study is to assess the performance of the composting process of biowaste from different plant data and to provide the industrial sector with simple and inexpensive tools to assess their processes.

2. Methodology

2.1. Data

The database used for this study, hereinafter referred as ARC-DB, is compiled by ARC and contains information about all the biological treatment facilities of Catalonia. The organic wastes treated in these facilities cover a wide range of origins: from biowaste to agri-food waste. The facilities operate in private and public ownership and the biological process can be composting or a combined cycle of anaerobic digestion and composting. The scope for this study includes public composting plants for organic fraction of municipal waste separated at source, in order to manage a more homogeneous data than also including anaerobic digestion plants. Thus, the material treated in these plants is the organic fraction from separate collection, hereinafter referred to as OFSC. The OFSC is obtained by separate collection in bring-banks or by door-to-door collection system. Fig. 1 shows the location of the 21 publicly owned plants for the treatment of the OFSC, including those with anaerobic digestion phase (Ecoparc 1 and 2, Granollers and Terrassa) not considered in the study.

Most of the total treatment capacity is concentrated in the Metropolitan Area of Barcelona, with a population of 3.2 million inhabitants (AMB, 2019), nearly half of a total of 7.5 million inhabitants of Catalonia (IDESCAT, 2019). The biggest dots depicting plant size in Fig. 1 are for Ecoparcs 1 and 2 (dot numbers 3 and 4). The total treatment capacity of the 21 plants is 390,000 tones, and in 2017, 378,942 tons of OFSC were collected separately (ARC, 2019), which is close to the total capacity of plants.

The general process in Catalan composting plants consists of the mixing of OFSC with yard trimmings (YT) in different ratios to balance the mixture physically and chemically to start the composting process. In order to remove improper materials, sieving can be done in different stages of the process. Also, at the end of the process a final sieving is done to remove smaller impurities and produce a compost sized for market. Part of the refuse generated in the final sieving, mainly consistent of non-degraded YT, can be partly recovered as recirculated material (RYT) if the quality is appropriate (López et al., 2010a) and be partly used in the initial mixture.

The ARC-DB contains a variety of data sets for every facility, including design features, quantities of materials treated and produced, contents of improper fraction of OFSC and information of quality of compost. Table 1 summarises the parameters considered. Data provided by the ARC correspond to the period of 2010–2017. At the end, more than 1500 records were included for the indicated fields (17 plants, 12 records per year, over 8-year period).

Samplings for compost quality and for improper material characterization are conducted by authorized companies, after a public procurement procedure, to take and to analyse samples.

According to Bartl (2014), in our research only criteria about material loss and quality of product are considered, while no analysis of energy and water demand is done.

2.2. Classification by size and technology

The efficiency of the composting plants is generally difficult to compare, because of their different technologies and capacities. Therefore, the facilities included in ARC-DB were classified by size and technology of the thermophilic process phase as summarized in Table 2. In Catalonia, the Waste Management Infrastructure Plan -PINFRECAT20- (Generalitat de Cataluña, 2014) establishes enough plant capacity for specific areas, according to population density. Classification by size was done according to the ranges established by ARC regarding plant design capacity: very small –VS– (< 5000 tons/year), small –S– (≥5000 to < 10,000 tons/year), medium –M– (≥10,000 to < 15,000 tons/year) and large –L– (≥15,000 tons/year).

Classification by technology included aerated channel (ACH), turned windrow (TW), aerated turned windrow (ATW) and in-vessel (V). The composting process is split into the two composting phases, decomposition (thermophilic) and maturation. Different technologies can apply to each phase. The classification by technology regarded only the decomposition (thermophilic) phase because it is the more intensive. Also, most facilities have turned windrows for the maturation phase.

Due to confidentiality issue, the results of the evolution of indicators and values by classes, are discussed regarding groups and not individual by plants. More details of plants can be found in PINFRECAT2020 (Generalitat de Cataluña, 2014).

2.3. Indicators for process assessment

Different indicators based in ARC-DB parameters are proposed, analysed and discussed in order to assess the performance of the

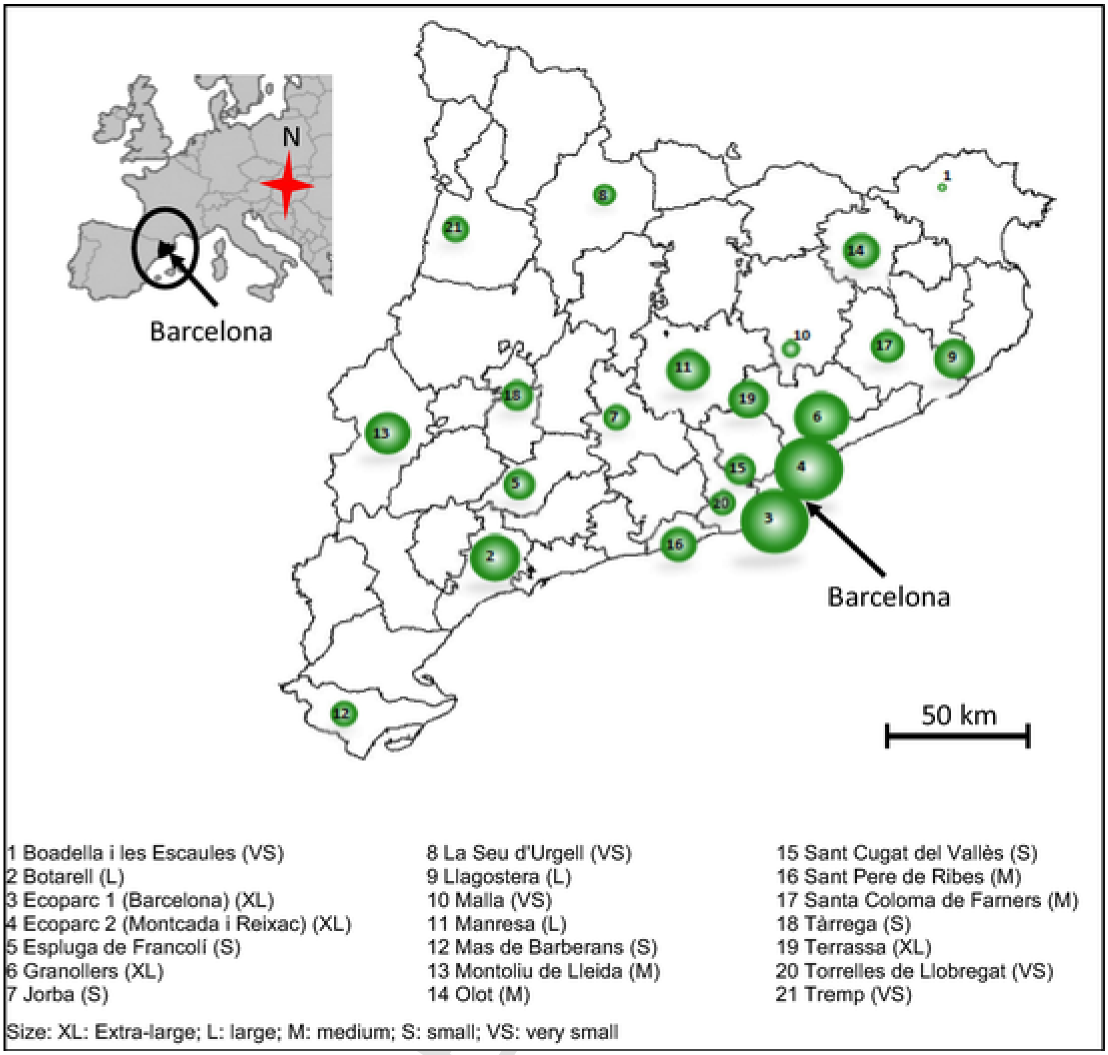

Fig. 1. Distribution of considered Catalan plants (Size of dot refers to plant size).

process and the quality of the product. Some other indicators were produced and initially analysed but the information obtained was not considered of relevance. The proposal of indicators gathers different combinations of available parameters of the ARC-DB, seeking to identify those that provide useful information.

2.3.1. Improper fraction content (IMP)

The content in improper fraction (IMP) is determined by experimental sampling of known quantity of OFSC in the plant, followed by a manually separation and weighing of non-biodegradable components such as plastic, glass or metal. The results represent the content in IMP respect the OFSC. The ARC-DB gathers the percentage in IMP for each plant, which is determined quarterly.

2.3.2. Yard trimming ratio (YT)

The composting process in Catalan plants include yard trimmings to elaborate and balance the initial mixture. The indicator is calculated from the YT treated respect the OFSC treated, as shown in Eq. (1).

$$\%\ Yard\ trimming\ (\mathrm{YT}) = \frac{YT}{OFSC} * 100 \quad (1)$$

Actually, composting plants make mixtures considering volume basis because it is easier as materials for mixtures are commonly charged with front-end loaders. In order to conserve homogeneity of calculation with other indicators the mass unit have been preferred instead of volume ones.

2.3.3. Total and process losses of material (TL and PL)

The efficiency of composting can be assessed through the degree of degradation. If the process is adequately managed, high degradation of organic matter and a partial loss of water take place, subsequently, weight and volume are reduced. Total process losses correspond both to physical and biological losses and can be assessed as a loss of matter in a balance. During separation and sieving operations in municipal waste composting, non-biodegradable materials are removed, microbial activity leads to loss of carbon and water vapour, and some leachates are produced. In the studied case, the only available data to estimate the losses is the total quantity of materials treated (OFSC and YT) and produced (refuse and compost). Leachates, water and gaseous emissions emitted during the process are neither recorded nor quantified. The inputs are OFSC and YT, the materials used to prepare the mixture and the biodegradable part. The outputs are the refuse, which represents the physical losses, and the compost, which is the product obtained. Considering these values, 2 equations are proposed to estimate the Total Losses (TL) and the Process Losses (PL), represented in Eqs. (2) and (3). TL considers all the losses incurred during the process, both biological and physical; PL refers to the biological losses due to microbial activity, but also includes the loss of water, which cannot be

Table 1
Parameters studied of the ARC-DB.

Parameter	Unit	Description
Plant features		
Design capacity	t/year	Maximum organic fraction from separate collection (OFSC) that can be treated per year
OFSC treated	t/year	Real OFSC treated per year
Improper fraction content	% or t	Content in non-biodegradable materials present in the OFSC, determined by quarterly characterisation (sampling) of the OFSC
YT treated	t/year	Yard trimmings (YT) treated per year
Refuse generated	t/year	Refuse from sievings of the process which is derived to final disposal
Compost produced	t/year	Compost produced
Technology	–	Composting technology used in the decomposition phase
Compost quality		
Dry matter	%	
Self-heating test	°C (max temperature)	
pH	pH units	
Electrical conductivity	dS/m	For general compost characterisation purpose
Ammonium	% dry basis	
Total organic matter	% dry basis	
Organic nitrogen	% dry basis	
Heavy metals	mg/kg dry matter	

Table 2
Plant by size and technology.

Plant locations	Capacity (tons/year)	Plant size	Decomposition technology
Boadella i les Escaules	350	VS	TW
Malla	1500	VS	ACH
Tremp	2000	VS	TW
La Seu d'Urgell	2300	VS	TW
Torrelles de Llobregat	4500	VS	TW
Mas de Barberans	5000	S	V
L'Espluga de Francolí	5000	S	TW
San Cugat del Vallès	7000	S	V
Tàrrega	7000	S	ATW
Jorba	7400	S	TW
Montoliu de Lleida	10,000	M	TW
Olot	10,000	M	V
Sta. Coloma de Farners	12,500	M	V
Sant Pere de Ribes	13,700	M	V
Llagostera	18,000	L	V
Manresa	20,000	L	ACH
Botarell	25,000	L	ATW

Technology: V: in-vessel; TW: Turned windrow; ATW: Aerated turned windrow; ACH: Aerated channel. Size: L: large; M: medium; S: small; VS: very small.

deduced from the available data. This means that loss of organic matter due to biodegradation cannot be estimated directly.

$$\%\ Total\ losses\ (TL) = \frac{OFSC + YT - Compost}{OFSC + YT} * 100 \quad (2)$$

$$\%\ Process\ losses\ (PL) = \frac{OFSC + YT - Refuse - Compost}{OFSC + YT} * 100 \quad (3)$$

The total losses will present a higher value than PL depending on refuse. In addition, refuse depend on the content of improper fraction of the OFSC, the efficiency of separation systems and the ratio of recirculation of the yard trimmings recovered in the final sieving.

In general, the higher the values of PL, the higher the loss of mass that could be considered as high biodegradation rate. Nevertheless, the loss of matter includes also the loss of water. Thus, excessive water losses may lead to an erroneous assessment of process efficiency.

2.3.4. Performance index (PI)

PI expresses the ratio of compost produced in relation to OFSC treated, as shown in Eq. (4). This is proposed because frequently the data used to assess performance facilities only considers the OFSC and the compost, in other words, the capacity of the plant, and the final product. The result of adding the YT to OFSC in the denominator could be considered as the compost yield (CY), which is complementary to TL (100 = CY + TL).

$$\%\ Performance\ index\ (PI) = \frac{Compost}{OFSC} * 100 \quad (4)$$

2.3.5. Refuse (RF)

RF expresses the refuse generated in relation to the OFSC treated, as shown in Eq. (5). Higher ratio of RF will indicate that less of the OFSC has turned into compost.

$$\%\ Refuse\ (RF) = \frac{Refuse\ generated}{OFSC} * 100 \quad (5)$$

2.3.6. Saturation index (SI)

The Saturation index (SI) was formerly formulated by Soliva et al. (2006). It is calculated by the ratio between capacity of the facility and OFSC actually treated, as shown in Eq. (6).

$$\%\ Saturation\ Index\ (SI) = \frac{OFSC}{Capacity} * 100 \quad (6)$$

The SI informs about the availability of space in the facility, which can affect the manoeuvrability of vehicles, the stocked materials and duration of the process. It uses the capacity as fixed feature of the facility, which does not directly depend on treated or produced materials.

Low values would indicate oversizing of the facility, and consequently a probable waste of resources in the investment, but also a forecast of space for future needs. Values over 100% would indicate under sizing and saturation of the facility. Thus, 100% value could be considered as optimum for the process as long as no problems arise.

2.4. Indicators for quality of the product

The quality of the compost produced in the composting plants is analysed periodically by an authorized laboratory. The frequency of data collection for this purpose is, at least, three times per year. The RD506/2013, on fertiliser products requires the characterisation for certain parameters (moisture, organic matter, impurities, granulometry, heavy metals, etc.) and consequent classification of the product to be named as a fertiliser. In this study not all the regulatory parameters included in the RD506/2013 are considered, because the legal compliance assessment is not object of the study.

The parameters considered for compost quality were moisture/dry matter, total organic matter, pH, electrical conductivity, ammonium and heavy metal content and maximum temperature by self-heating test or Rottegrad. The values of these parameters will be related to the value of the chosen indicators to infer if quality of compost can be related to certain values of the quality of process.

According to Saha et al. (2010), a pollutant factor (PF) for heavy metal content was calculated, as shown in Eq. (7).

$$Pollutant\ factor\ \ (PF) = Zn*1 + Cu*2 + Cr*3 + Ni*1 + Pb*3 + Cd*5 \quad (7)$$

Heavy metals symbols (Zn, Cu, …) represent the concentration (mg/kg dry matter) of each of them and the numeric value is attributed depending on the toxicity. In that way, a single value is given for all the pollutants.

2.5. Data and statistical analysis

Indicators (IMP, YT, PL, TL, PI, RF and SI) and chemical parameters were analysed for the 8-year period, for plant size and for technology applied in the decomposition phase.

Statistical analysis was performed using SPSS software. For all process indicators and compost parameters studied, differences between plant size and technologies were compared using the analysis of variance (ANOVA) with a Tukey test at 5% significance level. Also, a correlation analysis was carried out between all the parameters using the Pearson's correlation coefficient at 5% significance.

3. Results and discusion

3.1. General data

During this 8-year period, the considered composting facilities treated a total of 1.18 million t of OFSC and 389,899 t of YT, and produced 218,210 t of compost and 295,844 t of refuse. The OFSC treated per year comes close the total capacity of 145,000 tonnes. Compost production represents about the 18.5% of the OFSC treated. The refuse generated represents the 25% of the OFSC and comes mainly from the improper fraction of the OFSC, from the RYT not recovered for the process and for the losses of OFSC still adhering to the refuse after sieving. It is well known that improper fraction reduces quality of the raw material for composting (López et al., 2010b) and of the compost (Huerta-Pujol et al., 2010; López et al., 2010b; Zennaro et al., 2005; Campos-Rodrigues et al., 2019) and has a negative impact on the composting process. In terms of management, improper fraction increases the refuse, and the cost of its disposal treatment can be an important part of total costs of the biological process (Abad et al., 2019).

3.2. Assessment of the process. Indicators in relation to size and technology classification

The results include the average values of the indicators, classified by size and technology (Table 3). Analysis over time is not shown because in general main of values remain constant along the period.

The first parameter conditioning the process is the content of improper fraction (IMP), which depends on participation and performance of citizens in selective collection, rather than on plant management. In fact, Wei et al. (2017) state that composting should be implemented in conjunction with source-separated collection to ensure the production of high-quality compost. IMP value ranges between less than 1% and 30%; 75% of the samples are below 14% of IMP content. The cleanest OFSC arrive to plants size VS and technology ACH and most polluted to plants S and technology ATW and V. The content in improper materials can negatively affect the process, the generation of refuse and the quality of the compost produced. Also, IMP can cause technical and operational problems, mainly in AD plants as Abad et al. (2019) stated. Gallardo et al. (2014) mention that the RF produced in the mechanical separation of a MBT plant can still hold a high content of biodegradable organic matter, as high as 20.09%.

The process losses (PL) which account for all losses except the refuse, are near to 70%. Haug (1993) suggests that up to 90% of losses of biodegradable volatile solid can happen during composting. This reduction in weight also affects the final volume, which can reduce from 50% to 85% due to particle reduction by physical and chemical transformation (Sharholy et al., 2008). Lin et al. (2019) refers to values of 20%, being attributed the losses to the degradation of organic matter into CO_2 and evaporated water. PL are higher in VS size and lowest in V technology. Part of the losses are due to water evaporation, which can be higher in VS plants where technology is mainly turned windrow (Table 2), which favours evaporation. On the other

Table 3
Average values of indicators by plant size and by technology.

	% IMP		%YT		%PL		%TL		%PI		%RF		%SI	
Average	10.16		38.30		68.07		84.11		23.30		25.03		79.71	
	By size													
VS	4.50	d	27.69	a	76.34	a	86.58	a	21.91	a	16.03	c	62.09	c
S	15.24	a	34.50	a	66.49	b	85.13	ab	21.74	a	24.24	b	86.36	a
M	8.82	c	37.12	a	70.30	b	82.02	b	24.83	a	15.74	c	75.88	b
L	12.37	b	37.21	a	65.36	b	85.33	ab	24.43	a	31.12	a	91.10	a
	By technology													
ACH	4.83	c	26.38	b	74.18	a	85.64	ab	23.56	a	19.38	c	77.22	b
ATW	14.07	a	47.50	a	71.02	a	87.78	a	21.24	a	32.35	a	93.25	a
TW	8.29	b	26.71	b	71.59	a	82.56	b	24.71	a	15.26	c	63.62	c
V	12.86	a	40.68	a	64.88	b	84.18	ab	22.34	a	26.34	b	91.48	a

IMP: content in improper fraction; PL: process losses; TL: total losses; PI: performance index; RF: refuse; SI: saturation index
Size: L: large; M: medium; S: small; VS: very small.
Technology: V: in-vessel; TW: Turned windrow; ATW: Aerated turned windrow; ACH: Aerated channel
Note: Means labelled with the same letter in a column by size or by technology do not differ significantly at a 5% probability level by Tuckey Test.

hand, V technology can favour the conservation of water as it is conducted in a confined area. Total losses (TL) are about 10–20% higher than PL. Regarding the generation of compost (PI) the yield does not show differences in classification by size and technology. An efficient process produces low compost quantity because of the losses as CO_2, and evaporation is high. In the case of biowaste, the sieving for removing improper fraction and impurities contributes to reduce the final quantity of material from the initial mixture of OFSC and YT. Thus, the average value of 23.30% is lower than the usual assumption of 30% of yield of the initial mass. However, in composting of biowaste the refuse increases the total losses and produces lower compost quantity in relation to inputs. The average production of refuse (RF) is the 25% in the period, with minimum values below 1% and maximum values over the 50%. The refuse is highest in L plants and in ATW technology, which is in accordance with the findings for IMP, where S and L size present the higher values of IMP and also of RF. Nevertheless, the quantity of refuse is related to the improper fraction but also with type and efficiency of sieving systems, as well as to the ratio of recycling of yard trimmings: the more YT is recycled in the process, the less refuse is produced in the final sieving. This allows to recover a waste as a resource (López et al., 2010a), and to reduce refuse treatment costs. Sieving impurities such as plastic and small particles like gravel, glass, pips, bones, etc. constitute the rest of the refining refuse. The improper fraction in the OFSC is not biodegraded along the process, and can only be removed in part as refuse by sieving systems. The other part remains in the material and tends to be minced along the process. It is well known that efficiency of removing this fraction by mechanical means during the composting process is lower than previous separation by hand at source. Thus, it can be expected that part of the IMP still remains in the compost and affect its quality even after mechanical sieving.

The saturation of the plants (SI) is near 80% in average and only 25% of registers are over 100%. Values of SI around 100% indicate that the facility is used in total capacity and low values are mainly related to an oversizing of the plants. This may be due to the expectance of an increase in the OFSC to be treated over time, or to an underestimation of the quantity actually received in the plant. Values over 100% usually happen when plants are about to be refurbished, or when unexpected quantities of material have to be treated. S and L plants are over the SI average, indicating that some management problems may arise. VS plants account for the lowest value, which may indicate an oversizing in expectance of an increase in selective biowaste collection, or a lower content in IMP than considered by design. If separate collection of OF increases (that means increase of participation of citizens), some investment would be needed to increase the treatment capacity. On the other hand, the current capacity for mechanical biological treatment (MBT) in Catalonia is about 1475 million t/year (Generalitat de Cataluña, 2014). The conversion of these plants into biowaste treatment plants could absorb future increments of OFSC collection. By technology, the higher SI values in ATW and V plants can be related to a major content in improper fraction (about 10%) than expected by design.

3.3. Compost composition in relation to size and technology classification

The composition of compost does not present any significant difference over the years, and specific data is not shown. The chemical parameters present certain differences when related to plant size and technology, as shown in Table 4.

Moisture values of compost are below 30%, which can increase sieving efficiency. On the other hand, it can indicate incomplete stabilisation, because the lack of water slows down the microbial activity and in consequence reduces degradation of degradable organic matter. The technology can influence the water content: it seems that ACH plants tend to retain more water.

The average pH is close to neutrality (7.88) and the high electrical conductivity (8.61 dS/m) can be restrictive for growing media purposes, which should not exceed 1.5 dS/m (López-López and López-Fabal, 2016) and for soil, causing salinity in high doses (Meena et al., 2019). The value of total organic matter (TOM) is 53.10% on dry basis, which represents 39.04% of total matter (wet basis), slightly over the minimum of 35% on wet basis indicated in Spanish regulation RD 506/2013, on fertilising products. By size, the lowest content of TOM is found in VS plants. Along with higher content of moisture this can indicate more effective process, which is in accordance with higher PL (Table 3). On the other hand, compost from V technology plants present higher TOM and lower PL and moisture, which can indicate lower degradation of matter because of lack of water to adequately undergo the process. Another explanation could be the higher proportion of complementary material (YT), which can increase the content of organic matter and decrease the value of ammonium. It must be considered that in vessel technology usually uses a high quantity of YT both as a bed underneath the mixture to avoid collapse space for aeration and to balance the nutrients in the mixture. Organic nitrogen (orgN) presents adequate values for a compost (2.77% on dry basis) for all plant sizes. By technology, ACH plants present the highest orgN value and ATW the lowest. This could be due to the fact that ACH present higher content in YT (Table 3) than ATW. In the latter case, unbal-

Table 4
Chemical parameters of compost by size and technology classification.

	% Moisture		pH		EC (dS/m)		Tm (°C)		% TOM db		% orgN db		% N-NH4 db		%PF	
Average	26.62		7.88		8.61		49.17		53.10		2.77		0.40		686.39	
	By size															
VS	26.49	ab	8.14	a	7.69	b	36.68	c	46.61	b	2.82	a	0.31	c	502.69	c
S	26.21	ab	8.10	a	8.19	b	47.38	b	53.16	a	2.64	a	0.33	bc	756.81	a
M	23.93	b	7.64	b	9.64	a	57.91	a	56.16	a	2.85	a	0.39	b	663.18	b
L	29.66	a	7.70	b	8.73	ab	50.88	ab	54.87	a	2.77	a	0.54	a	769.45	a
	By technology															
ACH	32.83	a	7.79	ab	7.55	b	41.00	b	51.69	b	3.13	a	0.49	a	612.84	b
ATW	25.00	b	8.13	a	8.03	ab	56.96	a	49.46	b	2.44	c	0.41	ab	858.84	a
TW	26.43	b	8.06	a	8.66	ab	43.98	b	49.82	b	2.68	b	0.38	b	700.30	ab
V	25.33	b	7.60	b	9.19	a	54.52	a	58.66	a	2.87	b	0.39	b	622.69	b

Except moisture, pH and EC, all values are expressed on dry basis (db). Tm: maximum temperature of self-heating test. TOM: total organic matter; db: dry basis EC: electric conductivity; PF: pollutant factor.
Size: L: large; M: medium; S: small; VS: very small.
Technology: V: in-vessel; TW: Turned windrow; ATW: Aerated turned windrow; ACH: Aerated channel.
Note: means in a column labelled with the same letter do not differ significantly at 5% probability level.

anced ratio of C/N can favour nitrogen losses. Mineral nitrogen (N-NH4) is quite high for a finished material (0.40% on dry basis), whose value should be expected to be below 0.1% (Bernal et al., 2009). This can also suggest that there exists an unbalanced nutrient ratio (C/N) in the mixture, promoting ammonia losses. However, this high value of ammonium is in accordance with the high values of EC.

The sum of pollutants (PF) presents an average of 686.39 mg/kg, with lowest values in VS (size), which would be due to lower IMP content, even though the TOM is low, suggesting a higher mineralisation ratio than in other plant sizes. On the other hand, S and L plants account for higher PF and also higher IMP. The heavy metal concentration in compost, as well as the concentration of other minerals, depends both on the quality of the raw materials and the efficiency of the process: high concentration in raw materials and high biodegradation will involve high mineralisation and, consequently, increase the concentration of nutrients and pollutants in compost. Technology does not show as clear differences as plant size does, but it can be stated that ATW shows higher PF than ACH and V. Nevertheless, ATW have highest IMP but similar to V, but TOM is lower, which suggests higher mineral concentration.

3.4. Correlation study

The correlations were studied for the total average values without differentiation by size or technology. The parameters studied showed significant correlations between process indicators and compost quality (Table 5) and the main results are discussed.

Composting with high process losses (PL) will produce low compost quantity (PI) and refuse (RF) and is achieved when content in improper fraction (IMP) is low and the plant is far from saturation (SI). In this case, the compost produced will contain few organic matter (TOM), indicating a good biological degradation and few ammonium.

Instead, high total losses (TL) are due to the presence of improper fraction and refuse generated, and also to the saturation of the plant. Compost production (PI) is higher when SI and IMP are low; this indicates that the cleaner the raw material is and the more space the facility has, the likelier more quantity of yard trimmings (YT) are used in the mixture to improve the performance of the process. Thus, the refuse (RF) produced corresponds to the YT removed in the sieving. Also, the more compost is produced the lower is the dry matter content (or higher the moisture content). High RF is produced when saturation and IMP are high, and as mentioned before, provokes low PL. In relation to compost quality, the higher the RF and IMP, the higher are the TOM and PF. When saturation of the plant is high the PL are low and IMP and RF high, indicating that both affect the development of the process; also, the quality of compost would decrease in relation to TOM and PF. The IMP that comes along with the biowaste affects the process in the terms of reducing PL and increasing TOM and PF. This indicates that IMP can limit the efficiency of the process by limiting biodegradation, and it increases the content in heavy metals, which can limit the use of compost. The temperature of self-heating of compost is higher the lower the losses and the higher the saturation are. In relation to compost, Tm is higher the higher the DM and TOM are, indicating lower degradation.

3.5. Application to the industrial sector/analysis of relevance of the information

The present research provides an overview of the Catalan biowaste composting plants and information that can be transferred to similar places.

In order to assess the functioning of the facilities that treat biowaste, apart from the monitoring of materials treated in the plants, ARC organizes periodical meetings with managers of the composting plants to discuss the concerns and challenges in daily operation. They stated their interest in support tools for daily management using simple and low-cost parameters for monitoring the process efficiency and predicting the compost quality. The results of the present research can help in this issue. The objective of the composting process is to treat a large quantity of good quality raw material by reducing mass and volume and producing and acceptable quality product. According to the findings discussed, there are indicators related to raw materials quality and to plant design, as improper fraction and saturation, and others related to process management, such as process losses. Also, in order to improve monitoring of mass balance, periodical determination of moisture content of initial and middle materials would be helpful for data interpretation.

As the results show, the improper fraction contributes to the saturation of the plant, reduces efficiency of the process, increases the refuse and reduces the compost quality by hindering degradation and increasing pollutants (heavy metals). For all these reasons, the quality of the raw material is a main issue to improve the efficiency of the process, to reduce costs for mechanical systems removal of the improper fraction and refuse treatment and to improve compost quality. Saturation of plants hamper the process efficiency, by limiting the biodegradation of organic matter and producing high refuse rates and also lowers the product quality.

From the studied data, indicators SI and IMP are considered non-dependent on plant management. The first is an operational value usually defined by design that is only modified due to structural changes in regular plant operation. The second depends on participation and performance of citizens on effective separation of waste and the selective collection. Consequently, both indicators condition process performance and quality of product. To assess how they affect, three ranges for IMP and three ranges for SI are proposed to classify BD-ARC values (Table 6).

Ranges for IMP are according to percentile 25 (7%) and 66 (10%), and ranges for SI to the consideration that a reliable occupancy of the facility should be between 90 and 100%. Crossing the current values of the facility of IMP (range from <7 to >10) and SI (ranges from <90 to >100) allows to predict the compost quality and the performance of the facility.

4. Conclusions

The indicators proposed were useful to assess the composting process in terms of efficiency and compost quality. The regular collection of reliable data from public services can provide indicators to help in general plant monitoring and progress assessment.

Variations in size and technology of facilities showed differences for the indicators and parameters studied, revealing that not only management but design features condition the evolution of the process and the quality of product. Nevertheless, these differences are not meant to rate size or technology plant but highlight that are important key factors and that maybe particular management in each case would help to improve performance.

Values of indicators SI and IMP below 90% and 7%, respectively, produce better performance of the plant and product quality. None of them depend on plant managers but collection.

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.

Table 5
Values of correlation (Pearson's coefficient) for process and compost quality indicators.

	IMP	YT	PL	TL	PI	RF	SI	DM	TOM	NNH4	EC	Tm	PF
IMP		**0.111** **	**−0.303** **	**0.208** **	**−0.100** *	**0.558** **	**0.439** **	0.018	**0.207** **	0.057	0.083	0.111	**0.460** **
YT	0.111 **		0.056	0.023	**0.303** **	**0.590** **	**−0.220** **	**−0.165** *	−0.071	0.118	−0.04	−0.109	0.039
PL	−0.303 **	0.056		**0.693** **	**−0.622** **	**−0.413** **	**−0.227** **	0.077	**−0.386** **	−0.202 **	0.063	**−0.213** *	−0.115
TL	0.208 **	0.023	0.693 **		**−0.894** **	**0.150** **	**0.187** **	0.112	−0.126	−0.207 **	0.033	**−0.158** *	0.084
PI	−0.100 *	0.303 **	−0.622 **	−0.894 **		**0.149** **	**−0.279** **	**−0.164** *	0.132	0.265 **	−0.035	0.118	−0.082
RF	0.558 **	0.590 **	−0.413 **	0.150 **	0.149 **		**0.276** **	−0.078	**0.339** **	0.119	−0.056	0.084	**0.245** **
SI	0.439 **	−0.220 **	−0.227 **	0.187 **	−0.279 **	0.276 **		0.116	**0.320** **	0.097	0.042	**0.185** *	**0.307** **
DM	0.018	−0.165 *	0.077	0.112	−0.164 *	−0.078	0.116		0.087	**−0.320** **	**−0.138** *	**0.293** **	−0.085
TOM	0.207 **	−0.071	−0.386 **	−0.126	0.132	0.339 **	0.320 **	0.087		**0.344** **	**0.280** **	**0.592** **	−0.057
NNH4	0.057	0.118	−0.202 **	−0.207 **	0.265 **	0.119	0.097	−0.320 **	0.344 **		0.042	**0.365** **	0.009
EC	0.083	−0.04	0.063	0.033	−0.035	−0.056	0.042	−0.138 *	0.280 **	0.042		**0.375** **	0.013
Tm	0.111	−0.109	−0.213 *	−0.158 *	0.118	0.084	0.185 *	0.293 **	0.592 **	0.365 **	0.375 **		−0.084
PF	0.460 **	0.039	−0.115	0.084	−0.082	0.245 **	0.307 **	−0.085	−0.057	0.009	0.013	−0.084	

IMP: improper fraction; YT: yard trimmings; PL: process losses; TL: total losses; PI: performance index; RF: refuse; SI: saturation index; DM: dry matter; TOM: total organic matter; NNH4: ammonium; Tm: self-heating maximum temperature; PF: pollutant fraction.

* Pearson's correlation coefficient is significant at $p < 0.05$.

** Pearson's correlation coefficient is significant at $p < 0.01$.

Table 6
Expected average values for process and compost quality depending on plant saturation (SI) and improper content of biowaste (IMP).

	%PL	%PI	%RF	%TOM	Tm (°C)	PF (mg/kg dm)
	IMP ≤ 7					
SI ≤ 90	74.27 ± 16.09	23.64 ± 16.20	10.06 ± 8.82	46.05 ± 12.75	40.96 ± 18.93	474.22 ± 142.17
90 < SI ≤ 100	68.64 ± 15.34 [a]	22.05 ± 14.68 [a]	13.39 ± 9.33 [a]	58.70 ± 13.51 [b]	54.67 ± 33.94 [b]	606.88 ± 110.25 [b]
SI > 100	74.82 ± 15.15 [a]	18.23 ± 9.04 [a]	18.08 ± 14.49 [a]	53.98 ± 10.61 [b]	41.40 ± 16.10 [b]	609.98 ± 195.44 [b]
	7 < IMP ≤ 10					
SI ≤ 90	72.91 ± 18.03	20.24 ± 25.77	14.73 ± 10.50	52.45 ± 7.44	50.71 ± 16.68	665.53 ± 255.59
90 < SI ≤ 100	71.15 ± 15.48	16.50 ± 14.25	17.70 ± 9.49	55.39 ± 5.85	53.11 ± 18.81	633.61 ± 543.76
SI > 100	68.99 ± 13.50	14.99 ± 17.82	20.46 ± 8.57	56.15 ± 6.45	56.47 ± 14.34	631.03 ± 216.14
	IMP > 10					
SI ≤ 90	68.11 ± 9.45	31.03 ± 31.96	25.70 ± 55.78	51.96 ± 5.70	46.25 ± 12.47	700.48 ± 207.21
90 < SI ≤ 100	68.09 ± 16.45	21.11 ± 22.95	24.06 ± 17.02	53.41 ± 11.57	45.56 ± 14.01	879.20 ± 278.15
SI > 100	61.46 ± 13.27	11.72 ± 11.40	35.34 ± 15.93	56.36 ± 10.38	53.46 ± 15.41	851.69 ± 244.94

[a] Less than 15 values.
[b] Less than 10 values.

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