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Implementation of circular economy in the management of municipal solid waste in an Italian medium-sized city: A 30-years lasting history

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ABSTRACT

The Circular Economy model is gaining attention as a key factor for boosting sustainable development. Reducing the consumption of raw materials, as well as increasing the amount of recycled waste, are the current challenges the municipal solid waste management system is called for. In this study, the evolution of the municipal waste management strategies in the city of Brescia was analysed, covering a period of 30 years. The results obtained by a) progressively extending the separate collection with street containers, b) building a Waste to Energy plant, and c) moving to a door to door collection system, were assessed via numerical indicators and mass balances. In order to highlight the complexity of the system, the waste flow, from collection to the achievement of the end of waste attribute, was followed. Separate collection with street containers came to a saturation percentage around 40%. The realization of the incineration plant eliminated the direct disposal of waste to landfills. With the introduction of the new collection system, the separately collected waste increased up to over 73%, the per capita amount of collected waste decreased from 685.3 kg/(in y) to 579.6 kg/(in y), and a significant reduction of recyclable materials in the unsorted waste was gained. In the paper, these achievements and their affecting factors are analysed. Moreover, criticalities in the calculation of material recovery indices due to the complexity of the system (72 transformation sites were identified) are discussed.

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1. Introduction

Circular Economy has received much attention in the past decade as a new way to achieve a smarter, more sustainable and more inclusive development model (Fang et al., 2007; Naustdalslid, 2014; Ness, 2008; Mhatre et al., 2021), in turn helping to reduce the consumption of natural resources and waste generation (Ghisellini et al., 2016; Lieder and Rashid, 2016; Tsai et al., 2020). The adoption of proper industrial and municipal waste management policies, directed to the recovery of materials and energy, represents a key factor (CalabrŒ and Satira, 2020; Halkos and Petrou, 2019; Van Ewijk and Stegemann, 2020; Rada and Cioca, 2017; Tisserant et al., 2017). Material recovery must be prioritized, taking into account the quality of obtained SRMs, which must be as close as possible to that of the virgin ones (Bodova, 2017). For those materials that cannot be recycled, energy recovery provides the opportunity of valorisation, thus giving a contribution to the achievement of the targets of the EU energy and climate policy (Boesch et al., 2014; DAdamo and Rosa, 2016; Fruergaard and Astrup, 2011; Ragazzi et al., 2017).

To achieve these goals, MSW management strategies must address both the waste treatment (i.e. the reduction of the environmental impact) and its valorisation (i.e. the transformation into a valuable products) (Cobo et al., 2017; Ghisellini et al., 2016; Hrabec et al., 2020), as well as separate collection, in that it affects the characteristics of both the waste fractions sent to recovery, and the mixed waste undergoing subsequent treatments (i.e. Incineration, Mechanical and Biological Treatment, Landfilling) (CalabrŒ and Pangallo, 2020).

Some EU policies and actions adopted in the different national laws already provide tools and incentives in line with the circular economy model (Hill, 2016; Van Ewijk and Stegemann, 2020; Calisto et al., 2021; Ragossnig and Schneider, 2019). With the EU Waste Framework Directive, a five-stage waste hierarchy was introduced, with prevention as the priority strategy to be considered, followed by preparing for re-use, recycling, other recovery (e.g. energy recovery) and disposal. Particular attention has been

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Nomenclature

MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
SRM	Secondary Raw Material
WTE	Waste to Energy
WEEE	Waste Electrical and Electronic Equipment
ARPA	Agenzia Regionale per la Protezione dellAmbiente

paid to the preparation for re-use and recycling, that must be at least equal to 50% (in terms of weight) by 2020. Directive 2008/98/EC was later amended by European Directive 2018/851/EU (European Parliament and council, 2018a), which introduced further targets for re-use and recycling, namely, 55% by 2025, 60% by 2030 and 65% by 2035. The EUs Circular Economy package issued in 2018, included three more Directives, that are: i) Directive 2018/849/EU (European Parliament and council, 2018b), which amended the Directives 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment; ii) Directive 2018/850/EU (European Parliament and council, 2018c), which amended the Directive 1999/31/EC on the landfill of waste; iii) Directive 2018/852/EU (European Parliament and council, 2018d), which amended Directive 94/62/EC on packaging and packaging waste. Moreover, the Commission recently adopted a new circular economy action plan as part of the new industrial strategy, which identified packaging, plastics and textiles as key product value chains needing further targeted measures (European Commission, 2020).

The European Union Countries differently implemented the Directives into national laws (Guziana et al., 2014; Malinauskaite et al., 2017; Zorpas et al., 2014), this resulting in quite different achievements. Specifically, according to the European Environment Agency (EEA, 2016), a 3% reduction of the total amount of MSW generated was recorded in the EEA countries in the time period 20042014. Nevertheless, a 7% reduction was measured in terms of per capita amount produced. More in detail, while 19 out of 35 countries showed a decreasing variation, in the other 16 an increase was recorded (Supplementary material, Table S1). According to Eurostat (Eurostat, 2020), EU-28 per capita municipal solid waste production ranged from 470 kg/(in y) in 1995 to 515 kg/(in y) in 2005. Then, a reduction to 486 kg/(in y) was recorded in 2012 and a constant value was kept until 2018 (489 kg/(in y)) (Supplementary material, Table S2). However, significant improvements were observed in terms of waste treatment: a large decrease in the amount of landfilled waste and, on the opposite, the increase of waste amounts treated in composting, material recycling, incineration with energy recovery facilities (Supplementary material, Figure S1).

Focusing on the Italian context, the first attempt to regulate MSW management at the national level, accordingly with a modern approach, can be pointed out with the Legislative Decree 22/97 (Gazzetta Ufficiale della Repubblica Italiana, 1997). This issued former European Directives and laid the foundations of an increasingly framed system. During the 90s, Italy was characterised, as well as most of the European countries, by a large increase in the MSW production. Specifically, considering years 1991, 1995, 1997, 1998 and 1999, the per capita amount of waste generated was respectively 350, 450, 462, 466 and 492 kg/(in y), with a separate collection rate not higher than 20% (OCSE Rapporti Sulle Performance Ambientali: Italia 2002, 2003). Legislative Decree 152/2006 (Gazzetta Ufficiale della Repubblica Italiana, 2006) replaced the previous one, introducing separate collection targets for MSW to be reached in the following years, namely: 35% by 2006, 45% by 2008 and 65% by 2012. Finally, the Legislative Decree 205/2010 was introduced (Gazzetta Ufficiale della Repubblica Italiana, 2010), aiming to move the focus towards waste reuse and recycling, thus underlying the paradigm shift from linear to circular economy. Specifically, paper and cardboard, plastic, glass and metals prepared for reuse and recycling should be, at least, equal to 50% in terms of weight by 2020. Two important trends were observed in the last period: on the one hand the per capita amount of waste generated decreased, on the other hand the separate collection rate progressively increased (Supplementary Material, Table S3). However, at national level the target set by the Legislative Decree 152/2006 has not been achieved, yet. In Italy there are also some Ministerial Decrees governing the end-of-waste of materials such as refuse derived fuel, bituminous conglomerate, absorbent products for the person, recycled rubber from end-of-life tires, paper and cardboard; those Decrees join the three EU Regulations defining the end-of-waste criteria for iron scrap, copper scrap and glass cullet (Johansson and Forsgren, 2020).

Both in the Italian and European contexts, several studies were carried out on MSW management strategies. For instance, the Life Cycle Assessment (LCA) approach is commonly employed to compare alternative solutions (Blengini et al., 2012; Cherubini et al., 2008; Iriarte et al., 2009), as well as social (De Feo et al., 2019; Sessa et al., 2009) and economic (Cossu and Masi, 2013; Ferreira et al., 2014; Rigamonti et al., 2015) aspects are often analysed. However, studies describing the effects of changes in MSW management strategies over long periods and at the local scale, in relation to the targets set by EU Directives and National laws, are scarcely reported in the literature (an exception is Ragazzi et al., 2017), notwithstanding the benchmarking role they might play. In this case a careful selection of easy-to-calculate performance indicators is preferable, respect to more sophisticated approaches (e.g. LCA based methodologies), given the difficulty to provide detailed historical data. The case presented in this work can be considered as a model for other realities: focusing on the Italian context, several metropolitan areas are still unable to meet the legislative requirements. In 2018, Turin, Genoa, Florence, Rome and Palermo achieved a separate collection rate only equal to 46.6%, 33.5%, 53.5%, 43.7% and 10.5%, respectively (ISPRA, 2019). The authors tried to assess a local reality, looking for pieces of information potentially useful to create a benchmark.

In short, this paper presents a detailed analysis of the evolution of the MSW management practices adopted in the city of Brescia, all along a 30-years period, aiming at measuring, by means of selected performance indicators, the effects of three key actions: a) the progressive extension of the kerbside separate collection in the nineties, b) the construction of a WTE plant in 1998, and c) the adoption of a new collection system in 2016. Through the definition of detailed mass flows, tricky aspects related to the calculation of material recovery indices are also discussed.

2. Evolution of the MSW management system in the city of Brescia

Brescia is located in the Lombardy region, Northern Italy, and covers an area of 90,340 m^2 (elevation of 149 m above sea level). It is the second largest city in Lombardy with a population of 198,536 in 2018.

The waste management strategies have substantially evolved since the 1970 s. The main actions which were progressively put in place are shown in Fig. 1.

The history described in this paper covers a period of approximately 30 years. Quantitative evaluations are referred to 7 years (1990, 1997, 2000, 2015, 2016, 2017, and 2018), which were selected as check points to highlight the achievements from time to time obtained.

In 1990, 4 waste fractions (paper and cardboard, glass, tins, and mixed waste) were separately collected, by means of street containers. Moreover, bins for the collection of exhausted batteries and pharmaceutical wastes were located nearby some commercial activities (e.g. pharmacy), schools and public departments. The unsorted waste was directly disposed of in landfills, as well as the exhausted batteries (after stabilization-solidification). Paper, glass and tins were sent to sorting facilities in order to be prepared for recycling. Pharmaceutical waste was directly sent to incineration.

Since 1992, actions have been taken to better structure the MSW management system, from both a technological and organisational viewpoint, towards an integrated waste management system. Among other measures, food waste collection in schools, canteens and markets was promoted; moreover, non-domestic users were allowed to bring paper and cardboard to new civic amenity sites (which is a facility usually provided with recycling points where citizens and small companies can dispose of their waste; Williams and Taylor, 2004), where the collection of plastic also was started.

In 1997, waste containers were still largely used for MSW collection. The waste was sorted into five fractions: paper and cardboard, plastic packaging, multi-material (glass and tins), organic fraction, and unsorted waste. In addition, the introduction of civic amenity sites allowed to separately collect also other materials such as wood, metals, textile, waste electrical and electronic equipment (WEEE) and hazardous wastes. The unsorted waste and the street cleaning waste were landfilled.

With the aim of progressively reducing the amount of landfilled waste, in 1998, a WTE plant was built, to serve a large district, including the city of Brescia. Hence, the unsorted waste underwent energy recovery, while the amount directly sent to landfills progressively decreased, until it ceased, in 2004. The WTE facility consisted, originally, of two moving grates lines; a third one was set up in 2004. Nowadays the authorized capacity is 800,000 t/y of unsorted MSW and non-hazardous wastes coming from industrial and commercial activities. In 2018, 617,445 MWh of electric energy and 820,722 MWh of thermal energy (recovered in the existing centralized heating system of the city) were produced, respectively (ISPRA, 2019).

Separate collection, in these years, reached a saturation level (around 40%) which was lower than the expectations of the Municipality and the MSW management company. Thus, starting from April 2016, up to October 2017, the collection system strategy was modified. This allowed to quickly achieve the targets set by the Italian law for the percentage of sorted material. The new strategy was gradually implemented all over the city, which was divided into 6 areas (Table S4 of the Supplementary Material). At present, paper and cardboard, plastic packaging and multi-material (glass and metals) are picked-up door to door once a week, whereas the organic and mixed waste are collected in

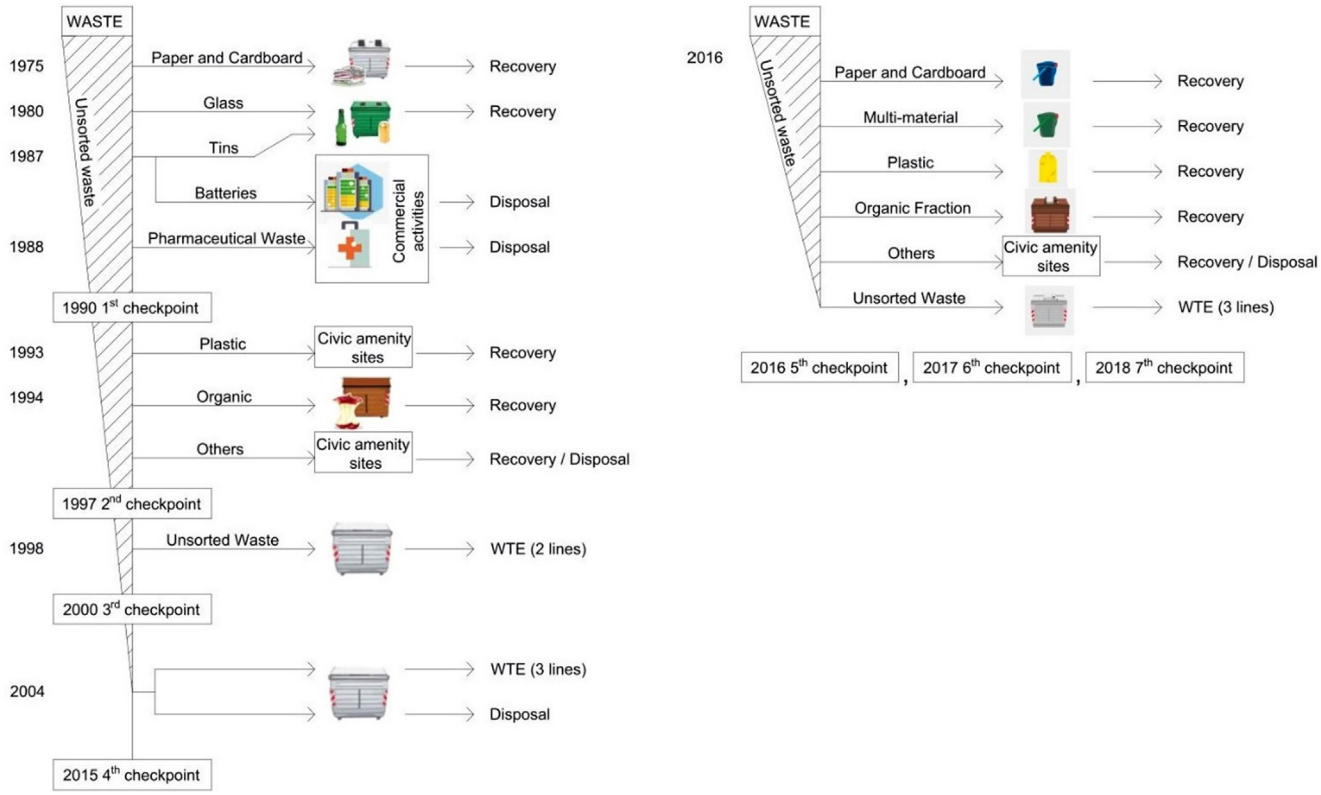

Fig. 1. Evolution of the MSW management system in the city of Brescia from 1975 up to now: progressive extension and intensification of kerbside separate collection and building of the WTE plant (on the left); adoption of a new collection system (on the right).

access-protected street containers. In the city centre (red zone 6-) also the multi-material is collected with a bring system. Access-protected street containers were preferred for the collection of the organic and the unsorted waste fractions, respect to the door to door system, in order to favour the population habits: wastes can be disposed in any moment, thus avoiding their accumulation at home and the formation of unpleasant odours. This choice was taken despite the expected worse quality of the collected organic fraction.

Before the introduction of the new collection strategy, a rather high per capita waste production was recorded, due to several factors.

First, a migration phenomenon was observed: people living in the neighbouring municipalities, where door to door collection system was already in force, used to bring their refuse to Brescia and discharge it, as unsorted waste, in the open (not controlled) street containers.

Additionally, 11 open-air large volume street containers were placed all around the city for the collection of some kinds of wastes (residual, bulky, street cleaning). Initially, they were not under control, but, over time, they have been regularized and managed by qualified personnel. Furthermore, the criterion, adopted by the municipality, to equate commercial/industrial waste to MSW did not impose quantitative limitations. It has to be noted that commercial/industrial users represent around 15% of the total.

Before and during the progressive adoption of the new collection system, the waste management company promoted several educational campaigns in order to raise citizens awareness for the environmental issues, this being recognized as a key factor for the effectiveness of the whole process (CalabrŒ and Komilis, 2019).

3. Assessment of the MSW management system: Methods

3.1. Database

The information needed to describe the development of the MSW management system in the city of Brescia and data required for the calculation of the selected indicators were gathered from reports and documents obtained from the local authorities and databases of the waste management company. Total production of MSW, unsorted waste, bulky waste, street cleaning waste and sorted materials are available off the shelf from annual reports of the Brescia Province Observatory of waste (Osservatorio Provinciale Rifiuti, 2019). The same set of data regarding more specifically the evolution of the new MSW collection system through the years 20162018 was directly acquired from the waste management company. Further pieces of information regarding the amount of waste received and treated by plants involved in the recovery processes were made available by ARPA Lombardia (which is the regional agency for environmental protection of Lombardy region) that shared its database. In some cases, direct contacts were also taken with the facilities.

Results of waste composition analyses were also made available by the waste management company.

3.2. MSW collection system performance indicators

Bertanza et al. (2018) described and compared several indicators proposed in the literature for assessing MSW collection systems. The authors suggested a set of indicators which are calculated on the basis of easily accessible data, and thus are considered to be robust and reliable. Consequently, they are also suitable to make comparisons with other realities (benchmark). Furthermore, they do not depend on site specific conditions (electricity cost, secondary raw material market, personnel cost, etc.). Among the indicators proposed by Bertanza and co-workers, in this paper, the following were considered meaningful for evaluating the waste collection strategies and quantitatively describe the results from time to time achieved:

D0 (%): fractions of separately collected waste (as a whole), bulky waste, street waste and unsorted waste, with respect to the total amount of waste collected.
D1 (kg/(in y)): per capita annual amount of collected waste fractions.
P4 (%): percentage of sorted material with respect to the produced amount of the same material. This indicator was calculated for the following waste fractions: paper and cardboard, plastic packaging, multi-material and OFMSW. The unsorted waste composition was used for the calculation.

3.3. Mass flow analysis and material recovery efficiency

The per capita waste amount sent to material recovery facilities, incineration and landfills, respectively, each year, was first calculated.

In addition, for the year 2018, the recycling rate was calculated. According to the Regional Council Resolution DGR 6511/2017 (BURL, 2017), this parameter is given by the ratio between the total recycled amount of paper and cardboard, metal, plastic, glass, organic, green, and wood and the generated amount of the same fractions. In order to come up with this value, data used in the calculation of material sent to recovery facilities were processed. Specifically, ARPA Lombardia databases were consulted. Here, pieces of information regarding the amount of waste received, treated and produced by all the facilities working in the region are annually recorded. By tracking the material flows, tricky aspects were pointed out: after the collection, depending on the material type, wastes are delivered to several recovery facilities. Output of these plants can be classified either as discarded material, recovered material (still waste) or SRM. In the latter case, the mass flow cannot be longer carried out, since ARPA databases only deal with waste data. Hence, in this work, the calculation of the recycling rate refers to the first phase of the recycling process, by considering the selection occurring in the facilities that receive the waste just after its collection.

4. Results and discussion

4.1. Performance improvement of MSW separate collection

4.1.1. D0 and D1 indicators: Evolution over the three decades period

Table 1 (last row) shows the growth of the amount of separately collected waste over the years. A first significant increase was achieved with the introduction of the integrated waste management system in 1992: the per capita amount passed from 26 kg/(in y) in 1990 to 117 kg/(in y) in 1997. The strengthening of the MSW separate collection system led to a further increase: in 2000, sorted waste reached 203.1 kg/(in y), namely the 30.5% of the produced amount with respect to 19.7% in 1997. Subsequently, for the next fifteen years, only a slight increase of separately collected waste was observed, by achieving 255.4 kg/(in y) (37.3%) in 2015. It was assumed that a kind of saturation level had been reached. A new collection system was then introduced, in 2016, as the only way to improve the performance: in less than 3 years, the percentage reached 66.2%.

On the opposite, while a percent reduction of the unsorted waste was measured during the period 19902015, the per capita amount grew up to 407.5 kg/(in y) in 2015. This is related to the

Table 1
Number of inhabitants in the city of Brescia over the considered period and yearly per capita amount (D1 indicator) and percentage (D0, in brackets) of macro waste fractions and sorted material.

Year	1990	1997	2000	2015	2016	2017	2018
Inhabitants	194,502	188,126	192,552	196,480	196,670	196,745	198,536
Unsorted waste (kg/(in y))	356.6* (93.2%)	427.4*(71.9%)	386.2 (58.1%)	407.3 (59.4%)	353.6 (52.4%)	187.0 (32.4%)	156.1 (26.9%)
Bulky waste (kg/(in y))			27.6 (4.2%)	10.5 (1.5%)	13.3 (2.0%)	23.1 (4.0%)	20.6 (3.6%)
Street cleaning waste (kg/(in y))	N.A	50.0 (8.4%)	48.5 (7.3%)	12.1 (1.8%)	10.8 (1.6%)	11.8 (2.0%)	19.1 (3.3%)
Separately collected waste (kg/(in y))	26.0 (6.8%)	117.0 (19.7%)	203.1 (30.5%)	255.4 (37.3%)	297.6 (44.0%)	356.6 (61.6%)	383.8 (66.2%)
Paper and cardboard (kg/(in y))	13.0 (3.4%)	43.4 (7.3%)	61.4 (9.2%)	66.6 (9.7%)	74.2 (11.0%)	84.2 (14.6%)	87.6 (15.1%)
Plastic packaging (kg/(in y))		0.9 (0.2%)	3.2 (0.5%)	9.2 (1.3%)	14.5 (2.2%)	26.1 (4.5%)	30.4 (5.2%)
Multi-material (kg/(in y))	12.8 (3.3%)	18.1 (3.0%)	21.4 (3.2%)	29.8 (4.4%)	35.4 (5.2%)	44.9 (7.8%)	47.4 (8.2%)
OFMSW (kg/(in y))		40.6 (6.8%)	49.6 (7.5%)	40.9 (6.0%)	50.7 (7.5%)	73.5 (12.7%)	83.2 (14.4%)
Other collected waste (kg/(in y))	0.2 (0.1%)	14.0 (2.4%)	67.5 (10.1%)	108.9 (15.9%)	122.8 (18.2%)	127.9 (22.1%)	135.2 (23.3%)

* Bulky waste is counted in the unsorted waste.

raise of the total per capita production recorded in the period (see the Introduction paragraph) together with the phenomena described in Section 2: the adopted integrated waste management system promoted waste migration from neighbouring municipalities, disposal of several wastes in uncontrolled large containers, etc., thus improperly diverting important waste streams.

The positive effect of the new MSW collection system on the reduction of the unsorted waste is clear: in 2018 the per capita amount dropped down to 156.1 kg/(in y) (26.9%).

Another relevant achievement concerns the bulky wastes, which increased with the adoption of the new MSW collection system. They almost doubled from 2015 to 2018 in terms of quantity (from 10.5 to 20.6 kg/(in y)). The reason of this increase lies in a new definition of the bulky waste concept. Specifically, since the introduction of the new collection system, the access-protected street containers used for the unsorted waste are characterised by a 20 L inlet (Supplementary Material, Figure S2). This poses a physical limitation to the size of materials that can be put inside. Now, these wastes are collected as bulky materials, instead of as unsorted wastes as it was before. Then, a significant amount of waste, that was previously disposed as unsorted, is now collected in the civic amenity sites as bulky material, thus being sent to recovery.

From 1990 to 2018, all separately collected waste fractions increased both in terms of quantity and percentage. A first remarkable increase was recorded from 1990 to 2000. Paper and cardboard (which constantly raised from 13 to 61.4 kg/(in y)) were the first materials to be separately collected with street containers since 1975; thus, their collection has been the most well-established since the early 90s and, as a result, this fraction always showed the highest rate among sorted materials. The collection of the organic fraction and food from canteens, supermarkets and fruit markets began in 1994. As a consequence, separated collection of OFMSW rapidly reached 40.6 kg/(in y) in 1997 and 49.6 kg/(in y) in 2000. First street containers for glass collection were placed in 1980, and in 1990 multi-material collection was finally established; as the second oldest separately collected fraction, multi-material seems to have taken good root into citizens habits. Indeed, separately collected multi-material amounted to 18.1 and 21.4 kg/(in y) in 1997 and 2000, respectively. Other separately collected waste grew from 14 kg/(in y) of 1997 to 67.5 kg/(in y) in 2000, thanks to the introduction of civic amenity sites in the mid 90s, which allowed the collection of wood, WEEE, metals and textiles. Apparently, only plastic packaging achieved poor results, due to the late introduction of separate collection. Civic amenity sites for experimental disposal of plastic packaging were established only in 1993 and the bring system came into operation even later, in 1997. Hence, it was only from 2000 onwards that the amount of sorted plastic gained a certain relevance. From 2000 to 2015 all fractions of per capita separately collected waste slowly increased or stayed almost stable: as stated before, it seems that the separately collected waste strategy based on bring system and civic amenity sites had reached its performance limits. The adoption of the new MSW collection system, in 2016, radically increased the separation extent of all fractions.

4.1.2. D0 and D1 indicators: Evolution during the introduction of the new collection system

D0 and D1 indicators were calculated every time a new area of the city adopted the new strategy of waste collection (Supplementary Material, Table S4). This allowed to appreciate the outcome, step by step, showing the importance of using such a kind of easy-to-calculate indicators to keep the system performance under control.

Percent composition of MSW (Fig. 2) shows that the separately collected amount progressively raised from 36.7% (January March

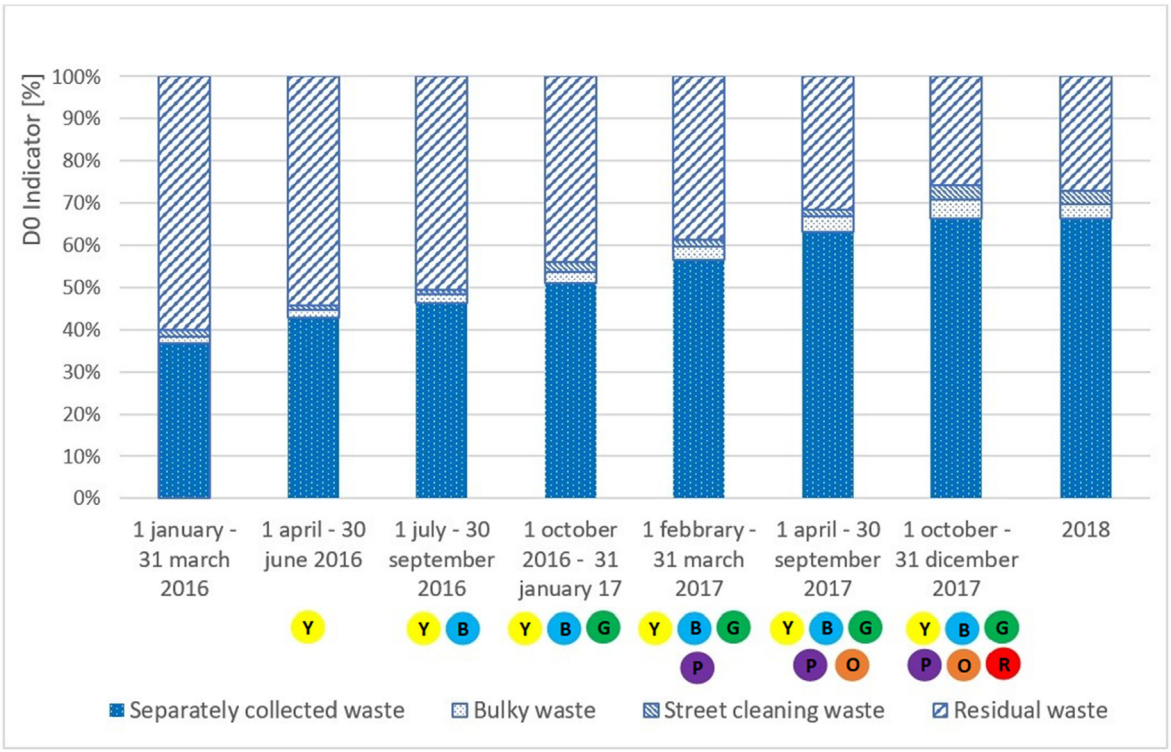

Fig. 2. Percent composition of collected waste (D0 indicator) and progressive extension of the new collection strategy in the city of Brescia over the period January 2016 - December 2018. Coloured circles (and the letters inside) indicate the zones of the city where the new collection system was in operation, accordingly with Table S4.

2016) up to 66.2% (October December 2017), when the new collection procedure had been extended to the whole city. The Ministerial Decree 26/05/2016 (Gazzetta Ufficiale della Repubblica Italiana, 2016) and the Regional Council Resolution DGR 6511/2017 prescribe a different method to evaluate the percentage of separately collected waste. Specifically, also the bulky materials and the street cleaning waste must be considered. Accordingly, the total percentage of separately collected waste is

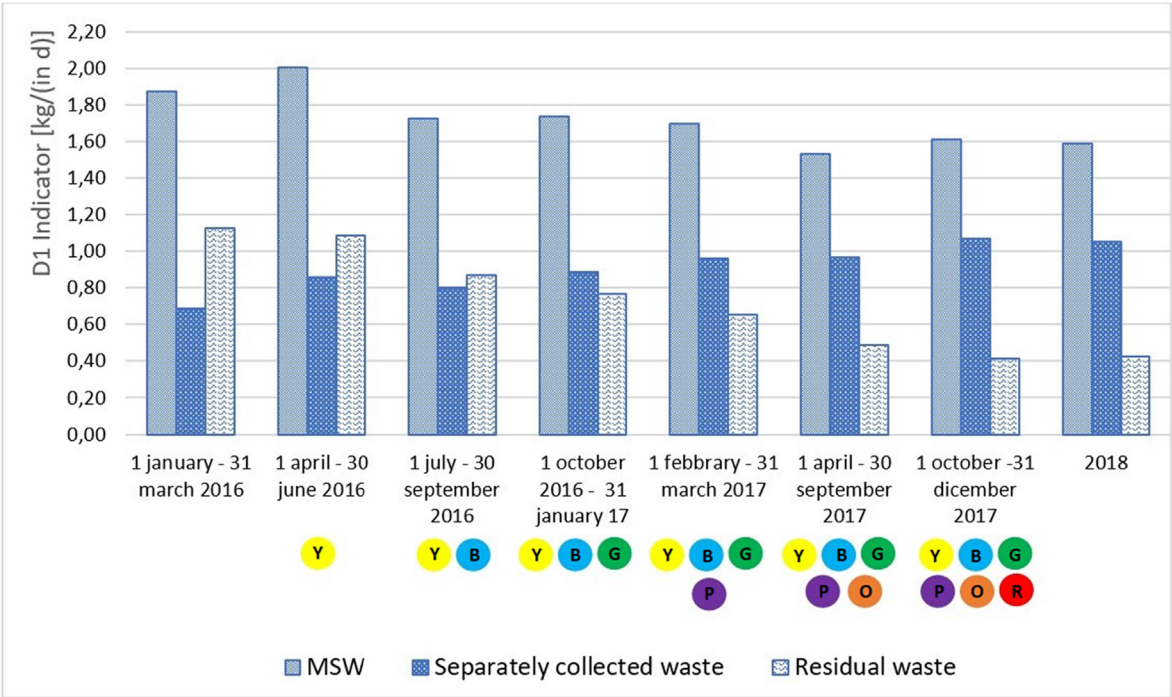

Fig. 3. Daily per capita amount of MSW, sorted waste and residual waste (D1 indicator) and progressive extension of the new collection strategy in the city of Brescia over the period January 2016 - December 2018. Coloured circles (and the letters inside) indicate the zones of the city where the new collection system was in operation, accordingly with Table S4.

equal to 74.3% over the period October December 2017 (73.1% in 2018), that is much higher than other medium-size Italian cities like Verona (259,000 in; 52.7% of separate collection), Venezia (258,000 in; 59.5%), Messina (227,000 in; 17,9%), Padova (210,000 in; 55.2%), Trieste (201,000 in; 42.1%). For comparison, the regional and national values, in 2018, were 70.7% and 58.1%, respectively (ISPRA, 2019).

Fig. 3 shows that the daily per capita amount of separately collected waste (bulky waste and street cleaning waste excluded) increased from 0.69 to 1.05 kg/(ind), while the residual waste dropped from 1.13 to 0.43 kg/(ind). Finally, the total daily per capita production decreased from 1.87 to 1.59 kg/(ind).

The per capita amount of collected MSW was significantly higher in Brescia than in other cities of the Lombardy Region, before the introduction of the new collection system (Supplementary Material, Table S5). Actually, the door to door collection, together with the adoption of access-protected street containers, helped in restricting the migration phenomenon of waste (see section 2) and in monitoring waste disposal of non-domestic users. Moreover, the criterion to equate special (commercial/industrial) waste to MSW was modified by the municipality, as it now sets a limit to the disposal of tertiary packaging (as defined by European Directive 94/62/EC) in street containers. All of these measures are thought to have led to the recorded decrease of the MSW production. However, per capita production of MSW in Brescia is still higher than regional (478.2 kg/(in y)) and national values (499.7 kg/(in y)) (ISPRA, 2019).

4.1.3. P4 indicator

All the waste fractions that, at present, are collected by means of a dedicated service (door to door or bring system) showed an increase in the P4 indicator (Table 2). The educational campaigns that were carried out by the waste management company are thought to have played a relevant role on this. The increase of the P4 indicator is an important achievement for the whole integrated waste management system, efficiently sorting the wastes at the source level being a key point to boost resource recovery. In this vein, the door to door collection can be seen as a tailor-made service for the user, who is better involved in this complex system.

4.2. Mass flow analysis

4.2.1. First destination of the collected waste fractions

Fig. 4 shows the destination of collected wastes, over the years, considering the amount sent either to recovery facilities, incineration or landfill. Since the 90s, the adoption of the integrated waste management system allowed to downsize the amount of waste directly sent to landfill. This decreased from 93.2% in 1990 to 80.5% in 1997, dramatically dropped after the WTE plant commissioning (only 9.3% in 2000), and eventually ceased in the following years. This led Brescia to line up with EU Waste Framework Directive 2008/98/CE that recommends landfilling to be only a residual option. Conversely, the amount of waste sent to material recovery gradually increased in the last 30 years (from 6.8% in 1990 to 40.6% in 2015), with a relevant and impetuous rise following the adoption of the new MSW collection system (from 40.6% to 73.1%). This was a fundamental improvement since waste recycling represents a strategic issue in the process towards implementation of circular economy principles (Tantau et al., 2018). Alongside recycling, the WTE plant played a key role in reducing landfilled waste and diverting an important amount of waste to energy recovery, thus reducing greenhouse gas emissions from landfill sites (Tisserant et al., 2017; Halkos and Petrou, 2019). Before 1998, all the unsorted waste was landfilled, whereas, in 2000, 97% of the unsorted waste was sent to energy recovery.

Table 2
P4 indicator improvement achieved thanks to the progressive extension of the new collection system to the whole city.

Waste fraction	2015	2016	2017	2018
Paper and cardboard	35,8%	51,2%	68,6%	73,5%
Plastic packaging	13,0%	20,3%	47,0%	54,1%
Multi-material	35,2%	55,4%	78,0%	88,2%
OFMSW	28,3%	32,6%	63,6%	68,3%

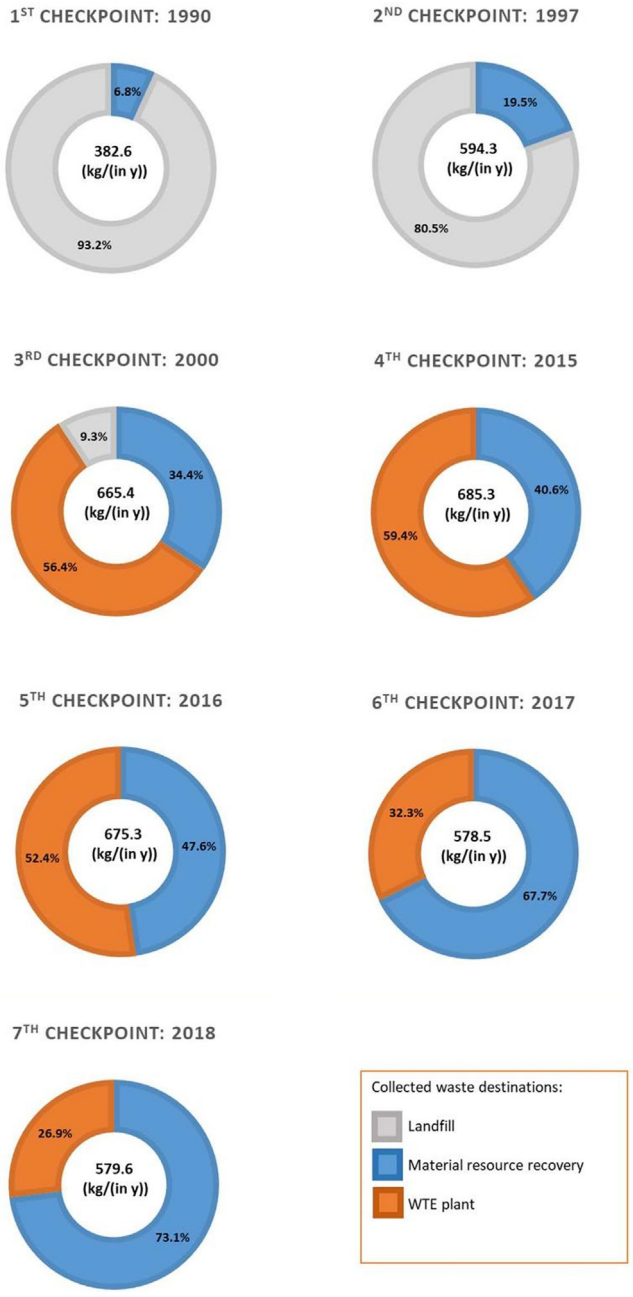

Fig. 4. Amount of waste collected, sent to material recovery facilities, incinerated and landfilled, respectively, over the period 19902018.

Although incineration is still an essential part of the MSW management system, its role has been downsized from 2015 to 2018, dropping from 407.2 down to 156.1 kg/(in y) of per capita incinerated waste, namely from 59.4% to 26.9%. Hence, despite the WTE plant can be argued to be a barrier in moving towards a circular economy model (Malinauskaite et al., 2017) - due to its potential to discourage recycling actions it can be stated that in the city of Brescia this trend was not recorded. On the opposite, the coexistence of the WTE plant and the combined collection system led to line with the European Commission (EC, 2017) guidelines to not prevent higher levels of prevention, reuse and recycling.

4.2.2. Mass flows and criticalities in the calculation of the recycled fractions

Fig. 5 shows the simplified mass flow for the year 2018. A more detailed scheme is available in the Supplementary Material 2: a total of 72 facilities were inventoried (26 of which receive the waste directly after the collection). The build-up of the detailed mass flow was time consuming, but very useful to show how complex the whole circular economy system is, even if it was not possible to track all the mass flows up to the final step. Waste databases keep track only of waste material flows, while, once a material loses the waste attribute end of waste , and can be classified as SRM, it is no longer recorded. It would be necessary, in this case, to analyse the mass balances of each one of the facilities involved in the treatment-transformation-delivery-marketing process.

Moreover, tricky aspects arose, in relation to the calculation of the recycling rate of different materials. Specifically, when calculating the total amount of a waste fraction that is produced, composition analyses of both separately collected and unsorted materials should be carried out. Usually, this kind of information is not available. In effect, Haupt et al. (2017) pointed out that the recycling rate may be defined in different ways. The simplest way is to refer to the amount of waste sent to recycling facilities; in the present paper, this information has been provided by the performance indicator P4. However, the real fraction which will be actually recovered is not calculated in this way, because the impurities that are discarded by the treating plants are neglected. Hence, in order to calculate a recycling rate as close as possible to the real figure, further considerations must be carried out.

Both in literature and directives, several methods have been provided. Specifically, according to the European Commission Decision 2011/753/EU (EU, 2011), that establishes rules and calculation methods for verifying compliance with the targets [] of Directive 2008/98/EC of the European Parliament and of the Council, 4 methods are identified (Supplementary material, Table S6). DGR 6511/2017 of the Lombardy Region refers to method 2 of Decision 2011/753/EU. Accordingly, as reported above, the overall recycling rate must be calculated as the ratio between the total recycled amount of paper and cardboard, metal, plastic, glass, organic, green and wood and the generated amount of the same fractions. A figure of 70.3% (65,756.6 t) results, for the year 2018, in Brescia.

Under the hypothesis that no other waste was recycled, the overall recycling rate (that is 65,725.6 t with respect to the whole waste production) would be 57.1%. Considering that the EU Waste Framework Directive imposes that recycled material must be at least equal to 50% in terms of weight by 2020, it can be stated that Brescia achieved the target 2 years earlier.

Among the selected recycled material, wood fraction presents the highest rate (93.8%), followed by green material (82.3%), glass and metals (81.7%), paper and cardboard (72.9%), organic waste (63.1%) and plastic (39.4%).

Of course, there is a link between the recycling rate and the P4 indicator. Specifically, the higher the amount of recyclable material that is subtracted to the unsorted waste, the higher the achievable rate. In effect, plastic waste, that is the fraction with the lowest P4 value, is also the material less recycled (39.4%). The low rate is also linked to the presence of mixed plastic types within the MSW that poses a limitation to the available technological sorting system (Ragaert et al., 2017). Furthermore, the high energy content of the plastic material leads to prefer the option of energy recovery when the quality of the waste collected is low.

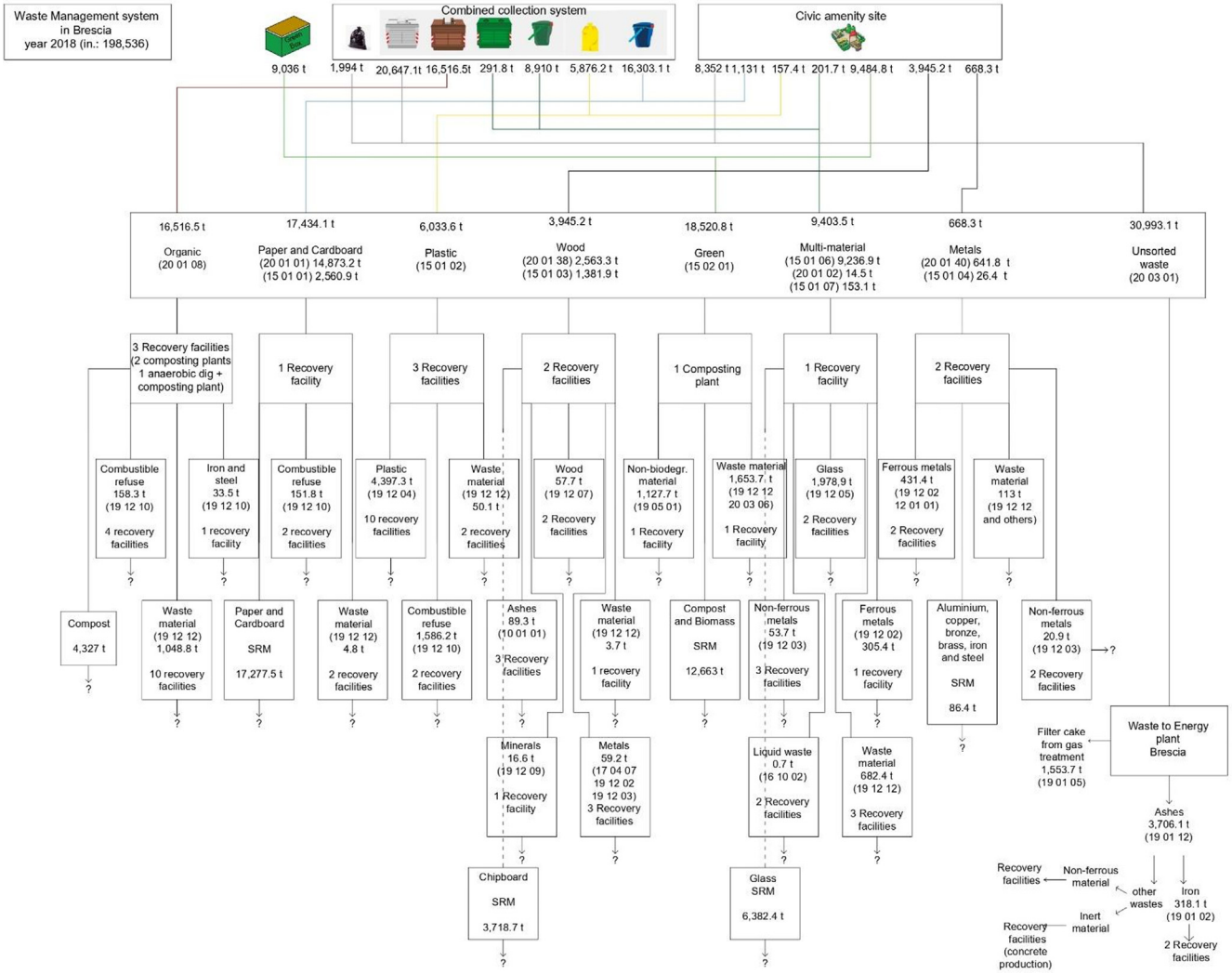

Fig. 5. Simplified MSW flow scheme for the City of Brescia in 2018.

Promising results were achieved referring to green (82.3%) and organic fractions (63.1%), that are turned into compost.

Dealing with paper and cardboard, a 72.9% recycling rate was obtained. A deeper analysis on paper and cardboard, taken as an example, shows that the amount of material outgoing the plant as SRM is almost the same amount of the incoming one (99%). This underlines the low quantity of impurities in the collected material, thanks to the door to door system. Nevertheless, it must be pointed out that a further sorting process occurs when the material reaches the paper mills, thus reducing the really recycled amount. Moreover, this also depends on the quality of the final product (Merrild et al., 2009) and on industrial constraints (as process related aspects affected by the presence of undesired material and/or market conditions). Unfortunately, as pointed out before, this information is not detectable in the ARPA databases, since material outgoing the sorting facility is no longer classified as waste.

For some materials, further limitations in the calculation of recycling rate based on mass balances lie in the difficulties to take into account changes in moisture content (paper and cardboard) and process losses (green and organic fractions).

Moreover, 81.7% of glass and metals were recycled in 2018, if calculated as described above. Considering the amount of iron recovered in the WTE plant (318.1 t, considered in the total amount produced, since composition analyses of the unsorted waste are available), an increase of 2.8 percent points could be obtained, leading to an actual recycling rate of 84.5%.

Furthermore, as explained, in this work the amount of recycled material was calculated based on the material flow of the recovery facility that treats a given kind of waste. If, for instance, the organic material is considered, 33.5 t of iron and steel leave the composting (or anaerobic digestion) facilities and are delivered to another sorting plant (as well as considering wood). A given extent of material recovery (and material produced) will result from this; nevertheless, this is not counted in the calculation of multi-material recycling rate. Actually, a further increase could be obtained, leading to a potential multi-material recycling rate of 84.7%.

Considering the calculation method 1 set by the European Decision 2011/753/EU, only paper and cardboard, plastic, glass and metals produced by household users should be considered (while OFMSW, green and wood are not included). Assuming that all these waste fractions were entirely produced by household users, the recycling rate would be equal to 67.0%. Also this value, as the one calculated before, is way higher than the 50% target set by Legislative Decree 205/2010. Table 3 summarises calculations described above.

Table 3
Amount of selected wastes (OFMSW, paper and cardboard, plastic, wood, green, multi-material) produced, recovered and recycling rates calculated according to different legislative requirements.

Waste fraction	Amount produced (t)	Amount recovered according to 2011/753/EU (t)	Recycling rate according to 2011/753/EU (%)
OFMSW	24,190.4	15,275.9	63.1%
Paper and cardboard	23,713.3	17,277.5	72.9%
Plastic	11,159.8	4,397.3	39.4%
Wood	4,025.8	3,776.5	93.8%
Green	19,131.3	15,739.3	82.3%
Multi-material (glass and metal)*	11,326.9	9,259.1	81.7%
Overall, method 2	93,547.6	65,725.6	70.3%
Overall, method 1	46,200.1	30,933.9	67.0%
Overall, neglecting other recovered materials	115,080.0	65,725.6	57.1%

* By considering metals recovered from OFMSW and wood, the amount produced, the amount recovered, and the recycling rate would be equal to 11,419.6 t, 9,670.0 t, and 84.7%, respectively.

5. Conclusions

This paper focuses on the actions adopted in the city of Brescia, over the last 30 years, for promoting circular economy in MSW management practices. A detailed analysis brought to the conclusions reported below.

Lessons learnt on waste collection were the following: (i) the door to door system revealed essential to overcome the 65% rate of separate collection set by the Legislative Decree 152/2006 of the Italian Parliament (the target was largely exceeded in 2018: 73.1%); (ii) the increase of the recycling rate reached the objective set by the EU Waste Framework Directive (50%) 2 years earlier respect to the deadline; (iii) the adoption of access-protected street containers for OFMSW and unsorted waste a) avoids keeping odorous wastes at home for days, b) contributed to the reduction of per capita MSW production (waste importation from outside the city was eliminated, as well as uncontrolled disposal of non-domestic wastes); c) diverted bulky wastes to civic amenity sites, thus promoting their recovery; iv) the more stringent criteria for the identification of commercial/industrial wastes set by the Municipality, contributed to the reduction of the per capita production of MSW.

The WTE plant, commissioned in 1998, in conformity with the waste hierarchy imposed by EU Directive 2008/98/CE, progressively reduced the percentage of directly landfilled waste until it completely ceased. At the same time, it did not represent a barrier in promoting material recovery, as shown by the encouraging achievements of the separate collection.

Thanks to a deep investigation of mass flows (72 waste treatment facilities were counted) tricky aspects in the calculation of the recycling rate were highlighted and discussed. These should be taken into account to obtain sound reference values. Nonetheless, the obtained mass flows pave the way towards further studies aimed to identify waste management scenarios which minimize the environmental impact and/or the operational cost.

Easy-to-calculate performance indicators were used, which allowed the assessment of the system all along three decades, as well as within short time frames (a few months). This might be useful to build up a real-time internal assessment procedure, as well as to establish a benchmark through data sharing.

The case of Brescia can be considered as a virtuous model for the implementation of the circular economy approach in the MSW domain.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2021.04.017.

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