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Definition of best practices for municipal solid waste management

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Contents

Summary

The deepened analysis of both European and Italian norms represented the starting point to evaluate the current implementation of legislation in Italy, with a particular focus on Ancona Province. This approach allowed the assessment of the current performance of MW collection and recycling system, highlighting the main criticalities connected to the biodegradable residue in the undifferentiated waste, intended for the disposal. A doubt emerged about the obligation of a treatment of undifferentiated waste, before the disposal in landfilling sites. Therefore, a real scale analysis was carried out selecting the Corinaldo landfilling site (which collects the MW of Ancona Province) as case study. The possibility of the real scale study represents a strength of the present research, compared to the available scientific literature, often referred to lab scale. The analysis evaluated the effect of the mechanical biological treatment (MBT) on MW, sent to Corinaldo facility. With this aim, the characteristics of disposal in two reference periods (before and after the MBT facility starting) were studied. The results did not identify significant improvements after the implementation of the MBT, considering the high efficiency of collection and recycling system in Ancona. The further environmental and economic assessments suggest that the best strategy of MW management should invest on recycling system, rather than the WM stabilization, in agreement with the circular economy principles. Starting from these observations, the manuscript presents a critical study of the technical criteria of the Italian norms suggesting a more deepened evaluation of parameters to assess the cases in which the MBT (before the disposal) produces real benefits on MW management. These evaluations should be able to balance the benefit with the MBT facility impact, both in environmental and economic terms, in the scenarios characterized by a virtuous recycling system.

DEFINITION OF BEST PRACTICES FOR MUNICIPAL SOLID WASTE MANAGEMENT

DOCTORATE DISSERTATION

Dissertation outline

1. **Overview**

1.1 Critical analysis of European and Italian legislation and guidelines

The Directive 2008/98/EC of 19 November 2008 of the European Parliament and of the Council establishes measures to protect the environment and human health by preventing or reducing the negative impacts of the production and management of waste, in particular to the art. 4 establishes the hierarchy of waste to be applied as the priority order of legislation and policy on waste prevention and management: a) prevention; b) preparation for re-use; c) recycling; d) recovery of other types, for example energy recovery; e) disposal. The Directive provides that in applying the above waste hierarchy, Member States shall take measures to encourage the options that give the best overall environmental result. The European legislator does not exclude that it may be necessary for specific waste streams to deviate from the hierarchy where this is justified by The MW sent in 2016 to treatment at the TMB plants corresponds to 76% of the undifferentiated waste produced. The concept of safe disposal operation was introduced by Council Directive 1999/31/EC of 26 April 1999 (relating to landfills of waste). The general objective of the Landfill Directive (Article 1) is to introduce measures to prevent and reduce as far as possible the negative effects on the environment, in particular the pollution of surface waters, groundwater, soil and the atmosphere , and on the global environment, including the greenhouse effect, as well as the risks to human health during the entire life cycle of the landfill. This objective has been transposed in the same way in the national legislation to the art. 1 of the D.lgs. n. 36/2003. In order to guarantee safe disposal, the Directive (Article 5) requires Member States to draw up a national strategy for the purpose of reducing biodegradable waste to be landfilled; this strategy according to the legislator should be pursued through measures such as recycling, composting, biogas production or materials / energy recovery. The Landfill Directive, in order to meet the concept of safe disposal, requires that only treated waste can be landfilled (art. 6). The Landfill Directive 1999/31/EC (Article 2) defines the "treatment" of waste as "physical, thermal, chemical, or biological processes, including sorting, which modify the characteristics of the waste in order to reduce its volume or the dangerous nature and to facilitate its transport or promote its recovery ".The term treatment includes all methods of treatment: from sorting to biological treatment. The EU Directive does not define which type of treatment can be considered sufficient to allow landfilling and to what extent the treatment obligation should apply. The directive 1999/31 CE and the legislative decree 36/2003 of the transposition, do not impose the absolute obligation of treatment and the treatment can be considered not necessary only when it does not contribute to the attainment of the finality of which to the art. 1 of the legislative decree n. 36/2003.

The minimum essential contents of the treatment activities have been defined with an opinion of the European Commission in the context of the open infringement procedure against the Italian Republic for violation of Directive 1999/31/EC and Directive 2008/98/EC. In Italy ISPRA with guidelines n. 145/2016 (30 July 2016) provided the technical support criteria to define when treatment is not necessary as it does not reduce the amount of waste or risks to human health and the environment.
In 2018, the European Commission has modified the Directive 1999/31/EC (about landfill) with the Directive 2018/850/EC. As concern the Italian scenario, the recent national implementation of Directive 2018/850/EC (and the Circular Economy Package), has modified the Italian landfill legislation (Legislative Decree 36/2003) by the new Legislative Decree 121/2020. The norm includes the criteria to define the necessity of a municipal waste (MW) treatment, before the disposal.

1.2 State of the art of MW management in Europe and in Italy

The research analyzed data on the production and treatment of solid municipal waste in Europe through the online publication MW Statistics available on the Eurostat platform. Data were extracted in July 2018. This publication analyzes trends in the production and treatment of MW in the European Union (EU) from 1995 to 2016. There is a very distinct trend towards less landfilling as countries move steadily towards alternative ways of treating waste. For 2016, MW generation totals vary considerably, ranging from 261 kg per capita in Romania to 777 kg per capita in Denmark. The variations reflect differences in consumption patterns and economic wealth, but also depend on how MW is collected and managed. There are differences between countries regarding the degree to which waste from commerce, trade and administration is collected and managed together with waste from households. Analyzing the situation in Europe (28) we can see an increase in production (kg per capita) in the period 1995-2005 (+ 9.0%) and a decrease in the period 2005-2016 (-6.3%) probably due to the effect of the economic crisis on consumption. In the section MW Treatment, differences in the management of MW are shown and treatment strategies are identified based on reported amounts of MW landfilled, incinerated, recycled and composted. The ‘other treatment’ category was calculated as the difference between the sum of the amounts treated and the amounts of waste generated. The ‘other treatment’ category reflects the effects of import and export, weight losses, double-counting of secondary waste (e.g. landfilling and recycling of residues from incineration), differences due to time lags, temporary storage and, increasingly, the use of pre-treatment, such as mechanical biological treatment (MBT). In the reference period, the total MW landfilled in the EU-28 fell by 85 million tonnes, or 59 %, from 145 million tonnes (302 kg per capita) in 1995 to 60 million tonnes (118 kg per capita) in 2016. As a result, the landfilling rate (landfilled waste as share of generated waste) compared with MW generation in the EU-28 dropped from 64 % in 1995 to 24 % in 2016.

The amount of waste recycled rose from 25 million tonnes (52 kg per capita) in 1995 to 72 million tonnes (141 kg per capita) in 2016 at an average annual rate of 5.2 %. The share of MW recycled overall rose from 11 % to 29 %. The recovery of organic material by composting has grown with an average annual rate of 5.1 % from 1995 to 2016. Recycling and composting together accounted for 45 % in 2016 relative to waste generation. Waste incineration has also grown steadily in the reference period, though not as much as recycling and composting. Since 1995, the amount of MW incinerated in the EU-28 has risen by 34 million tonnes or 112 % and accounted for 68 million tonnes in 2016. MW incinerated has thus risen from 67 kg per capita to 133 kg per capita. Mechanical biological treatment (MBT) and sorting of waste are not covered directly as categories in the reporting of MW treatment. These types of pre-treatment require an additional final treatment. In practice, the amounts delivered to mechanical biological treatment or sorting should be reported on the basis of the subsequent final treatment steps. The research work continued through the analysis of data relating to the management of MW in Italy by consulting the ISPRA database. MW produced in 2016 totaled 30 million tonnes, of which 15,82 million tonnes of separate waste collection; therefore in 2016, on a national scale, separate waste collection reached 52.54%. There are still strong differences between the different areas of the country (north, center and south). The separate collection data includes, where available, the quantities of organic waste destined for domestic composting, equal, in 2016, to over 220 thousand tons. In the North, separate waste collection stands at around 9.1 million tonnes, in the South at 3.5 million tonnes and in the Center at 3.2 million tonnes. These values translated as percentages, calculated with respect to the total MW production of each macro area, equal to 64.2% for the northern regions, 48.6% for those of the Center and 37.6% for the Southern regions. The analysis of data for 2016 made it possible to derive the quantity, on a national and regional scale, of biodegradable waste from separate collection (paper and cardboard, organic fraction, wood and textiles). It is interesting to observe how the biodegradable waste from separate collection represents on a national scale 35.22% of all MW produced and about 67% of MW from separate collection. Data processing continued with the analysis of the various forms of MW treatment (composting, integrated aerobic and anaerobic treatment, anaerobic digestion, incineration, co-incineration, landfilling and other). The recovery of organic material by composting represents about 11.3% of the total MW produced; the integrated aerobic and anaerobic treatment represents approximately 6.9%, incineration 17.94%, co-incineration 1.53%, landfilling 24.68% and another 36.85%. Mechanical biological treatment (MBT) and sorting of waste are not covered directly as categories in the reporting of MW treatment. These types of pre-treatment require an additional final treatment. The MW (2016) sent to treatment at the TMB plants corresponds to 76% of the undifferentiated waste produced.

2. Aim and objectives of the research activity during the Doctorate

The aim of this study is to identify the best practices for the management of municipal solid waste (MW). The best practices term includes the measures to protect the environment and human health by preventing or reducing the negative impacts of production and waste management, reducing the overall impacts of resource uses and improving its effectiveness.

The deepened analysis of both European and Italian norms represented the starting point to evaluate the current implementation of legislation in Italy, with a particular focus on Ancona Province. This approach allowed the assessment of the current performance of MW collection and recycling system, highlighting the main criticalities connected to the biodegradable residue in the undifferentiated waste, intended for the disposal. In this regard, a doubt emerged about the obligation of a treatment of undifferentiated waste, before the disposal in landfilling sites.

In this context, the present research considered the case study of Ancona Province which implements a mechanical biological treatment (MBT), before the disposal in landfilling sites. The possibility of the real scale assessment represents a strength of this study research. Indeed, the evaluation of landfill parameters, combined with sustainability assessment (both economic and environmental), aimed at answer to the main questions:

- Which is the current situation of collection and recycling system in Ancona Province? Is it possible to improve the separate collection of urban waste in order to avoid the necessity of a TMB?
- The activation of the TMB in Ancona province has really improved the environmental and economic sustainability of urban waste management?
- How can current Italian regulation be improved towards a true sustainable urban waste management?

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CHAPTER 1

The MW collection in Marche: state-of-art and criticality identification

1. Introduction

1.1 The recycling

The identification of the best practices for the optimal MW management represents a hot topic in Italian regions. Many difficulties are connected to the territory peculiarities which can act on the real effectiveness and sustainability of the chosen system.

In the present chapter, the Marche region in Italy was chosen as case study to compare the effect of waste collection in the five provinces. The target was the identification of both weaknesses and strengths. The data report a collected waste amount around 800,000 tons in 2017 (about 518 kg*person^{-1}*year^{-1}), shared among: Ancona (30% del totale), Pesaro-Urbino (27%), Macerata (19%), Fermo (10%) e Ascoli Piceno (14%).

The waste production can be affected by several factors, including the number of cities in the referred province, the inhabitants, the geographical extent, the economic performance of the territory and the responsibility level of the population. Considering all these variables, the Marche region reports a whole collection efficiency around 65% (REGIONE MARCHE, 2017).

This result is the average value considering all the regional provinces, with a high variability due to the collection system chosen in each city. In this regard, Figure 1 shows the Ancona results, highlighting the positive effect of the door-to-door collection (chosen by 31 out of the 46 cities of the province) which allowed a collection efficiency increase up to 85% (Bueno et al., 2015).

The main strength of this system, compared to the roadside containers, is the possibility of reaching all the areas of the territory. Furthermore, the simple service increase the population awareness, with positive effect on both the quantity and the quality of the collected fractions (Battini et al., 2018).

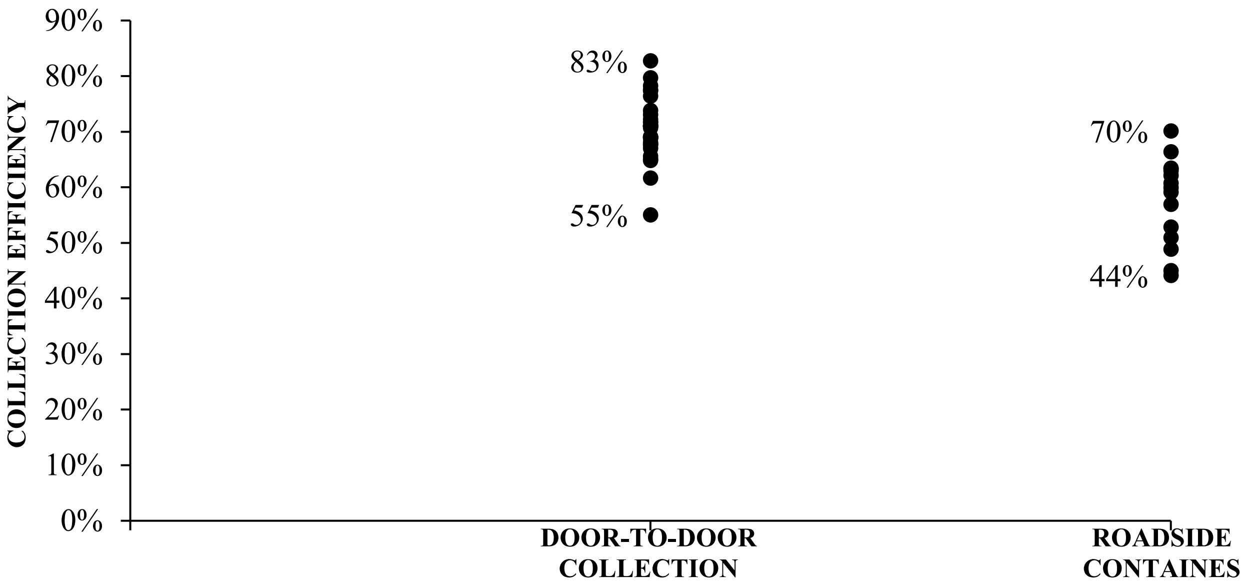

Figure 1. Correlation between collection efficiency and collection system in Ancona province

Despite the high collection efficiency, some criticalities were identified, mainly due to the biodegradable percentage within the mixed waste. This contribution is connected to both the pruning waste from gardening and the food residue, as confirmed by the Regional Environmental Protection Agency in Marche (Arpam), which analyses this fraction every year. The results in Figure 2, assessed by Arpam to further improve the collection system, identify an organic fraction around 25%, unvaried between 2013 and 2017.

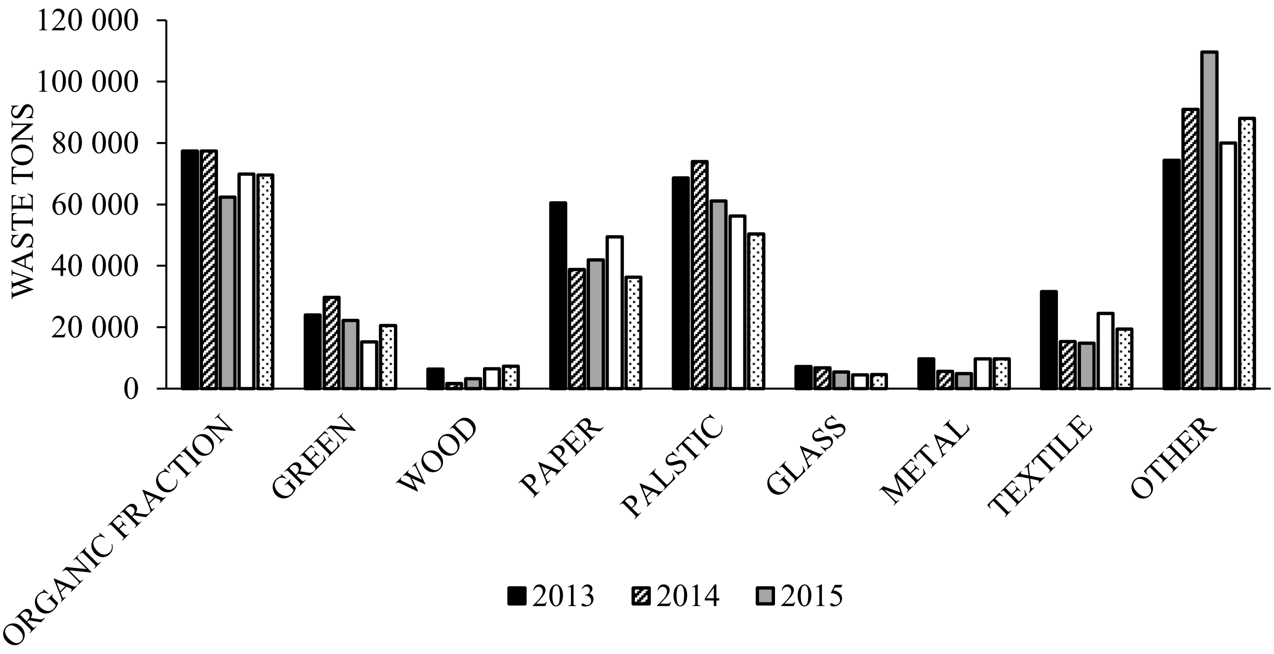

Figure 2. Waste mixed composition in Marche 2013-2017 (REGIONE MARCHE, 2017).

1.2 The mechanical biological treatment

Currently, the European norms about MW provide for the application of the best strategies of waste management, able to protect both the human and the environmental health. These best practices are organized according to a pyramid scheme, which includes all the available options. The first step, the most sustainable is the waste prevention (if possible) followed by: re-use, recycle, energy recovery and the disposal in landfilling sites, for the not exploitable fraction (European Parliament and Council, 2008). In addition, the European regulation includes a mechanical biological treatment (MTB) for the mixed waste, for the stabilization of the biodegradable fraction, before the final disposal (European Parliament and Council, 2008). This process, classified among the recycling operations (Gharfalkar et al., 2015), should act for the increase of biological stabilization of the organic fraction in the mixed waste to prevent the greenhouse gases (Lasaridi and Stentiford, 1996). The current limit of these emissions, measured by the dynamic respiration index is 1000 mgO_2*kgSV-1*h^{-1} (Ministero dell'ambiente, 2015).

2. The case study: the Corinaldo landfilling site

The Corinaldo landfilling site is one of the most important for the province of Ancona, together with the SOGENUS Spa facility (next to close). It is placed in a 140,300 m^2 area (old site + 1st expansion lot of land). As highlighted in planimetry (Figure 3), it includes three areas related to the temporal extension (from 1999 to 2017).

- Red area, 1st lot of land;
- Blue area, 2nd lot of land;
- Purple area, 3rd lot of land.

Starting from 2017 the landfilling activities also include the yellow area, partially superimposed on the old area. The overall capacity of the expansion (1st lot) is 614,000 m^3 excluding the definitive capping and the drainage layer, with a lifespan around 10 years.

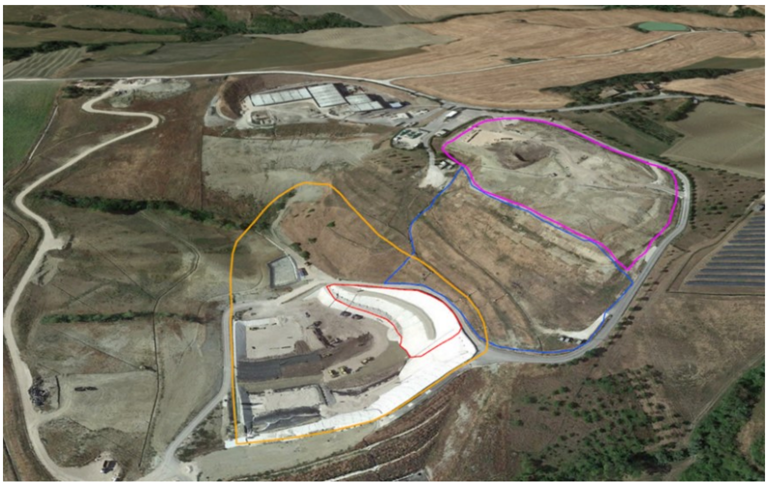

Figure 3. The Corinaldo landfilling site, managed by ASA Srl

The ASA Srl Company manages the Corinaldo facility and it has a license by Ancona Province (number 106/2015 and the following modification and supplementing) for the disposal of not hazardous waste. This license, in agreement with art. 29-sexies del D.Lgs. 152/2006 e s.m.i is valid for 16 years from 03/06/2015. The environmental integrated authorization has been modified (for the integration of CER codes) with provision number 132/2016 / AIA of 14/12/2016 by Province of Ancona. In agreement with the European regulation, the MW is treated by MBT, before the final disposal, in a facility close to the landfilling site. Considering the catchment area of the landfill, the MBT facility treats the MW of province of Ancona (CER 20 03 01 mixed waste, excluding the waste from street sweeping CER 20 03 03, which is treated outside the region), where a high efficiency collection system ensures the removal of high percentages of exploitable fraction. Figure 4 shows the TMB facility, where the waste is pre-treated with the production of two main fractions: the over screening and a under screening, with a further separation of the metallic residue. This step allows the removal of the inert fraction that cannot be treated. Thereafter, the under screening is stabilized by biological oxidation and drying for the decrease of the dynamic respiration index. After 2 weeks, the stabilized organic fraction is disposed of in the landfilling site, together with the over screening. Overall, the MBT should have a double target: the decrease of greenhouse gases and the reduction of waste volume of about 20%.

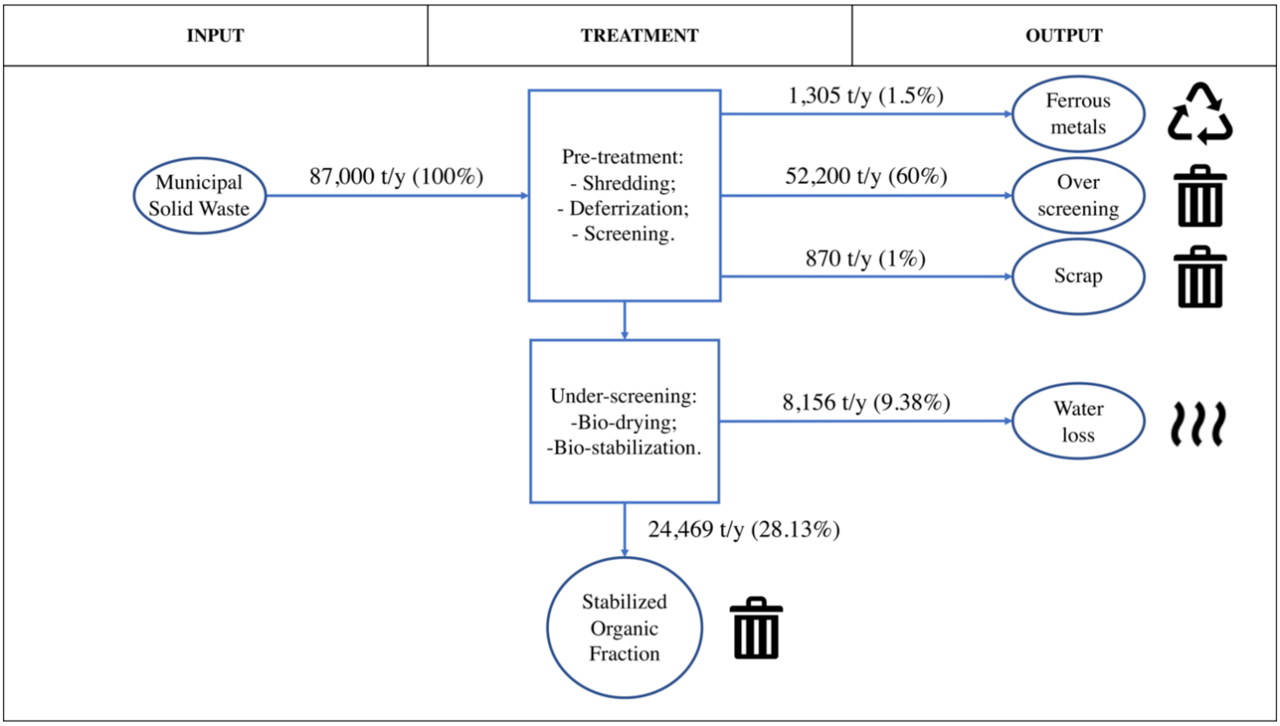

Figure 4. Description of MBT of Cordinaldo (Barucchiello et al., 2016).

Data in Figure 5 show the waste characterization by ARPAM considering samples from MBT facility in Corinaldo. The results highlight the presence of a significant exploitable fraction, mainly due to the incorrect collection of the biodegradable waste (the organic fraction).

Two main reason were identified: waste from pruning and grass mowing activities (CER 20 02 01) and food scraps (CER 20 01 08). The organic fraction represents about 30% of the whole mixide waste, in agreement with the regional results (pie chart in Figure 5).

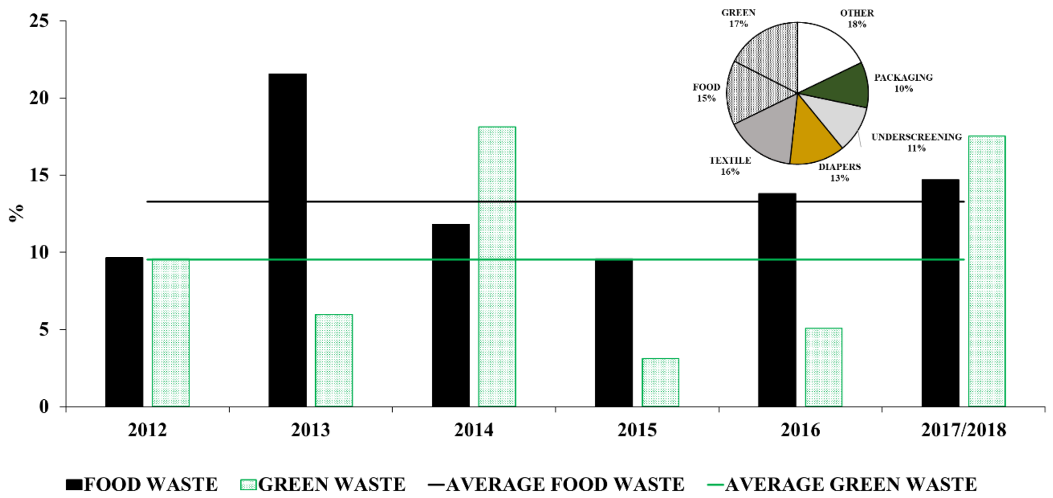

Figura 5. Characterization of mixed waste input of Corinaldo landfilling site, taking into account the whole waste (pie chart) and the organic fraction (histogram) (ARPAM, 2018).

Figure 6 shows the trend of organic percentage in the mixed waste input to both ASA Srl and SOGENUS Spa, between 2012 and 2018 (ARPAM, 2018, 2016, 2015, 2014, 2013, 2012).

As highlighted in the pie chart in Figure 6, the Corinaldo facility showed an average percentage around 25%, without improvements connected to the additional MBT, from 2018. The necessity of an improvement of the organic collection system (both from pruning and grass mowing activities and the food sector) is confirmed by the comparison with SOGENUS Spa sample analysis, which shows comparable results.

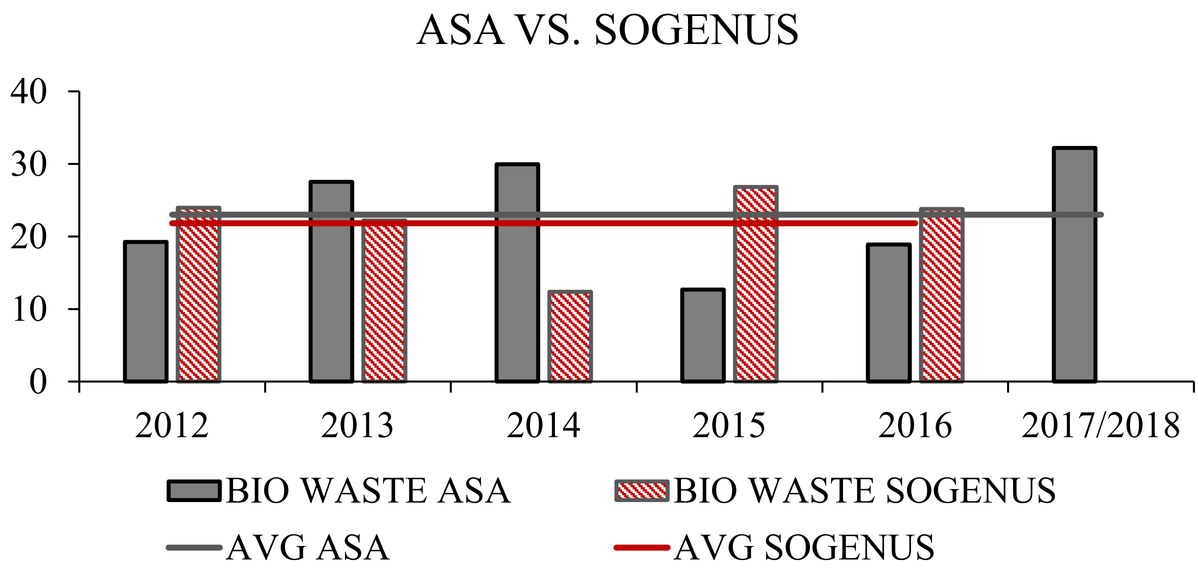

Figure 6. organic fraction composition within the mixed waste: ASA Srl vs. SOGENUS Spa

Table 1 reports an essential information related to the quantity of waste disposed of in the Corinaldo landfilling site with a potential contribution to the greenhouse gases production (on the chemical characterization basis). The amounts are related to a period between 01/03/2017 al 30/12/2019, considering the current used lot of land.

Tabella 1. Waste with a potential contribution to greenhouse gases production in Corinaldo landfilling site.

Codice CER e descrizione	**2017 (tons)**	**2018 (tons)**	**2019 (tons)**
19 05 01 + 19 05 03 Stabilized under screening	7,094	17,052	17,217
19 08 05 Sludge from municipal wastewater	1,910	4,562	4,578
19 08 12 Sludge from biological treatment of industrial waste water, different from CER 19 08 12	477	427	472
19 08 14 Sludge from biological treatment of industrial waste water, different from CER 19 08 13	32	485	699
TOTAL	9,514	22,526	22,965
Percentage	**15%**	**32%**	**31%**

The results discussed in the present chapter represent and essential information for the stakeholders of waste management system. The main issues emerged are reported below:

- The door-to-door collection system is the most effectiveness. The possibility to cover the whole territory favors the correct behavior of inhabitants and increase their awareness.
- Despite the good results currently achieved in Marche, the organic fraction represents a relevant criticality. Further actions should be implemented to increase the collection of both waste from pruning and grass and the food scraps, often disposed of as mixed waste.

The results raise some doubts over the real effect of MBT. The further increase of organic collection rate could avoid the impact of this further treatment carried out before the final disposal. Future studies should focus on the sustainability assessment of stabilization treatment within the current MW management scenario.

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CHAPTER 2

Waste management: current approaches and bottlenecks

Abstract

The MW (MW) management represents a debated topic since incorrected choices can be translated into negative effect for both population and the environmental health. This aspect is confirmed by the evolving regulation which identified the prevention and the recycling as the best choices. Nevertheless, the disposal in landfilling sites plays an essential role since the complete zero-waste scenario is not realistic, currently. To increase the landfilling sites sustainability, policies require a preliminary waste stabilization to decrease the putrescible content and the consequent emissions. The mechanical biological treatment (MBT) has replaced the previous crushing, used for the volume reduction. Literature has proved the effectiveness of MBT, mainly when MW collection system is ineffective. In this context, the present paper considered a facility, in an area characterized by a high-performance MW collection system. A long-term (1999-2019) on-site sampling activity allowed the comparison between two sites (at the same facility): the old site (before the MBT activation) and the new area, where the stabilized waste is disposed of. Detection of biogas, leachate and odorous emissions, was selected to verify the positive effect of MBT, even though a high efficiency separation of organic fraction is obtained thanks to the waste collection system. Both the considered long period and the possibility of on-site samples support the relevance of the results, compared to those reported in the literature, often referred to lab-scale. The results proved the almost total absence of advantages of stabilization, at the considered facility, which cannot justify the energy consumption of MBT.

1. Introduction

Starting from the industrial revolution, the exponential human population growth, combined with the technological development, has started the production of a waste flow continuously increasing. The recent Circular Economy action plan, published by European Commission, reports a prevision of the annual waste generation increase around 70% by 2050 (European Commission, 2020).

The waste problem is due to both the amount and the modification of the waste type which affect the management system (Ripa et al., 2017). This topic represents a priority for the modern society, since the management choices have multiple effects: social, environmental, technical and economic (Hornsby et al., 2017; Ranieri et al., 2017; Vaccari et al., 2012). The well known waste hierarchy identifies the prevention as the most important strategy, nevertheless, it is evident the necessity of integration of all the available options by decision making tools, able to involve all the stakeholders (Cucchiella et al., 2014; European Commission, 2008; Foggia, 2020; Gharfalkar et al., 2015; Hornsby et al., 2017). Among the waste, MW (MW) covers an essential role for the whole management system. Many definitions of MW are used in each country, often affected by different aspects, mainly waste origin, waste materials and waste collectors (European Commission, 2017; European Environment Agency, 2013). The Directive 99/31/EC defined MW as “waste from households, as well as other waste which, because of its nature or composition, is similar to waste from household” (European Union, 1999). Furthermore, EUROSTAT reports: “A large extent of waste generated by households, but may also include similar wastes generated by small businesses and public institutions and collected by the municipality; this part of municipal waste may vary from municipality to municipality and from country to country, depending on the local waste management system. Waste from agriculture and industry is not included” (Eurostat, 2015). The management of MW is currently one of the most serious and controversial issues, at local and regional scales, even more in developed countries (Ripa et al., 2017). Despite the evolving regulations and the trend changes, the disposal in landfilling sites represents the most common strategy of MW management, also in developed countries (Calabrò et al., 2011; Cossu et al., 2016; Trulli et al., 2018). This practice produces significant environmental impacts if the disposed waste flow has a high putrescible content and it is managed with low technical and management precautions (Trulli et al., 2018). Indeed, this fraction acts on the production of two flows: the leachate (mainly critical for aquifer) and greenhouse gases (GHG, cause of the global warming).

The leachate production is promoted by rainwater infiltrations, combined with chemical and physical phenomena and the result is a flow containing inorganic and organic contaminants, with potential effects for the human and environmental health (Bolyard and Reinhart, 2016; Kjeldsen et al., 2002). To prevent these impacts, the modern facilities include containment systems to prevent the pollutants release (Bolyard and Reinhart, 2016). As concern the GHG, they include a mixture of mainly carbon dioxide and methane in comparable concentrations, with traces of H2S, H2, N2O and NH3 (Desideri et al., 2003; Di Maria et al., 2013). The reduction of climate change impact due to the emission of these gases represents a current European priority (Di Bella et al., 2011; European Commission, 2019). The possibility of a mechanical biological treatment (MBT), before the final disposal, could be implemented to stabilize the biological degradable components, with the main advantages of: recovery of recyclable materials, reduction of the volume of waste to dispose of, reduction of the organic matter content (Commission, 2018; Di Maria et al., 2013). More in detail, MBT is a simple practice able to combine mechanical separation with the biological stabilization of organic matter by aerobic stabilization, anaerobic stabilization and biodrying (Boer and Jędrczak, 2017; Cesaro et al., 2016; de Araújo Morais et al., 2008; Di Maria et al., 2013; Fei et al., 2018; Fucale and Pernambuco, 2015; Grzesik and Malinowski, 2017; Sutthasil et al., 2020; Trulli et al., 2018). The number of MBT facilities has increased in Europe (about 570 active MBT facilities, in 2017), mainly in the last two decades to satisfy the legal obligation to both limit biodegradable waste in landfilling sites and to increase recycling and energy recovery from waste (Boer and Jędrczak, 2017; ecoprog, 2017; European Commission, 2018; Fei et al., 2018; Grzesik and Malinowski, 2017). The Italian scenario identified 131 MBT in 2018, since this country adopted the European Union sanitary landfill regulation by Legislative Decrees 36/2003 (implementation of Directive 1999/31/EC) and 205/2010 (transposition of European Directive 2008/98/EC), which specifies that the disposal of solid waste is possible after a ‘‘pre-treatment” when the composition limits defined by the regulation are not respected (apat, 2003; European Commission, 2008; European Union, 1999; ISPRA, 2018; Italian Republic, 2003; Republic, 2010).

Several papers summarize the benefit of a MBT implementation (Bockreis and Steinberg, 2005; Boer and Jędrczak, 2017; Lakshmikanthan and Babu, 2017; Leikam and Stegmann, 1999; Wassermann et al., 2005), nevertheless some authors highlight the impact (both environmental and economic) due to MBT operations, suggesting to critically assess when the treatment is really advantageous (Amato et al., 2019; Arena and Di Gregorio, 2014; Ripa et al., 2017; Trulli et al., 2018). In this regard, some studies proved, by different approaches including the life cycle assessment analysis (LCA), that the improvement of recycling system produces higher positive effect than a MBT, before the disposal (Gordon et al., 2020; Grzesik and Malinowski, 2017). The reason is the low content of organic fraction in the input flow to MBT facility and the low value of the resulting product, which is considered a waste to dispose of (Arena and Di Gregorio, 2014). In agreement with these conclusions, Trulli et al. (2018) recommended the pretreatment for developing regions with low separate collection levels.

Considering the current state-of-art, the present paper considered a landfilling site for MW, located in Central Italy, where satisfying recycling levels are achieved. The facility, operating from 1999, includes a MBT from 2018, able to stabilize MW before the final disposal. The site peculiarities allowed a deepened study of the landfill behavior before and after the MBT introduction, by monitoring: biogas emissions, leachate production, odors and site settlement. The possibility of a long-time on-site detection represents a strength of the present paper.

2. Materials and methods

2.1 The landfilling site

The Corinaldo landfilling site, built in 1974, is one of the most important for the Ancona Province (one of the regional capitals of Central Italy), placed in a 140,300 m2 area. The facility serves the Ancona Province for a total population of 475,000 inhabitants and it treats around 68,000 tons of MW per year (with the average composition reported in Figure 1), value which is going to decrease following the circular economy principles.

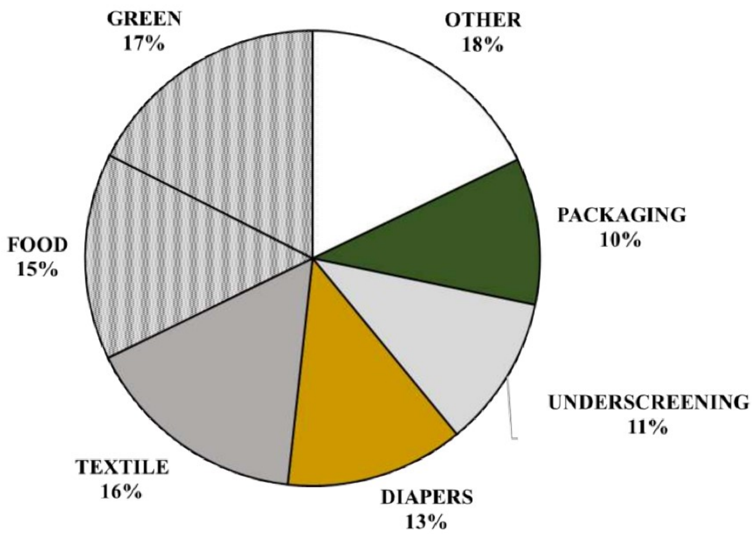

Figure 1. Average composition of MW input to the Corinaldo facility.

In agreement with the European regulation, the disposed waste is previously stabilized by MBT, in a facility close to the landfilling site, since 2018. Considering the catchment area of the landfill and the high recycling achievement (around 65%) of the Marche Region, the MBT facility treats a waste fraction composed of mixed waste, excluding the waste from street sweeping (Marche Region, 2015). The flow chart in Figure 2 shows the two main fractions produced at the end of the stabilization: the over screening and a under screening, with a further separation of the metallic residue for the inert fraction removal. Thereafter, the under screening is stabilized by biological oxidation and drying for the decrease of the dynamic respiration index. After 2 weeks of treatment, both the stabilized product (with a dynamic respiration index, DRI, lower than 1000 mgO2*kgSV-1*h-1 (Ministero dell'ambiente, 2015), compared to a starting value that usually exceeds 4000 mgO2*kgSV-1*h-1 (Trulli et al., 2018)) and the over screening are sent to the landfilling site, similarly to the facility described by Calabrò et al. (2011). All data discussed in the present paper were supplied by ASA S.r.l., the company which currently manage the landfilling site.

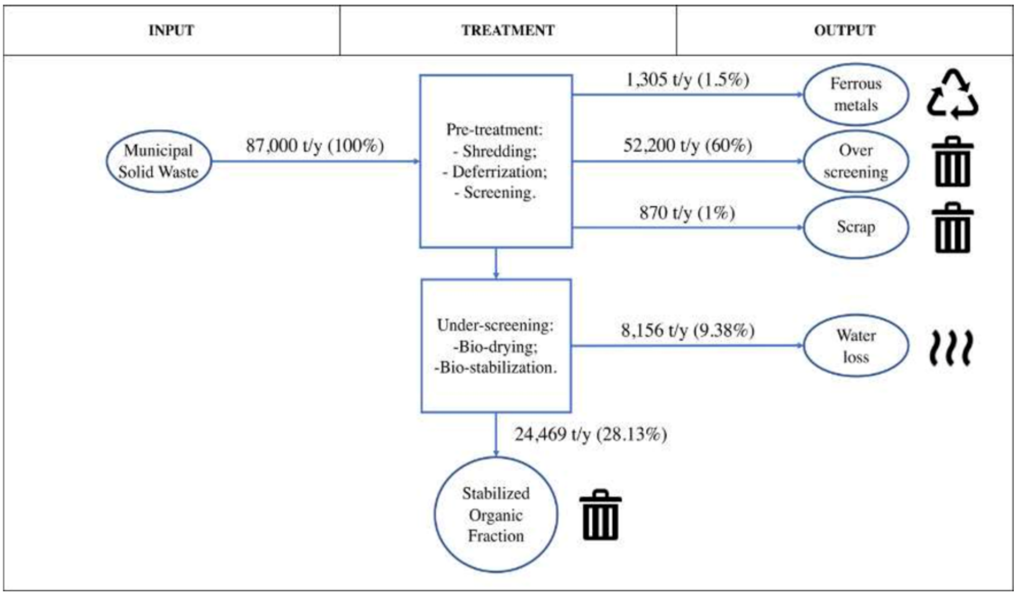

Figure 2. Description of MBT of Cordinaldo

2.2 Collection and analysis of samples

2.2.1 Biogas

Data about the biogas production at the landfilling sites were supplied by the company which manage the facility. A multi gas detector allowed the determination of gas composition by a direct reading. The sampling activity was carried out monthly at the suction lines activated on both the landfilling sites of interest (the old area and the operative area).

2.2.2 Leachate

ASA S.r.l. supplied data of leachate production. Samples are monthly collected from the collection tank (one for each landfilling area). The analyzed parameters included: pH (APAT CNR IRSA 2060 Man 29 2003 (APAT-CNR-IRSA, 2003a)), BOD5 (APAT CNR IRSA 5120 B1 Man 29 2003 (APAT-CNR-IRSA, 2003b)), COD (ISO 15705:2002) (ISO, 2002), TOC (UNI EN 1484: 1999 (UNI EN, 1999)), ammonia-nitrogen (N-NH4+) (APAT CNR IRSA 4030 C Man 29 2003 (APAT-CNR-IRSA, 2003c)), quantified on standard basis, reported in parentheses.

2.2.3 Odorous emissions

Odorous emissions were determined in agreement with the European Standard (EN) EN 13725:2003 which describes the method determination of the odor concentration of a gaseous sample by dynamic olfactometry with human assessors and the emission rate of odors emanating from point sources, area sources with outward flow and area sources without outward flow (CEN EN, 2003). The monthly sampling activity involved five stations (common for both the old and the operative landfilling sites).

3. Results and discussion

3.1 Waste flow analysis

The data related to 2019 waste flows, supplied by the Corinaldo landfilling site manager (Figure 3), shows fairly regular input to the MBT facility. Ancona is a seaside town and the tourism increase in summer months can explain the highest values recorded in August (around 25% higher than the MBT input flow in February, and 10% more than the average value of 6,000 tons/month). Overall, about 70,000 tons/year are sent to the facility for the stabilization, 20% lower than the process design planning (Figure 2). The output flows, ready to be sent to the landfilling sites, show an average value of 5,000 tons/month, which increases of about 10%, considering the leachate resulting from the under screening stabilization. The detail of output composition identifies the over screening and the stabilized under screening as the most relevant fractions, with a contribution of 60% and 25%, respectively. On the other hand, the leachate resulting from MBT is about 8% of the whole amount to send to the landfilling site. Overall, the treated amount is about the 86% of the starting waste, which grows up to 94% considering the leachate from the stabilizations cell. A further percentage, lower 1% is composed of ferrous metals to send to recycling.

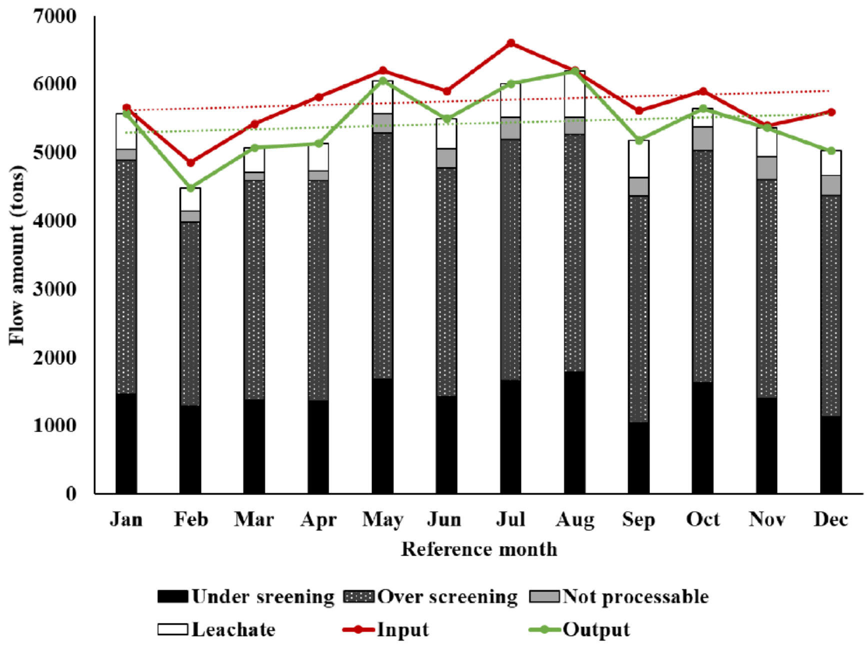

Figure 3. Monthly input and output flows at Corinaldo MBT facility (reference year: 2019).

From an economic point of view, the weight loss of about 6% causes a relevant cost increase from 79,20 €/ton for the waste management at the landfilling site to € 113.0 €/ton, which includes both the MBT and the final disposal. Therefore, the evolution from a simple mechanical pre-treatment to the most innovative stabilization has caused an economic cost growth of 30%. Following the APAT guidelines, this cost increase should allow the removal of pollutants and undesired materials and the decrease of: volume to dispose of (thanks to both the recovery of valuable fractions and the organic component degradation), emissions (both biogas and leachate), odors, compaction costs and settlement phenomena (apat, 2003).

3.2 The biogas analysis

The study of the biogas trend was essential to prove the effect of the MBT on waste stabilization. With this aim, a deepened analysis was carried out to compare the biogas production in the old area (only mechanical pre-treatment) with that in the current operative section (disposal after a preliminary MBT). The detail of collected data was reported in Table S1. Two factors can affect the produced biogas amounts: the quantity of the disposed waste and the age of landfilling site.

To include both factors in the assessment, two performance indexes were evaluated as following:

$$\text{Index 1} = \frac{\text{total extracted biogas (m3)}}{\text{total disposed waste quantity (tons)}} \quad \text{(Eq. 1)}$$

$$\text{Index 2} = \frac{\text{monthly extracted biogas (m3)}}{\text{lanfilling site age (months)}} \quad \text{(Eq. 2)}$$

Each value of Index 1 correlates the whole biogas produced within the considered period with the disposed waste amount. On the other hand, Index 2 correlates the monthly collected biogas with the age of the site.

As reported in Figure 4a, the two areas showed comparable increasing trends of Index 1 with the highest slop value in the old area case. This difference is mainly due to the highest putrescible content in the old waste, because the separated collection of organic fractions, on Ancona Province territory, has started in 2006. The results include a data variability connected to the seasonal variation of biogas production, irrespective of the reference area, since the degradation is promoted by rains, at no too cold temperature (Barlaz et al., 2004; De Gioannis et al., 2009).

Figure 4b shows the trend of Index 2 in the old landfill (January 2005- January 2006, corresponding to a site age between 61 and 73 months) and the operative area (January 2019-April 2020, corresponding to an age between 22 and 37 months). Overall, the values of Index 2 are comparable, except for the date recorded in July 2019 (age: 28 months) of the new landfill. Nevertheless, the old site shows the highest stability with an Index between 4.0•103 and 4.8•103 m3month-1. Data related to the operative landfilling area in April 2020, show a biogas extraction around 2.000.000 di m3, resulting from a total disposed of 223.000 tons, at 37 months of landfill age (Index 2= 5.2•103 m3month-1). The same biogas quantity results from a total disposed of 328.000 tons at 67 months of landfill age (Index 2= 4.7•103 m3month-1). The results suggest that the MBT implementation did not produce a drastic effect on the biogas production. The same management conditions, and the comparable physical/environmental peculiarities of the two areas exclude a possible effect of these factors on the biogas production.

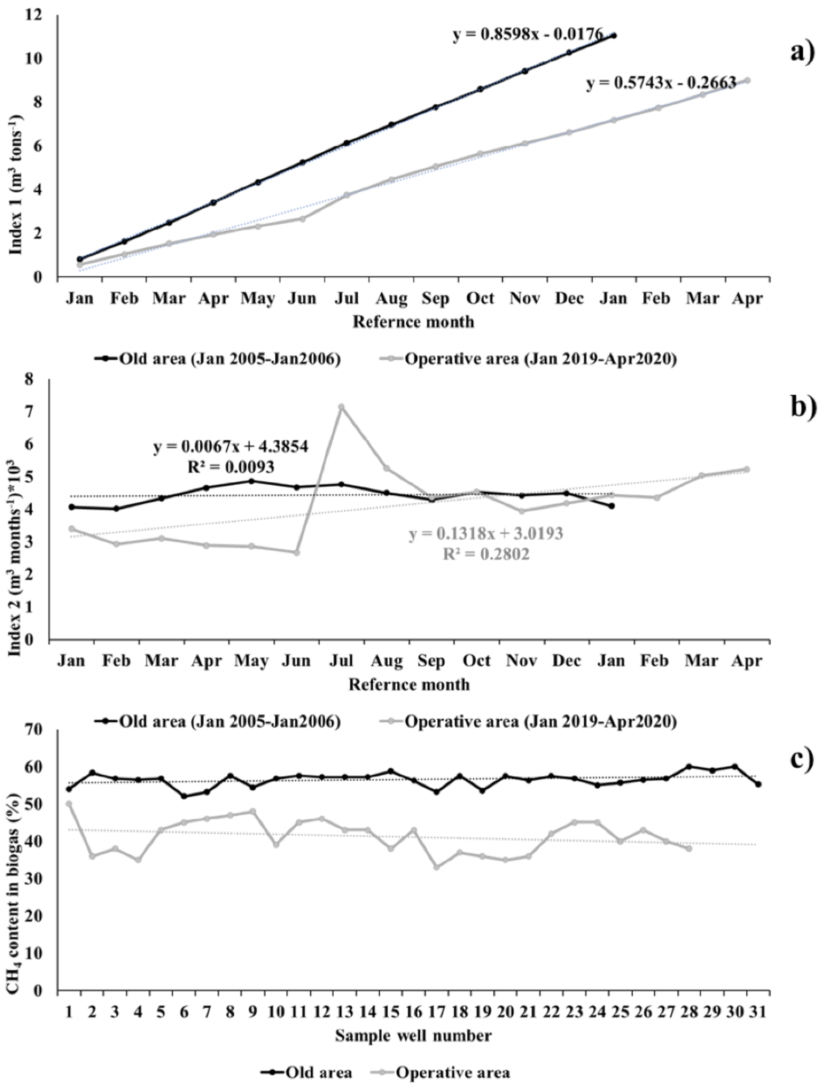

Figure 4. Biogas production: Trend of a) Index 1 b) Index 2, old site (sampling time: January 2005-January 2006) vs operative landfilling area (sampling time: January 2019-April 2020) c) CH4 content, comparison between the old site (only waste grinding before the disposal) and the new area (MBT for the preliminary stabilization)

30 samples from each area, (1 for each sample wells) related to one month of 2005 and 2020 for the old and operative sites respectively, were collected for the gas characterization. The high number of measurements (between 20 and 30) ensures a good interpretation of the overall landfill gas emission (Mosher et al., 1996).

The average composition of samples of the old sites (Figure 4c) showed a content of 56% ± 2 of CH_4 and almost total absence of O_2. On the other hand, contents of 40% ± 5 of CH_4 and 2% ± 1 of O_2 were detected in the biogas extracted from the operative site. On the qualitative characterization basis, the new biogas has a lower calorific value with a consequent decrease of energy production around 20%, compared to the old site. Different hypothesis could be linked to variation of biogas composition: the reduction of organic fraction composition (for the improvement of the waste collection system on Ancona Province) and the effect of MBT. This aspect represents a criticality since, as proved by literature, the possibility of biogas exploitation for energy recovery could make the landfilling more sustainable than MBT (Caresana et al., 2011; Maria and Micale, 2015; Zappini et al., 2010). Indeed, considering its energy request and the resulting emissions, relevant environmental loads are estimated, mainly in the categories of global warming potential and ozone layer depletion (Maria and Micale, 2015). Furthermore, no differences were observed, (between 2010 and 2019) on the emissions resulting from the powered co-generators which use the biogas produced at the facility (Table S1).

3.3 The leachate analysis

The leachate production is the second factor chosen to compare the two landfilling scenarios (only waste grinding before the disposal vs MBT for the preliminary stabilization). As confirmed by the literature, there is a close connection between the leachate production and the rainfall, which significantly increase the production (Baucom and Ruhl, 2013; Chen, 1996; Pantini et al., 2014; Wassermann et al., 2005). In order to confirm the consistency with the literature data, Figure 5a correlates the annual rainfall with the annual leachate production at the landfill. With this aim, a range between 12.4 and 50.0% of rainfall converted into leachate was considered in agreement with both Linde et al. (1995), which reported 15-50% and Baucom and Ruhl (2013) which considered a range between 12.4 and 27.2% (Baucom and Ruhl, 2013; Linde et al., 1995). The results, estimated considering the exposed surface, the rainfall quantity and the produced leachate, are included within the estimated range in all the selected years (2005-2018) proving the representativeness of the assessed data.

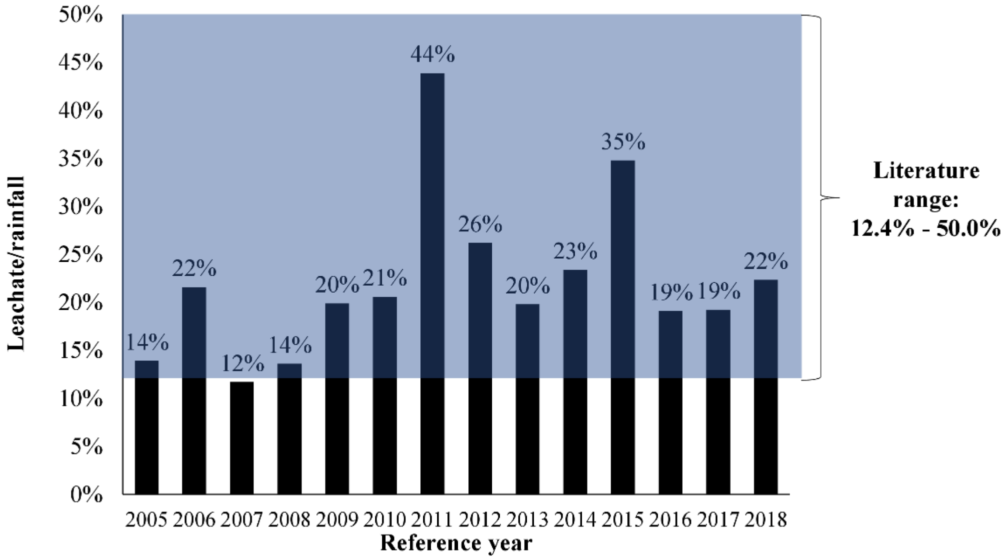

Figure 5. Rainfall and leachate production: a) Assessment of the water conversion into leachate, comparison with the literature

Further evaluations focused on the assessment of Index 3 (Eq.3) to quantify the real production at the landfilling site, considering both the disposed waste and the site age, in agreement with the previous assessment of biogas production.

$$\text{Index 3} = \frac{\text{collected leachate (m3)}}{\text{total disposed waste quantity (tons)} * \text{landfilling site age (month)}} \quad \text{(Eq. 3)}$$

Where, the collected leachate is the volume produced during the reference year and the total disposed waste included the whole quantity in the period of interest. Two annual ranges were chosen to compare the two areas: 1999-2002 for the old site (750 mm average rainfall) 2017-2019 for the new area (670 mm average rainfall). In both cases, a total disposed waste quantity of 200,000 tons was selected and the same executive of the two areas ensured the same management conditions.

Furthermore, considering the comparable quantity of rainfall in the two periods, this aspect cannot affect the results. Figure 6 shows comparable results in both scenarios, with an average value of Index 3 around 0.8. This result suggests that the implementation of a preliminary MBT did not significantly reduce the leachate production in the new landfilling area.

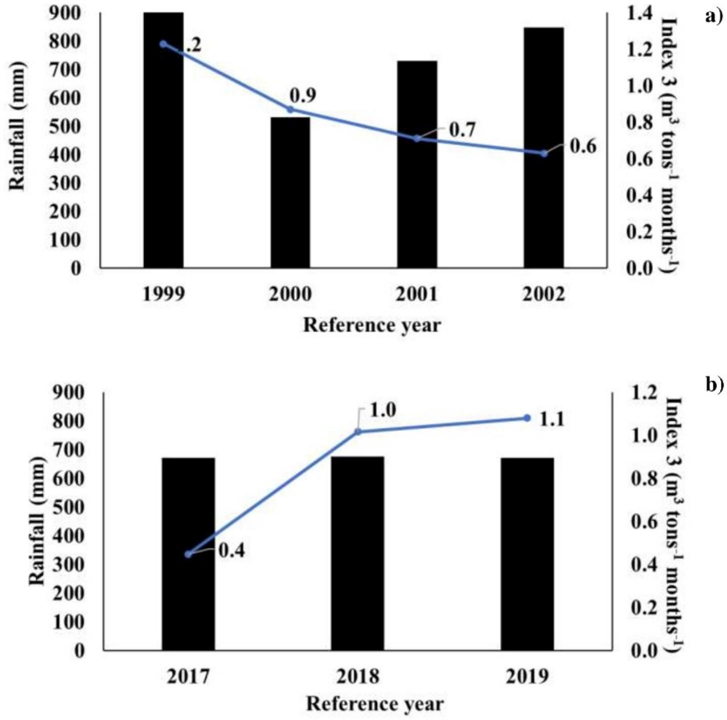

Figure 6. Trend of Index 3 on the rainfall and landfilling site age in the cases of a) the old are b) the new area (total disposed waste quantity of 200,000 tons).

The additional leachate characterization is an essential step to study the landfill behavior, as explained in Table S2. Indeed, biodegradation processes are carried out by three groups of bacteria: hydrolytic and fermentative bacteria (polymer hydrolyzation and fermentation of monosaccharides to carboxylic acids and alcohols), acetogenic bacteria (conversion of carboxylic acids and alcohols to acetate, hydrogen, and carbon dioxide), methanogens (conversion of end products to methane and carbon dioxide). Variation of pH value is linked to the specific biodegradation phase; the neutral pH decreases for the carboxylic acids accumulation and increase for their consumption during the methanogenic phase (range:7.5-9 (Ehrig, 1989)).

In addition to pH, the BOD/COD is a parameter representative of the landfill state, since high ratio indicates the presence of biodegradable compounds, still present in the leachate (Cossu et al., 2016, 2012; Sekman et al., 2011). This ratio decreases during the biodegradation phase, with values around 0.6 which are reduced up to 0.1 in the methanogenic phase (Cossu et al., 2003; Ehrig, 1983; Kjeldsen et al., 2002; Sekman et al., 2011).

The trend of both pH and BOD/COD was analyzed during the 3-year periods 2004-2006 for the old site and 2017-2019 for the new site. The choice was due to an analytical issue, since the sample collection and analysis were carried out by the same certified laboratory.

The results in Figure 7a prove the achievement of methanogenic phase, with stationary pH (around 8.5) and BOD/COD values (between 0.05 and 0.2) in both the sites of interest (Ehrig, 1989).

The identification of methanogenic phase is further support by the TOC results, lower than the limit of 4500 mg/L, in spite of the data variability (Figure 7b). Overall, the characterization shows comparable results, without relevant advantage in the case of stabilized waste. Figure 7b shows a significant difference of $N\text{-}NH^{4+}$ concentration in the leachates from the two areas.

This aspect could be connected to the landfill age (around 90 months of the old site vs 36 months of the operative one), since ammonia often represents a long-term pollutant in leachate (Kjeldsen et al., 2002).

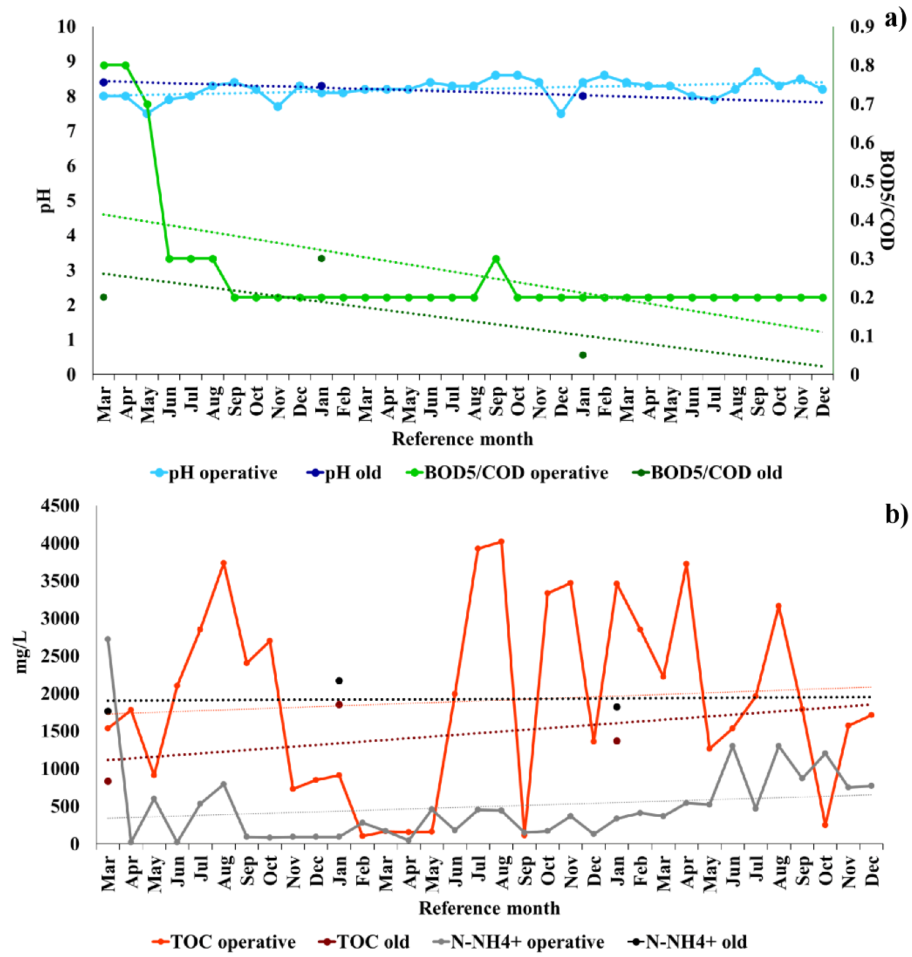

Figure 7. Trend of a) pH and BOD$_5$/COD b) TOC and N-NH^{4+} parameters detected at the two analyzed landfilling areas: 3-year periods 2004-2006 for the old site and 2017-2019 for the new site.

3.4 Odorous emissions

The decrease of odorous emissions from landfilling site is included in the list of APAT guideline targets (apat, 2003), therefore it was considered important the inclusion of this aspect in the present study. With this aim, 5 sampling stations were chosen to compare the landfilling site impact, before and after the MBT implementation. The time periods selected for the sampling activities were March 2008-March 2009 and April 2017- December 2019. This choice ensured the same sampling stations. Data collected between 2009 and 2016 were not taken into account for the entry into operation of a composting facility close the landfilling site, that could negatively affect the odor detection. The same facility was converted into the MBT, currently operating, in 2017.

Results in Table 1 report the average values detected at each sampling station during the reference period, without relevant improvement after the stabilization start-up. On the other hand, the odors measured between 2004 and 2006 (when the separated collection of organic fraction was not activated) showed an average value of 48 ±10, suggesting the significant effect of the high efficiency collection system.

Table 1 Odor emissions at 5 sampling stations before and after MBT

Sampling station					
Old landfilling site					
	S1	S2	S3	S4	S5
Average value (uo/m^3)	23	23	24	22	21
St. dev.	6	11	9	9	15
New landfilling site (MBT)					
Average value (uo/m^3)	29	28	28	33	25
St. dev.	9	9	8	31	7

3.5 Soil settling assessment

The waste settlement can be described by three steps, similarly to the soil phenomena. The first phase is the immediate waste settlement due to the gas and particle expulsion or compression. The second stage, named consolidation stage, is time dependent and it is due to the dissipation of pore pressure excess. The third step is connected to the biodegradation processes (Petrovic, 2016). In the present experimentation, the assessment of MTB effect on soil settling phenomena is complicated since it is mainly affected by the method used for the waste disposal at the landfilling site.

In this regard, the compactor characteristics has an essential role since an increase around 30% by replacing a compactor system with 35 tons capacity with another with a 57 tons capacity. The waste grinding level is another essential variable of the soil settling effects, as confirmed by the literature (Petrovic, 2016). Considering these aspects, the comparison between the two sites was not reliable, since the new landfill area uses higher-performance equipment for both the compactor and grinding operations.

4. Discussion and conclusions

The waste management is a debated critical topic since it is affected by several variables, including the waste composition and the local peculiarity. Wrong choices can be translated into negative effect for all the spheres: environmental, economic, and social. Therefore, the extensive large-scale scientific research is necessary to support the decisions of the stakeholders involved. Many studies were carried out in Regions with critical waste management situation, proving the relevance of MBT (Fei et al., 2018; Fuss et al., 2020; Ripa et al., 2017; Trulli et al., 2018). Nevertheless, the present paper proved the almost total absence of advantages achieved by a MBT implementation in an area with satisfactory collection and recycling level. In this regard, literature has already proved the key role of the preliminary management steps for the creation of a sustainable system, able to avoid the MBT use (Cesaro et al., 2016; Gordon et al., 2020).

As explained in the present work, the use of a MBT as preliminary treatment, before the disposal of all the resulting fractions, produces scares results, without decrease of emissions (leachate, biogas, odors). The only difference detected was a change in the biogas composition. This aspect, partially attributable to the improvement of organic fraction collection, represents a weakness of the waste management chain because the possibility of biogas exploitation partially balances the environmental burdens of landfill. The energetic aspect is further aggravated by the energetic demand of stabilization facility with the consequent growth of the waste management costs, as proved by the present analysis.

Many authors quantified the negative environmental impacts due to electricity demand of MBT in several impact categories, at the expense of final low process efficiency (Grzesik and Malinowski, 2017; Maria and Micale, 2015; Ripa et al., 2017). This aspect is also converted into the economic cost raise, as explained in the present paper and confirmed by the literature (Foggia, 2020). Some consideration should be done about the possibility to give value to the stabilized product, as an alternative to the current disposal (Wiśniewska and Lelicińska-serafn, 2018). At this regard, literature reports the possible energetic enhancement of this flow (Cherubini et al., 2009; Hornsby et al., 2017; Maria and Micale, 2015).

Considering the achieved results, the present work aims to provide a support for the development of new policies focused on the improvement of waste collection strategies, able to produce high quality separated fractions, both from qualitative and quantitative point of view (e.g. door-to-door collection). Further actions should be addressed at the improvement of downstream management.

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CHAPTER 3

Sustainability assessment of Corinaldo landfilling site

Abstract

The sustainability has an essential role for the development of a municipal waste (MW) management system in agreement with the circular economy principles. The attention for this topic is confirmed by the policies evolution which has characterized the European reality, further implemented at Italian level. Many aspects of the management system were debated, including the necessity of a biological stabilization of the MW, before the disposal, in areas characterized by high efficiency collection and recycling system. In this context, the present paper considered the case study of Corinaldo landfilling site (Central Italy) to perform a sustainability analysis (both environmental and economic) and to suggest the possible improvements. The possibility of a real scale analysis made the results representative and adaptable to other scenarios. Overall, the analysis highlighted the relevance of high-performance collection and recycling system able to preliminarily decrease the organic content of MW, reducing the necessity of a biological stabilization before the disposal. On the other hand, a more efficient mechanical pre-treatment (including a pressing step) proved to be a promising solution to decrease the current impact of MW management. Overall, the paper combined the achieved results to provide a general model, adaptable to different Italian scenarios able to answer to the necessity of the specific municipalities with consequent environmental and economic gains.

1. Introduction

The waste management is a widely debated topic since the increasing volume and complexity of waste, connected to the modern society, represent a risk for both human and environmental health. UNEP estimated 11.2 billion tons of solid waste collected every year worldwide (UN Environment Program (UNEP), 2019). The municipal waste (MW) amount represents around 10% of the European waste production; this value increases up to 30% excluding mineral waste (Eurostat, 2020; Luttenberger, 2020).

More in detail in 2018, the European waste generation per capita was between 272 kg (in Romania) to 814 kg (in Denmark), reflecting the consumption patterns and the economic wealth of each country. Italy is placed at the half of the range, 499 kg per capita in 2018 (Eurostat, 2020). Different strategies of MW management were performed in each country, nevertheless, landfilling is still the most common (Trulli et al., 2018). Overall, as a results of European policies, the landfilling rate (landfilled waste as share of generated waste) in the EU dropped from 61% in 1995 to 24% in 2018 (Eurostat, 2020). Many policies deserve to be mentioned to have contributed to the implementation of the well-known waste hierarchy, which includes: preventing waste generation, preparation for reuse, recycling, other recovery processes, and disposal of waste that cannot be recovered. More in detail, the principles of landfilling reduction and recycling and recovery improvement were reflected in: Directive 62/1994 on packaging and packaging waste, Landfill Directive 1999/31/EC, Waste Framework Directive of 19th November 2008 and the most recent Directive 2018/850 on the landfill of waste and the new Circular Economy action plan of 2020 (Euroepan Commission, 2020; European Commission, 1999, 1994). With the aim to achieve the European target of reducing the waste to landfill the mechanical biological treatment (MBT) has taken hold (European Commission, 2018; Fei et al., 2018; Grzesik and Malinowski, 2017). MBT combines mechanical separation with the biological stabilization of organic matter by aerobic stabilization, anaerobic stabilization and biodrying (Boer and Jędrczak, 2017; Cesaro et al., 2016; Di Maria et al., 2013; Kossakowska and Grzesik, 2019; Sutthasil et al., 2020). This pre-treatment is widely used since it significantly reduces the environmental impact of landfilling sites, mainly in the area with a low efficiency system of MW collection and recycling (Amato et al., 2021; Trulli et al., 2018). The adoption of European regulation in Italy has been translated into the implementation of 130 facilities on the territory (ISPRA, 2019). Indeed, the MBT ensures the achievement of the fixed limits concerning the MW composition, reducing the pollutant releases and increasing the useful life of the landfilling site (Trulli et al., 2018).

In this regard, the Legislative Decree 3 September 2020, n. 121 (implementation of Directive (EU) 2018/850, which amends Directive 1999/31/ EC on the landfill of waste) reports the technical criteria to determine the necessity of waste stabilization before landfilling. In addition of a recycling rate al least 65%, the Decree reports two alternative necessary conditions to dispose of the undifferentiated MW: an IRDP value $<1{,}000 mg\ O_2 * kgSV^{-1} * h^{-1}$ or a organic material putrescible content which does not exceed 15% (including quantity present in the underscreening <20 mm) (Italian Republic, 2020). Several scientific papers have focused on the MBT, highlighting both benefits and criticalities, mainly due to the possible impacts (both economic and environmental) in areas with effectiveness collection and recycling systems (Cesaro et al., 2016; Fei et al., 2018; Fuss et al., 2020; Gordon et al., 2020; Ripa et al., 2017; Trulli et al., 2018). In this regard, a deepened analysis of case study of Corinaldo landfilling site, in Central Italy, described by Amato et al. (submitted to Waste Management), identified a MBT effect on MW volume reduction (around 10%), without relevant effects on the emissions. This achievement is probably due to the high recycling achievement (around 65%), before the waste disposal which decrease the organic content.

Considering the results, in emissions terms, the present paper took into account the case studies of Corinaldo landfilling site to verify the possible advantages and criticalities connected with the MBT implementation, with a view to the sustainability aspects. The life cycle assessment (LCA) tool was chosen to provide informed and science based results (Luttenberger, 2020). Thanks to the combination of an environmental and economic assessments, the analysis aimed at the identification of the main criticalities of the current waste management in Corinaldo, suggesting improvements to increase the sustainability level. Despite the paper focused on a specific areas, it aims to provide relevant information for the stakeholders involved within the MW management system, useful and adaptable for comparable cases to answer to the sustainability challenge.

2. Materials and methods

2.1 The case study of Corinaldo landfilling site

The present analysis focused on the Corinaldo landfilling site (Ancona, one of the regional capitals of the Central Italy). This facility is placed in a 140,000 m^2 area and it serves around 475,000 inhabitants, corresponding to around 69,000 tons/years of MW (around 30% of this amount is composed of organic waste). These characteristics make it an average landfilling site in Italy and an excellent case study.

Starting from the results described by Amato et al. (submitted to Waste Management), the present paper aimed at the assessment of the sustainability level of the current MW management strategy at Corinaldo landfilling site, compared to alternative options. The possibility of using real scale data made the results very useful to answer to the research questions:

- Is the current MW management strategy (in agreement with Italian legislation) the most sustainable choice when high recycling level has been reached?
- Which are the main criticalities of the current MW management system in Corinaldo landfilling site?
- Which improvements could be implemented to increase the sustainability level of the current strategy?

2.2 The sustainability analysis

With the aim to answer to the research questions, the evaluation considered both environmental and economic assessment, referring the results to the annual waste flow sent to the Corinaldo landfilling site (69,000 tons), chosen as functional unit for the present study. More in detail, the environmental impact assessment was carried out by life cycle assessment (LCA) tool, following the recommendation of International Organization for Standardization (ISO) 14040:2006 and 14044:2006 norms. The thinkstep GaBi software system, integrated with Database for Life Cycle Engineering (compilation 7.3.3.153; DB version 6.115) was used for the production processes of energy and raw materials and the quantification of the environmental load of the treatments.

The results, normalized and weighting, were expressed as person equivalent (p.e.), which is the number of individuals that generate that same impact in a year. The method selected for the analysis was Environmental Footprint (EF) 3.0.

The average European value was selected as unitary impact of the municipal solid waste on landfill. As concern the The economic evaluation was performed using the real management costs supplied by the Corinaldo facility manager.

2.3 The scenarios description

The assessment hypothesized 3 scenarios, summarized in Figure 1 (2 for the environmental aspects and a further one for the economic evaluation):

- scenario 1 (current scenario) involves a waste grinding and screening (mechanical treatments) and the consequent bio-stabilization of the underscreening (around 40% of the whole flow). Overall, the MBT decreases the flow to dispose of about 10% of the process input. This waste amount has a specific weight of 0.27 tons/m3.
- scenario 2 consists of the waste grinding followed by a pressing step to increase the waste density up to 0.49 tons/m3. This additional mechanical treatment produces a double advantage: the decrease of the number of lorry travels from MBT facility to landfilling site (1.7 km) and the simpler (and cheaper) disposal than a loose material. The biological treatment is excluded from this scenario, considering the scarce achievement observed in Amato et al. (submitted to Waste Management).
- scenario 2bis, considered only for the economic analysis, includes the treatment of an additional waste flow, from a different province, with low quality which makes the bio-stabilization an imperative necessity. The possibility to offer this service to third part would allow to avoid the decommissioning of biological section. The assessment of scenario 2bis was considered important for the waste management choice at landfilling facility since the possible economic income could be invested for the improvement of collection and recycling system.

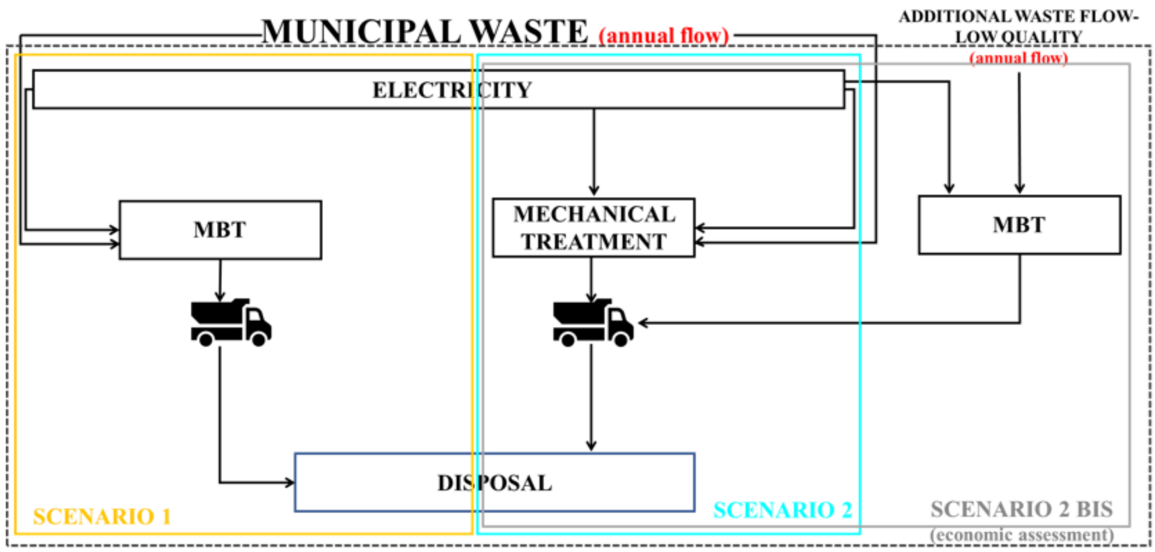

Figure 1. System boundaries considered for the sustainability assessment (functional unit: annual waste sent to Corinaldo facility, 69,000 tons). The mechanical treatment includes grinding and pressing

The data used for both environmental (Table 1) and economic (Table 2) analysis were real information supplied by the Corinaldo facility manager. The number of travels in Table 1 includes the round trip necessary for the waste movement by the available lorry (Euro 0-6, 22 tons total weight, 71.3 tons max payload).

Table 1. Mass and energy balance used for the environmental assessment (functional unit: annual waste sent to Corinaldo facility, 69,000 tons)

Contribution	Scenario 1	Scenario 2
Electricity consumption (MWh)	1800 (grinding + biological treatment)	1800 (grinding + pressing)
Transport (number of 1.7 km travels)	5650	3150
Waste to disposed of after pre-treatment (tons)	62100	69000

The possible income for the treatment of the additional waste flow (around 13,300 tons/year), included in the scenario 2bis, was estimated as the price requests by the Corinaldo facility minus the costs of treatment and transport.

Table 2. Cost detail for the economic assessment

Cost	Scenario 1	Scenario 2	Scenario 2bis
	€/tons		
Pre-treatment	4.28	2.57	2.57
Transport	0.21	0.14	0.14
Disposal	79.20	77.84	
Possible income for the stabilization of additional flow			52.32

3. Results

Figure 2 reports the results of the environmental assessment of the two considered scenarios. Overall, the two options show an EF around $3.5 \cdot 10^5$ p.e., with an advantage of the second one. It is evident that the main contributions which affect the two scenarios are the transport and the waste disposal, with low effect of pre-treatment steps.

This result can be explained by the relevant contribution of both transport and landfilling on the climate change category, responsible for 60% of the whole EF. In Scenario 2, the highest impact of disposal is due to the avoided MBT, which prevented the waste loss of 10%. Nevertheless, the benefit of the most stringent treatment is evident with an environmental impact decrease around 15% thanks to the most efficient transportation of pressured waste (translated into the reduction of necessary lorry travels).

An additional hypothesis could be the decrease of the landfilling impact by the energetic exploitation of the over-screening (corresponding to the 60% of waste amount sent to MBT) by incineration.

Preliminary estimations showed an environmental gain around 20%, compared to the proposed scenarios.

Nevertheless, the sustainability of this option varies widely with the incineration facility distance (and the consequent transport impact) and the real possibility to use the resulting energy. Therefore, this alternative could improve the whole scenario if both incinerator and MBT facilities are placed in the same/neighbouring regions.

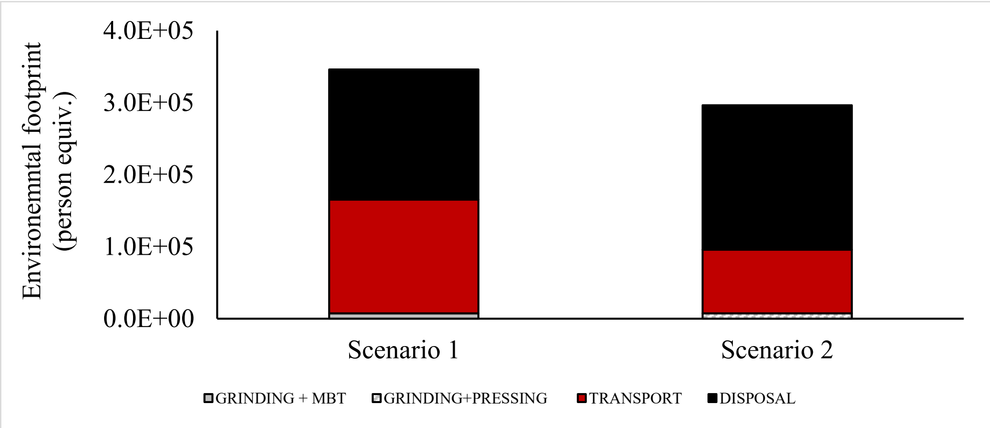

Figure 2. Environmental footprint of two scenarios considered for MW management at Corinaldo landfilling site. (Functional unit: annual waste sent to Corinaldo facility, 69,000 tons)

As concern the economic aspect (Figure 3), the three scenarios do not show relevant differences, with the highest costs due to MW landfilling. The best result of the scenario 2 bis (a minimum improvement) can be explained by the combination of the decrease of the transport cost and the possible service of waste bio-stabilization for third parts.

This aspect is very important to avoid the decommissioning of the bio-stabilization process. Furthermore, this income represents the opportunity of investment for the improvement of waste collection and recycling system.

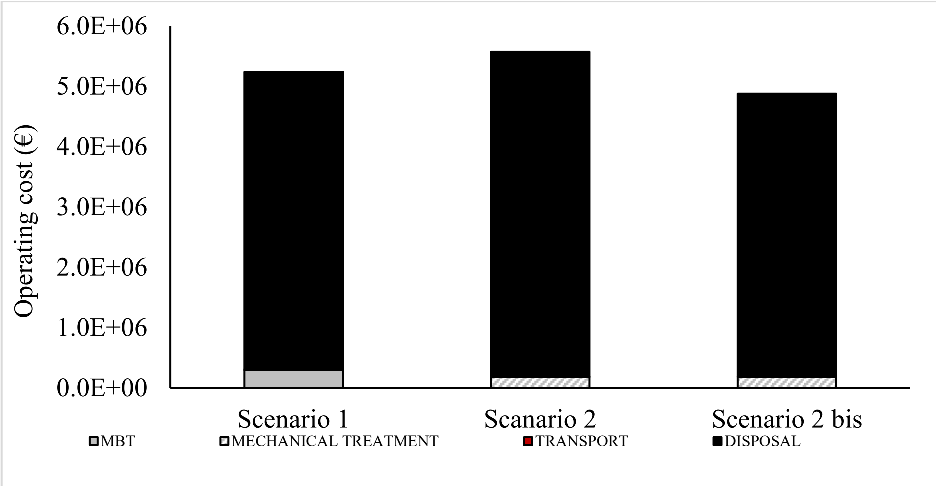

Figure 3. Economic assessment of three scenarios considered for MW management at Corinaldo landfilling site. (Functional unit: annual waste sent to Corinaldo facility, 69,000 tons)

4. Discussion

The sustainability assessment proved the environmental advantage of MBT, achieved by the biostabilization of the putrescible fraction and the consequent decrease of MW to disposed of. This observation can be done despite the minimum achieved reduction of 10%, already discussed by Amato et al. (submitted to Waste Management), connected to the high efficiency waste selection and recycling in the studied territory. Considering the referring context, the present paper proposed an alternative mechanical pretreatment (scenario 2) able to improve the environmental sustainability of the MW strategy, avoiding the biological stabilization. The treatment, which includes a pressing with bale production, is able to solve a relevant landfilling site problem connected to the weather conditions, mainly windy day, which make difficult (or impossible) the landfilling operations. This issue represents a real problem at Corinaldo facility, since the MBT has a maximum storage capacity of 2 days (due to safety issues) and several strong wind days could be translated into a temporary stop of stabilization treatment, with negative impacts on the whole MW management chain.

Furthermore, these weather conditions, could cause the dispersion of the lightest fractions, during the landfilling operations with consequences on both environment (plastic dispersion) and facility economy (use of workers and means for cleaning operations). Another relevant aspect to discuss is that the proposal of Scenario 2 does not provide the decommissioning of MBT facility but its conversion. The available biocells of MBT could be used for the treatment of high waste amounts, with significant organic content, from emergency situations, as the beached waste after a flood, increasingly common with global warming (Amato et al., 2019; Gabrielli et al., 2017). To better clarify the relevance of this proposal, Figure 4 reports the trend of this kind of waste in Ancona Province, showing a production increase higher than 95% in 2015 (compared to the previous two years), after the Senigallia flood event of 2014.

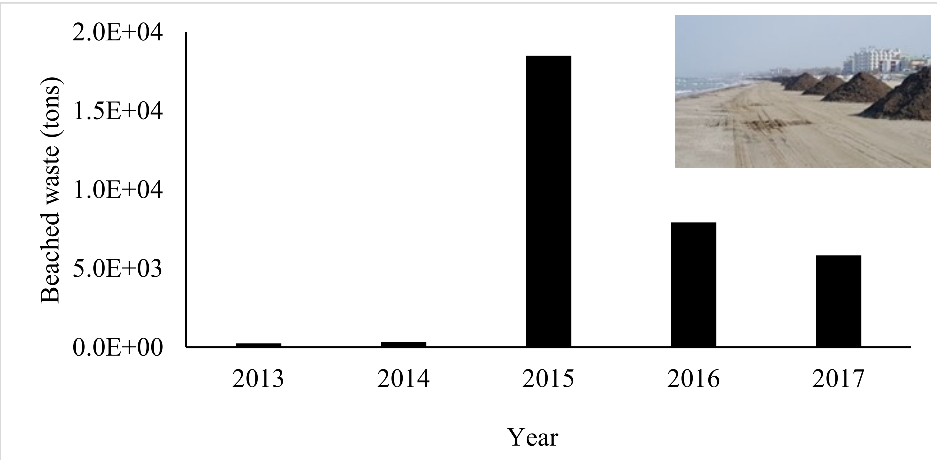

Figure 4. Trend of beached waste in Ancona province

Considering the obtained results, an interesting proposal for the MW management (suitable not only for the Corinaldo landfilling site) could be a "flexible strategy", able to implement the scenario 2 based on the performance of collection and recycling of each municipality. In this way, the real necessity of the biostabilization could be assessed, for each municipality served by the same landfilling site, on the basis of the specific putrescible fractions.

The combination of this strategy, with economic incentives (e.g. differential charges for MW flows which need the further treatment in biocell) could be favor the creation of a virtuous system with two relevant advantages:

- the increasing efficiency of recycling and collection system of municipalities (promoting the door-to-door collection and improving the waste collection from private green maintenance)
- the possibility of higher residence times in the biocells (thanks to the lower quantities to treat) for the MW with high organic content, able to increase stabilization level.

5. Conclusions

The improvement of the MW management represents an important topic since the related choices can cause relevant effect on environmental, economic and social spheres. The present paper showed an evaluation focused on the Corinaldo landfilling site (chosen as case study) but the adaptable results are relevant for all the stakeholders involved in this field.

Starting from the research questions reported in the previous sections, the presents paper identified the main strengths of the current system, providing some suggestions to further improve the sustainability level.

More in detail, it was highlighted that the optimization of the collection and recycling system of each municipality is the essential precondition for the most sustainable MW management system, consistent with the circular economy principles.

Furthermore, the results showed as the MBT represents an essential process, mainly in the contexts characterized by a low efficiency collection of the organic fraction. On the other hand, a flexible strategy could be an excellent solution in the geographic areas with effective collection systems (Ancona Province has already reached the 65% target), to join environmental and economic aspects. This flexible approach could further free up economic resources to invest for the optimization of the whole collection-MBT-landfilling system, closing the sustainability loop.

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