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Environmental Comparison of Different Mechanical–Biological Treatment Plants by Combining Life Cycle Assessment and Material Flow Analysis

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Abstract: The role of Mechanical–Biological Treatment (MBT) is still of the utmost importance in the management of residual Municipal Solid Waste (MSW). These plants can cover a wide range of objectives, combining several types of processes and elements. The aim of this work is to assess and compare, from an environmental point of view, the performance of seven selected MBT plants currently operating in different countries, which represent the main MBT layout and processes. For the scope, a combined Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) approach has been adopted to assess plant-specific efficiencies in materials and energy recovery. Metals recovery was a common and high-efficiency practice in MBT; further recovery of other types of waste was often performed. Each assessed MBT plant achieved environmental benefits: among them, the highest environmental benefit was achieved when the highest amount of waste was recovered (not only with material recycling). Environmental results were strongly affected by the recycling processes and the energy production, with a little contribution from the energy requirement. The impacts achieved by the MBT process were, on average, 14% of the total one. The main condition for a suitable MBT process is a combination of materials recovery for the production of new raw materials, avoiding disposal in landfill, and refuse-derived fuel production for energy recovery. This work can be of help to operators and planners when they are asked to define MBT schemes.

Keywords: residual waste; Mechanical–Biological Treatment; WRATE; material recovery; RDF

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1. Introduction

In recent years, the amount of Municipal Solid Waste (MSW) generated by municipalities and industries has dramatically increased [1]. Different strategies have been developed in order to reduce the amount of potentially recoverable MSW. Generally, source separation at individual households and subsequent separate collection systems are the most used approach [2]. In this way, it is possible to extract from waste flows a great amount of recyclable materials to reprocess them in the manufacturing of goods production [3]. Unfortunately, even if a perfect separation of waste is performed, an amount of residual waste is nevertheless produced. Not so many years ago, the ordinary management of residual waste was the disposal in landfill [4]. Recently, the European Waste Framework Directive [5] has emphasized the priority of recycling over waste disposal. According to this regulatory context, several strategies have been developed, such as incineration or waste pre-treatments before landfilling, with the objective of reducing the need of landfill space [6]. Nevertheless, mostly because of its more positive public acceptance, Mechanical–Biological Treatment (MBT) is considered as the main system for residual MSW management [7], and its importance is evident especially in contexts where the percentage of separate collection is not high [8,9]. Generally, MBT of residual MSW includes: (i) mechanical pre-processing stages to sort out recyclable and/or dry materials, such as paper, metals, and plastics; and

(ii) biological stages to reduce and stabilize the biodegradable organic matter under controlled anaerobic and/or aerobic conditions [10]. The stabilized stream, named Stabilized Organic Fraction (SOF), is generally disposed, whereas the dry one can be mechanically refined for the production of Refuse-Derived Fuel (RDF), delivered to dedicated Waste-to-Energy (WTE) plants [11]. Within this general classification, multiple varieties and configurations of MBT plants can be found all over the world [12]. The MBT term has come to embrace several types of processes and elements that are combined in a wide variety of ways to meet a range of objects [13–15]. For example, MBT can also be considered as a pretreatment to improve the beginning of biogas production in the anaerobic digestion process [16]. MBT may be designed for the production of marketable outputs or RDF, energy generation through biogas combustion produced in anaerobic biostabilization, as well as biologically stabilized waste to be used for land/soil applications [17].

Currently, there is still a missing clarification about the performance of each type of MBT plant in the waste management system. From an environmental point of view, if MBT plant worked in an anaerobic environment for biogas production, they achieved more benefits than other WTE treatments (e.g., incineration) [18]. On the other hand, aerobic MBT facilities resulted in high impact, due to their energy-intensive process, relative low yields, and the disposal in landfill of the majority of the output flow [19]. Regarding the sorting process, in some cases, a light mechanical pre-treatment could generate less impact than the production of high-heating value RDF, followed by its combustion into a dedicated plant [20]. However, there is an evident lack in scientific literature on specific assessments and comparisons of different MBT schemes. Montejo et al. [12] analyzed, from an environmental point of view, eight MBT operating in Spain with different recovery efficiencies, but the analysis involved only two main types of biological treatment. The state of art of environmental assessments of MBT plants reveals how the studies refer to few technologies adopted by the plants. What is generally missing is an assessment that takes into account a wider number of plant configurations and specific efficiencies (i.e., materials and energy recovery).

Hence, the objective of this work is to thoroughly evaluate the impacts that the current operation of different MBT plants operating in the waste treatment has on the environment. In this context, combining Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) approaches could be a suitable technical support for decision-making processes. LCA is a holistic approach widely adopted in MSW management that quantifies all the environmental impacts throughout the life cycle of products or processes [21]. MFA quantifies the mass flow and loss in a system throughout the entire pipeline of waste management, and also facilitates data reconciliation in a well-defined space and time [22]. MFA and LCA are a suitable tool for the comparison of different scenarios, especially in the waste management field [23].

Therefore, the aims of this work are to assess and compare the current environmental performance of seven selected MBT plants with different operational systems in order to illustrate the processes contributing to significant environmental burdens or benefits. For the scope, WRATE (Waste and Resource Assessment Tool for Environment) software has been used. A quantification of the mass balance for each MBT assessed and the environmental impact of the corresponding process have been carried out. At the end, a thorough discussion about the comparison of the different MBT schemes has been provided. In this context, this paper helps to determine the most sustainable options for the management of residual waste through MBT according to the necessity of the context.

2. Materials and Methods

In order to evaluate the different processes adopted in the management of residual waste in terms of environmental impacts, a combination of MFA and LCA methodology was employed. Both MFA and LCA was carried out through WRATE software, provided by Golder [24]. WRATE is a tool based on an LCA-approach for evaluating the environmental aspects of waste management activities for MSW during their whole life (from collection to ultimate disposal). This work aims to assess and compare the environmental impacts generated by the current operation of 7 different MBT plants, which covers the main plant configuration currently adopted, and can generalize the main treatment (e.g., aerobic–anaerobic environment, RDF production, residence time, etc.). For the scope, MFA was carried out to first understand the flow of material and explicate the associated losses. Then, LCA evaluated the potential environmental impacts during the treatment, the disposal, and the material recovery of residual waste. The scope of conducting LCA was to evaluate the most sustainable MBT process among different plant layouts.

2.1. Functional Unit and System Boundaries

In this work, the functional unit was defined as 1 ton of residual waste entering the MBT plants. The composition of the input waste is reported in Table 1, according to previous studies [8,13,25]. In this way, the functional unit served as the objective yardstick for the comparison among systems to which the inputs and outputs of the inventory were related.

Table 1. Composition of incoming MSW feeding the 7 MBT plants.

Fractions	%
Paper and cardboard	21.03
Plastic film	4.55
Dense plastic	10.61
Textiles	2.99
Absorbent	2.30
Wood	2.80
Combustibles	5.89
Non-combustible	6.89
Glass	5.80
Organic	25.96
Ferrous metal	4.25
Non-ferrous metal	0.75
Fine < 20 mm	5.43
WEEE	0.40
Hazardous	0.35

The system boundaries of the analysis included the residual waste processing in the MBT plant and the following destination of all the output streams. The waste generation and collection were not included in the analysis because they were in common in all scenarios [11]. Any environmental burdens for energy and material costs arising during the manufacture or use of the waste were excluded in this study (zero burdens approach) [26].

2.2. Life Cycle Inventory

Each individual MBT plant was modelled as a combination of mechanical separation and biological treatment. To facilitate comparison, the plant capacity has been normalized at 1000 ton/y in each scenario. The energy consumption, construction, maintenance, and operational materials required by the plant under assessment were based on experimental data. Table 2 summarized the description of each MBT plant. Further details and the layout schemes of each assessed MBT plant are provided in Supplementary Materials, from Figures S1–S7. The electricity mix assumed was the medium carbon mix provided by WRATE. It comprised 15.0% of coal, 0.5% of fuel oil, 27.5% of natural gas, 40.0% of nuclear power, 12.0% of hydropower, 0.2% of geothermal, and 4.8% of wind. This is consistent with the current situation of most developed countries, in which fossil fuels, nuclear, and natural gas represent the main primary energy sources [27].

Table 2. Schematic description of the plant layout and the process for each MBT assessed.

	Haa.	Ent.	Arr.	Glo.	Eco.	Her.	Lin.
Country	**DE**	**UK**	**IL**	**AUS**	**IT**	**DE**	**DE**
Pre-treatments	✓	✓	✓	✓	✓	✓	✓
Anaerobic digestion	✓		✓	✓			
Aerobic biostabilization		✓		✓	✓	✓	✓
RDF production	✓	✓			✓	✓	✓
SOF production	✓	✓	✓	✓	✓		✓
Metals recovery	✓	✓	✓	✓		✓	✓
Other waste recovery		✓	✓ *	✓		✓	
Retention time		10–14 d			24 h	6 d	28 d

Haa.: Haase; Ent.: Entsorga; Arr.: Arrowbio; Glo.: Global Renewables; Eco.: Ecodeco; Her.: Herhof; Lin.: Linde.
*: liquid-based separation.

2.2.1. Haase

Haase MBT was located in Neumünster (Germany): the plant removed light-density material for the subsequent wet anaerobic digestion process (dry matter content of about 10–15%). After the digestion, the suspension was separated into solid and liquid matter. Whereas the liquid was further treated, the solids were first dried, then landfilled.

2.2.2. Entsorga

Entsorga MBT represented a typical Italian MBT plant, despite it working in Westbury (UK). The waste feeds a rotary drum that opens the waste bags and removes any oversized material (typically plastic film and cardboard—which can be recycled—but also rogue objects, such as large pieces of metal, can be removed). Then, the waste was moved into the bio-stabilisation section, where the temperature was controlled through ventilation. After 10 to 14 days, the waste was dried, sanitized, and stabilized, and was moved to the removal of further recyclables (particularly metals). The main outputs of the process were RDF and SOF.

2.2.3. ArrowBio

The ArrowBio MBT of Tel Aviv (Israel) was characterized by an innovative liquid-based separation technology and anaerobic digestion. The waste passed through a bag opening unit and a wet shredder. Then, inorganic and organic materials were separated through a liquid-based separator: the first was composed of clean recyclables (glass, metals, and plastic); the latter was sent to the next biological stage. Thus, two continuous anaerobic digestion stages were performed: acidogenic and methanogenic (40 °C) fermentation, respectively. Biogas production far exceeded in-house energy needs. The stabilized biomass discharged from the second reactor was landfilled or, if compliant to the national standard, used as an organic soil amendment.

2.2.4. Global Renewables

Near Sydney (Australia), the Global Renewables plant performed a preliminary mechanical and manual sorting, which removed bulky, recyclable, ferrous, and non-ferrous materials. Metals were removed two times through electromagnets and eddy current separators. The undersize fraction was split into two flows: the fines went to the biological process; the oversize to landfill. Fines were fed into a percolator where they were irrigated and aerated. Then, the liquid percolate stream was sent to a three-stage anaerobic digestion. At the end, an intensive composting process and a subsequent screening converted the crude compost into a mature and quality one.

2.2.5. Ecodeco

The Ecodeco plant was located in Vigevano (Italy), and its treatment consisted of shredding (20–30 cm), bio-drying, and mechanical refining. Bio-drying was a 24 h process in a temperature and oxygen content-controlled environment. Due to its limited amount (<2% of the input), the leachate produced was re-circulated and sprayed on waste. Once the bio-drying process was completed, waste was automatically sent to the refining section. The refining section was constructed with double stage screening, iron removal, eddy current separator, aeraulic separation, and shredding.

2.2.6. Herhof

Herhof MBT (Rennerod—Germany) achieved a complete recycling of residual waste, eliminating the landfilling for the processed waste. The input waste in Herhof MBT was shredded (size of <150 mm) and bio-dried through a six-day aerobic degradation process with forced aeration and high temperature. The dried waste was divided into lightweight material (which consisted of combustible constituents, such as wood, paper, plastics, textiles, and organics) and heavy fractions (composed of inert waste and glass). Glass, ferrous, and non-ferrous metals were recovered from the latter stream, and the remaining mineral fractions were used in road construction.

2.2.7. Linde

Linde MBT was located in Dresden (Germany), performing a waste shredding and metal extraction. Then, the materials fed a screening drum where the high and middle caloric material were separated for further use/combustion. The smaller material was conveyed to a bio-tunnel (where it was composted for 4 weeks) and, at the end of the process, landfilled. Before landfilling, a further biological treatment of 8–10 weeks was carried out in open windows.

2.3. Impact Assessment

The assessment was carried out according to the LCA method CML 2001 [28,29], and Ecoinvent database (version 2) for background data. The assessment included six impact categories covering potential burdens to air, soil, surface, and groundwater, and potential hazards to humans. The impact categories were: Global Warming as climate change GWP 100a (kg CO_2-Eq), Acid Rain as acidification potential average European (kg SO_2-Eq), Eutroph'n as eutrophication potential generic (kg PO_4-Eq), Aqua Ecotox as freshwater aquatic ecotoxicity FAETP infinite (kg 1,4-DCB-Eq), Health as human toxicity HTP infinite (kg 1,4-DCB-Eq), and Resources as depletion of abiotic resources (kg Sb-Eq).

In order to get a better understanding of the relative magnitude between different environmental impacts, the results were normalized to the common unit of European Inhabitant Equivalent (EIE: number of 'average' people that would cause the same impact over the course of a year). The adopted normalization factors, as presented in Table S1 in Supplementary Materials, were assumed from Hischier et al. [30].

3. Results

3.1. Material Flow Analysis

As shown in Figure 1, the Sankey diagram summarizes the mass flow of the residual waste treatment of each MBT assessed (mass losses are not reported in the figures). High quality figures are provided in Supplementary Materials (Figures S8–S14).

The main output streams in each MBT were RDF (if provided) and SOF. It is important to note that for ArrowBio and Global Renewables plants, a further transportation of rejected materials to the landfill was necessary, and material recovery seemed to be much lower than the previous ones. Generally, ferrous and non-ferrous (except for Linde) metals were recovered in every plant. A more articulated selection of other waste was performed in ArrowBio and Global Renewables plants. Herhof and Global Renewables MBT were the only plants that recovered inert waste and paper waste, respectively.

The mass balance of every MBT plant is reported in Figure 2, showing the corresponding percentage amount of recovered materials, RDF, SOF, and mass loss streams.

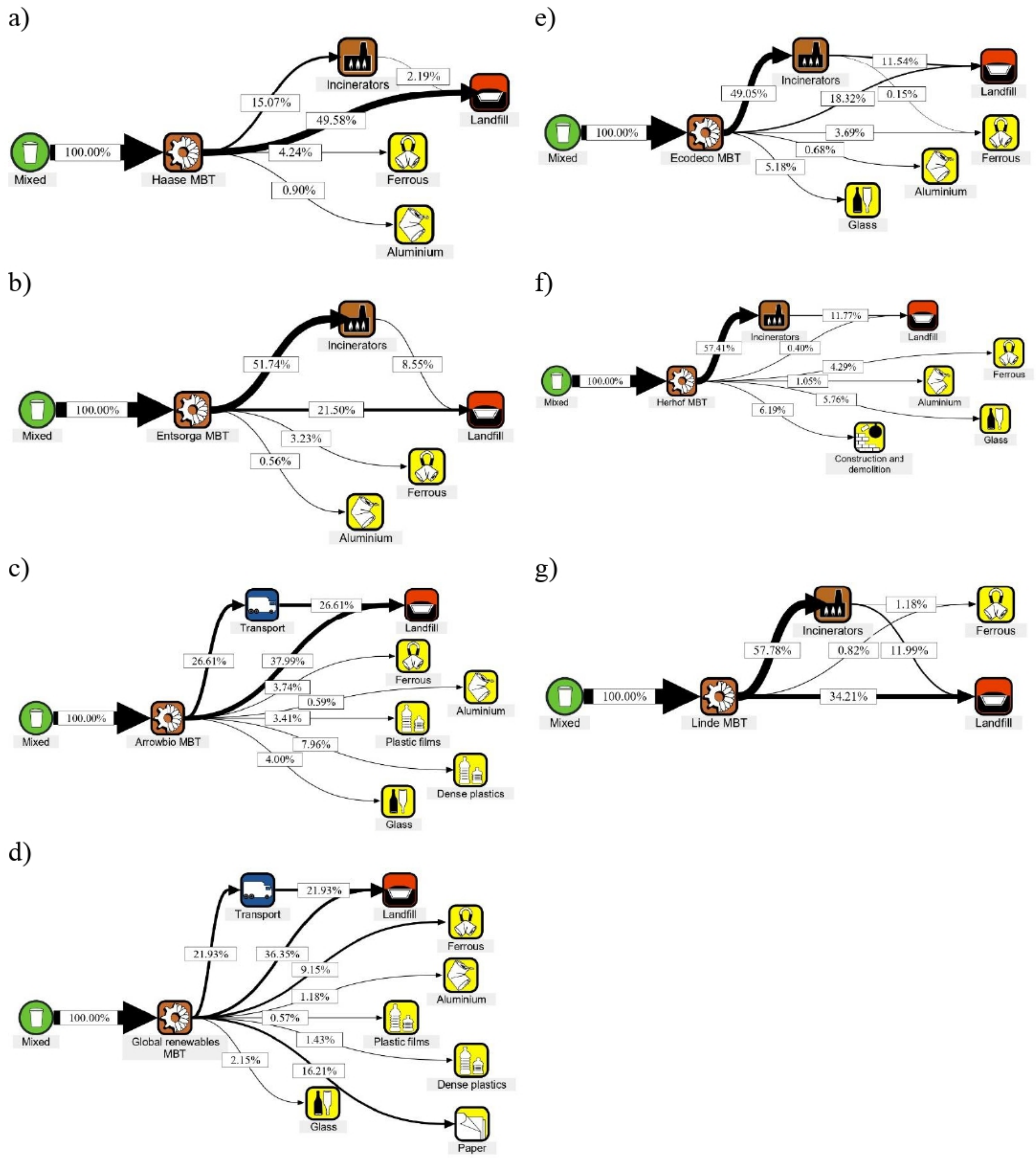

Figure 1. Material flow analysis results of the (**a**) Haase, (**b**) Entsorga, (**c**) Arrowbio, (**d**) Global Renewables, (**e**) Ecodeco, (**f**) Herhof, and (**g**) Linde MBT plants.

In Figure 2, it is shown again that ArrowBio and Global Renewables MBT plants were not provided for the RDF production. On the other hand, Herhof plant achieved a negligible amount of SOF because its scheme could dispense with landfill of it. The highest and lowest (not considering Herhof plant) SOF streams were achieved by ArrowBio (65%) and Ecodeco (18%). RDF streams appeared to be more consistent, ranging from 58% to 49%. The minimum value of 15% was obtained by Haase plant. Generally, material recovery did not exceed the value of 30%. Linde MBT did not perform any recovery, and high amounts were obtained by ArrowBio and Global Renewables plants. Focusing on the mass loss, values ranged from 7% (Linde MBT) to 30% (Haase MBT). On average, Entsorga, Ecodeco, and Herhof plants achieved a mass loss of about 25%.

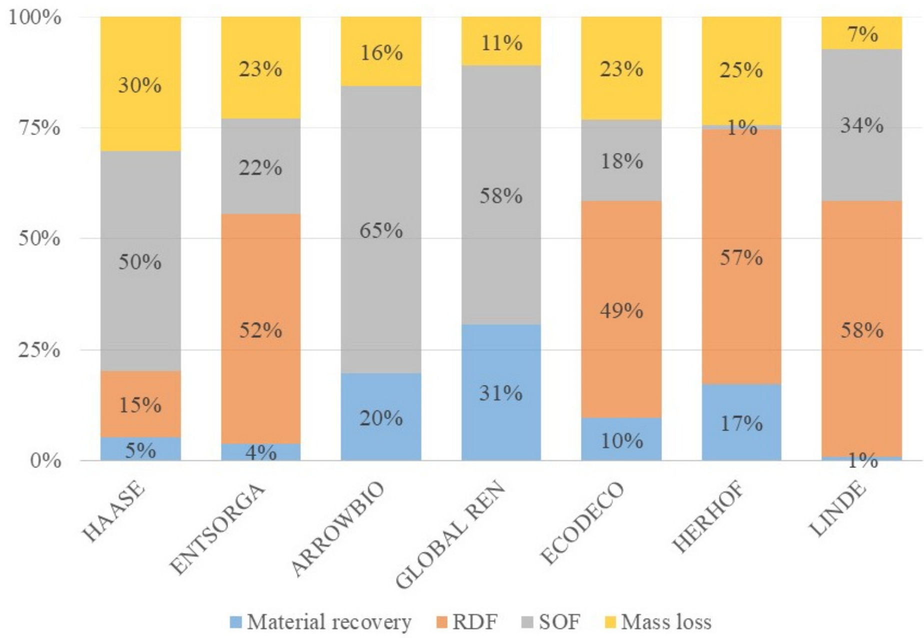

Figure 2. Mass balance of each MBT plant assessed in terms of material recovery, mass loss, RDF, and SOF production.

Focusing on the RDF and SOF streams, Figure 3 shows their composition in terms of waste fraction. SOF was characterized by a significant presence of putrescible (as organic and fine waste) and non-combustible materials (especially glass and inert waste). Indeed, Entsorga SOF flow achieved a half composition of inert waste, but dry waste (such as plastic, combustibles, and textiles) was almost null. Other relevant results were the high values of paper, metals, and wood in Haase, Entsorga, and Ecodeco SOF streams, respectively. Concerning RDF, it is clear that the putrescible fraction decreased when compared to SOF flows. On the other hand, plastic, paper, and combustibles waste had a considerable presence. In most RDF streams, combustibles waste was about 80% of the whole flow. Haase MBT achieved an RDF flow with an absence of waste that did not contribute to the WTE process, such as inert, metals, and putrescible waste. The higher presence of metals in Linde MBT compared to the other ones was remarkable. The RDF stream of Herhof MBT was characterized by a significant presence of putrescible fraction, in line with the aim of the plant that also involved organic waste in such a stream.

3.2. Life Cycle Impact Assessment

In this section, a comparison of the environmental performance among all the seven MBT plants in terms of six different categories is provided. Table S2 of Supplementary Materials presents the characterization results of the seven MBT in each one of the six impact categories considered in this study. Normalized results of the seven MBT for each impact category are shown in Figure 4. A negative value means an environmental benefit/credit, whereas a positive value indicates an environmental burden.

Concerning Global Warming, all the MBT achieved environmental benefits. This was mainly due to the avoided landfilling of the residual waste. Moreover, the increase in the percentage of RDF utilized in the WTE process decreases the environmental benefit (as expressed in Linde MBT). ArrowBio was the best option in this impact category.

For Acid Rain, environmental credits were reached by all the MBT. The release of ammonia, NO_x, and SO_2 during aerobic biodegradation or WTE treatment affected this impact category. On the other end, the production of energy from waste avoided the use of a fossil source for energy generation. In addition, the material recovery helped to obtain an environmental benefit. Again, ArrowBio was the best option in this impact category.

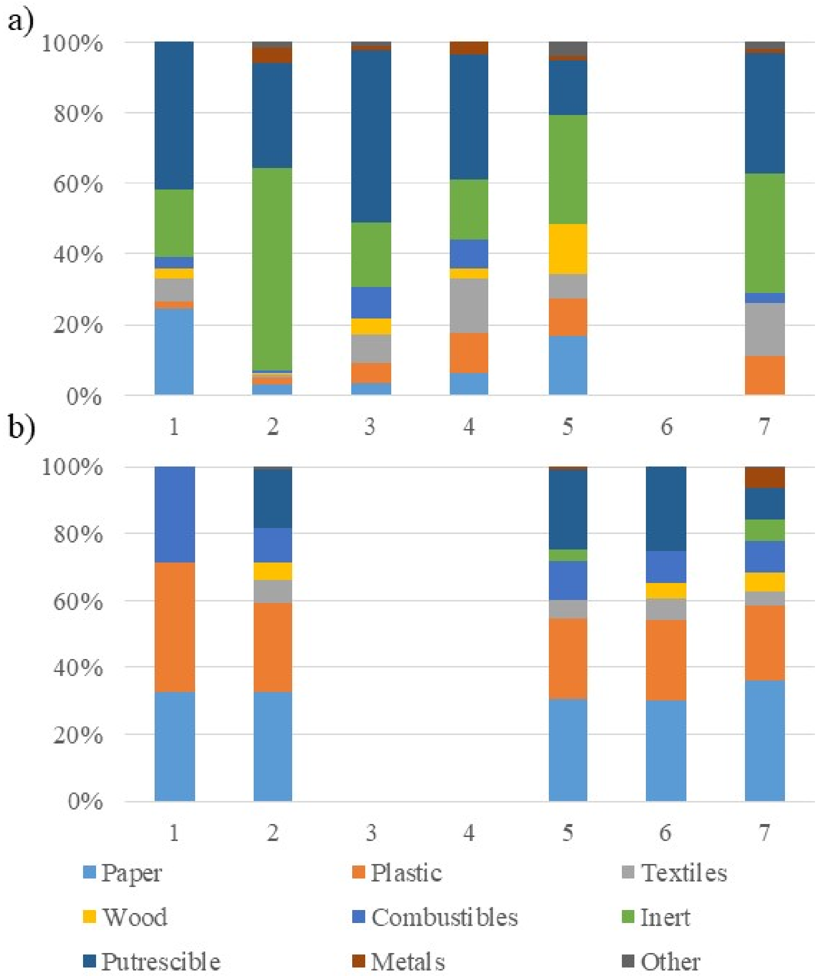

Figure 3. Composition of (**a**) SOF and (**b**) RDF for Haase (1), Entsorga (2), Arrowbio (3), Global Renewables (4), Ecodeco (5), Herhof (6), and Linde (7) MBT plants.

Regarding Eutroph'n, six MBT presented an environmental burden, with the exception of the Herhof one. The release of leachate and the production of phosphoric compound during the process were the causes of these values. The values were lower than the environmental credits of the other impact categories.

Considering Aqua Ecotox, all the MBT were characterized by environmental benefits. The influence of recycling strongly affected the results, since the release of heavy metals that characterize the MBT process [31] was not so high for this category. It is important to note that the recirculation of leachate performed by Ecodeco MBT did not have an evident effect on this category. The best result was achieved by Linde MBT.

Referring to Health, environmental credits were achieved by all the MBT, except for Linde plant. The small amount of recovered materials affected the benefit. Again, the impact due to heavy metals emission was exceeded by the environmental benefits related to recycling. Global Renewables MBT (characterized by the highest recovered materials amount) was the best option for this impact category.

Resources was the impact category in which results achieved the highest absolute values. All the MBT exceeded −0.08 EIE; ArrowBio presented the best value among the other MBT. The environmental burden for Global Renewables was caused by the high need of energy from the plant. Indeed, the numerous pre-treatments, the percolation stage, the three-stage anaerobic digestion, and the final composting process required an amount of energy that exceeded the energy produced through RDF usage. Figure 5 shows the contribution of landfill, MBT, recycling, and the incinerator stage on the LCA cumulated results.

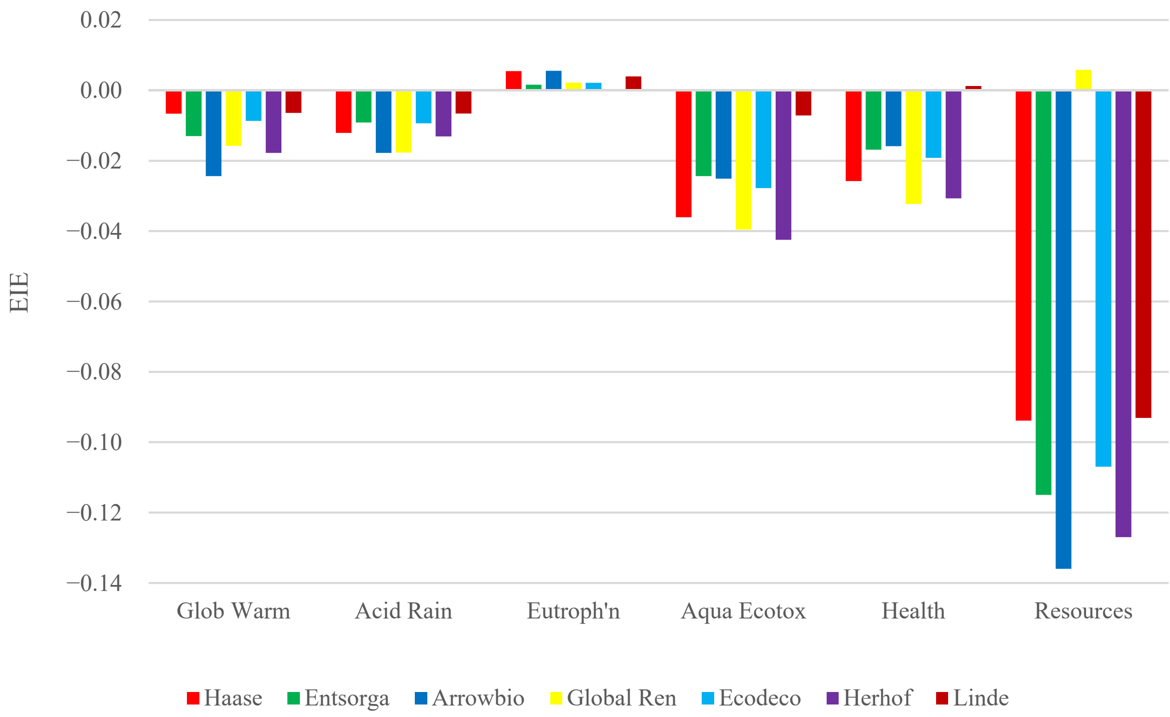

Figure 4. Normalized impact category results from LCIA for each MBT.

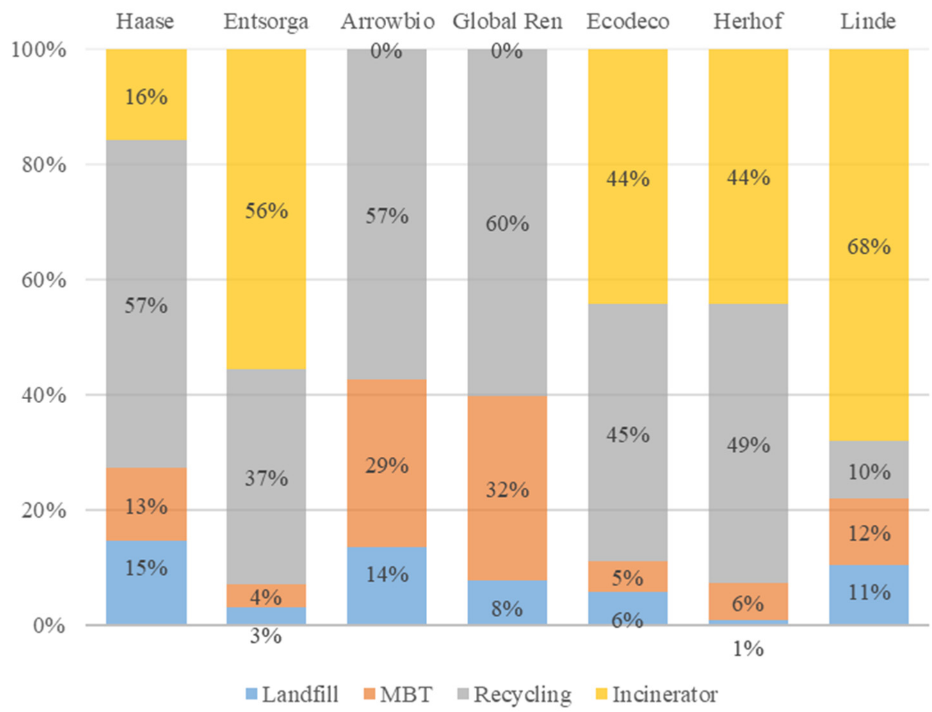

Figure 5. Contribution of landfill, MBT, recycling, and incinerator stage on the LCA cumulated results.

From the analysis of Figure 5, it is evident that the main contribution to the environmental impact was given by materials and energy recovery. The sum of these two processes ranged from 93% to 57% of the total impact. Moreover, the MBT affected less LCA results: the MBT contribution was, on average, 14% of the total impact, with maximum and minimum values of 32% in Global Renewables and 4% in Entsorga, respectively. The contribution of landfill did not exceed 15%. From this kind of evaluation, it was not possible to directly evaluate the type of contribution (environmental benefit or burden) in the LCA results, which is possible through the analysis of characterization results in Table S2.

4. Discussion

The environmental performance of seven different MBT plants have been evaluated through a combined LCA and MFA analysis.

The layout of the plant is fundamental to understand its role and the reason it was designed. Most of the MBT plants were designed for RDF production, but there are other plants (such as the ArrowBio and Global Renewables ones) that do not provide this stage. Landfilling was a common allocation for plant outputs, especially for SOF streams. Herhof MBT aimed to recover even SOF streams, eliminating the need of landfill. Ferrous and non-ferrous materials recovery was an operation generally provided in every MBT plant. On the other hand, other materials, such as glass and plastics, but also paper and inert materials, could be recovered from waste during the MBT process. From Figures 1 and 2, it can be seen that the two highest amounts and types of recovered materials were achieved in the MBT plants where the RDF production was not provided (Global Renewables and ArrowBio). In addition, the amount of recovered materials for each MBT plant assessed and the corresponding efficiency of separation are shown in Table 3. Ferrous and non-ferrous metals recovery show a high efficiency of separation: in most cases, all the input metals were removed through magnetic separation, and, in two plants, the recovery efficiency exceeded 99%. This condition could be associated with the fact that the recovered materials were not composed of metals only. The contamination of foreign fractions, such as plastic, organic, and paper, could affect the quality of recovered materials, increasing the corresponding amounts [32]. Due to its difficulty in selection and recovery, plastic film is the is the principal fraction involved in contamination [33]. The efficiency of 19% reached by Linde MBT could be associated with the process itself. Differently from the other MBT, the metals recovery was performed at the beginning of the process, before the biostabilization, causing a decrease in the recovery efficiency. The low metals recovery of Linde MBT was confirmed by the high presence of metals in its RDF stream (Figure 3). The great amount of ferrous and non-ferrous metals recovered by Global Renewables MBT was the result of a double recovery stage. Regarding the selection of plastic, results showed that ArrowBio MBT, characterized by a liquid-based technology, achieved better efficiency then the other [34]. The glass selection gave mixed results for the scarce information about the selection process. A large amount of paper could be recovered too, despite the quality being quite low.

Table 3. Amount and efficiency of separation of recovered materials for each MBT plant.

		Haa.	Ent.	Arr.	Glo.	Eco.	Her.	Lin.
Ferrous	kg % recovered	42.4 99%	32.3 76%	37.4 88%	91.5 >99%	36.9 86%	42.9 >99%	8.2 19.3%
Aluminium	kg % recovered	9.0 >99%	5.6 74%	5.9 78%	11.8 >99%	6.8 90.7%	10.5 >99%	
Plastic film	kg % recovered			34.1 75%	5.7 12%			
Dense plastic	kg % recovered			79.6 75%	14.3 13%			
Glass	kg % recovered			40.0 69%	21.5 37%	51.8 89%	57.6 99%	
Paper	kg % recovered				162.1 77%			
Inert	kg % recovered						61.9 89%	

Haa.: Haase; Ent.: Entsorga; Arr.: Arrowbio; Glo.: Global Renewables; Eco.: Ecodeco; Her.: Herhof; Lin.: Linde.

MFA results can be discussed in terms of mass loss. Ecodeco MBT showed that even a 24 h-long process could achieve a significant biostabilization (23%). The adoption of a bio-tunnel did not seem to be a great choice because, in Linde MBT, the mass loss hardly exceeds 10%. Indeed, to avoid troubles in the reuse of the organic fractions (e.g., landspreading) or in the landfill disposal (e.g., biogas generation without recovery system), a further biostabilization was necessary [35]. Anaerobic digestions reached important values if also considering the energy production during the biological process. Haase MBT reached a higher mass loss than the ArrowBio one, due to its wet process and its further dewatering stage at the end of the digestion. Overall, the mass loss during anaerobic biostabilization of residual waste was similar to the one obtained from source-separated organic waste [36]. Aerobic biostabilization showed a mass loss of about 25%: this value was achieved by both Entsorga and Herhof MBT, despite the first performing the process in twice as long a time.

The discussion of MFA output could be strengthened with the normalized LCA results. As it has been stated above, the environmental benefits that characterized most of the impact category results were due to the materials and energy recovery process of the scenario. Indeed, as confirmed in previous works [12], recycling and the operational product output stage of the system affected the LCA results, giving an environmentally-friendly direction (Figure S15 in Supplementary Materials). Figure 5 shows that, despite the low contribution of landfill on the environmental impacts, the amount of produced SOF was directly proportional to the effect of such treatment in the results. In addition, the energy output, such as incineration, WTE process, or the gas recovery in the anaerobic digestion stage (if provided in the MBT), was the main part of the environmental benefit (from 40% to 73%). On the other hand, the energy required for the operational MBT process appeared to be negligible compared to the other contribution (<5%). Global Renewables was excluded by this trend because the energy request for the MBT process was very high. For this plant, the energy input affected for 33% the LCA results in a burden way, and the MBT treatment gave the maximum contribution among the other MBT. In addition, energy output could not balance the energy needs of the plant. As a consequence, the LCA results (especially for the Resources category) were very distant from the ones reached by the other plants. Another remarkable aspect is that, despite Haase MBT having an RDF flow entirely composed of combustibles waste and anaerobic digestion producing energy from the biogas recovered, the full recovery of waste in Herhof MBT showed the highest energy production. Indeed, the amount of RDF produced by Haase was very low compared to the Herhof one. Despite anaerobic digestion having great energy production efficiency, the nature of MSW (which, in this study, was almost poor in putrescible fractions) did not allow a high methane yield [37]. On the other hand, the amount of energy produced during the anaerobic digestion process of Haase plant was enough to fulfil the energy needs of liquid digestate dewatering. In particular, the digestate dewatering through reverse osmosis in Haase did not reveal a significant difference in energy needs (Figure S15), since the impact contribution of that plant was comparable with the one of ArrowBio (which performed a liquid anaerobic digestion with other dewatering systems). Therefore, from an environmental point of view, the maximum energy production of a MBT plant was not always achieved by reaching a high-quality or quantity RDF stream, but through a balanced combination of them. In addition, by combining the results shown in Figures 4 and 5, it can be seen that with the rising of the putrescible fraction in SOF, the contribution of landfill on the LCA results increased.

To sum up, Figure 6 shows the aggregation of the LCIA normalized results. Aggregation was performed by the simple summation of the normalized results of all impact categories, without a weighting step. As indicated in Den Boer et al. [38], it should be noted that one EIE in an impact category does not have an identical physical meaning to one EIE for another category. As such, this condensed result does not present a physical sense, but it enables a comparison among several scenarios, allowing the classification of them in terms of global environmental effect [31]. As expected, the combination of anaerobic and aerobic processes with the further implementation of pre-treatments (Global Renewables) presented the worst results, due to the highest energy consumption. Linde

MBT reached a near value for its low amount of recovered materials. Haase, Entsorga, and Ecodeco reached a similar value, revealing how neither the anaerobic or aerobic process affected the results, as well as the residence time of the plant (10–14 days, 24 h, and 1 month for Entsorga, Ecodeco, and Linde, respectively). The higher amount of recovered materials helped ArrowBio and, in particular, Herhof MBT to achieve better results (regardless of anaerobic or aerobic environment, respectively). Material recovery was not the only recycling process, as the WTE process also had an influence in the scheme.

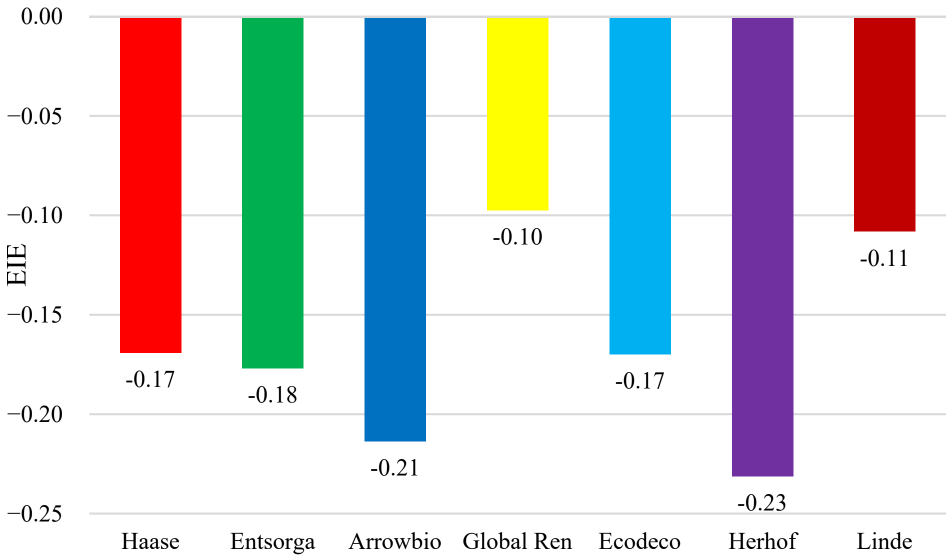

Figure 6. Aggregated LCIA impact results for each MBT plant in terms of European Inhabitant Equivalent (EIE).

It is important to underline how these results refer to an environmental point of view only. Economic and technical analysis would need to be carried out in order to have a comprehensive overview on the sustainability of the different MBT configurations assessed, since those aspects have significant relevance on MBT facilities [18].

5. Conclusions

The aims of this work were to assess and then compare the current environmental performance of seven selected MBT plants with different operational systems in order to illustrate the processes contributing to significant environmental burdens or benefits. Concerning the plant layout examination, the metals recovery was a common practice in MBT, which achieved a sorting efficiency of over 80%. Further recovery of different types of waste were also performed; plastic recovery seemed to be most effective through a liquid-based technology. The RDF production was not a constant operation in the MBT process. Regarding the mass balance, the adoption of bio-tunnels in the biostabilization stage achieved an insufficient value in terms of mass loss. LCA results showed that every MBT plant achieved environmental benefit, ranging from −0.11 to −0.23 EIE. From, an environmental point of view, results revealed that, among the seven MBT plants, the best performance was achieved when the highest amount of waste was recovered (not only with material recycling). LCA results were strongly affected by the recycling processes and the energy production, with a small contribution from the energy requirement. For the latter, the case of Global Renewables (characterized with several pre-treatments, a percolation stage, a three-stage anaerobic digestion, and a final composting process) showed a significant energy consumption that created an environmental burden in the Resources impact category. The re-circulation of leachate produced during the biostabilization stage did not have a significant environmental benefit. The impacts achieved by the MBT process were, on average, 14% of the total one; they ranged from a maximum value of 32% to a minimum one of 4%. The RDF quality (in terms of putrescible content) was not the only condition to achieve the highest energy production. Indeed, despite no trace of putrescible matter found in the RDF flow, the energy output could be lower than other MBT with worse RDF quality. Thus, the main condition for a well-performing result is not a perfect material recovery or a high-quality RDF, but a combination of materials recovery for the production of new raw materials, avoiding disposal in landfill, and RDF production for the WTE process. Focusing on the role of landfill in LCA results, it can be seen that the rise of putrescible fractions in SOF increased the contribution of the disposal on the total impact achieved. This work is one of the first environmental assessments that takes into account plant-specific efficiencies (i.e., materials and energy recovery) and the type of marginal energy source replaced. From these results, future investigations can be carried out, focusing on the role of MSW composition and energy-mix. The impact estimation of different MBT plant configurations can be of help to operators and planners when they are asked to define the most suitable treatment schemes for an MBT plant. Thus, this work could be a suitable benchmark for researchers and practitioners working in the municipal solid waste sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cleantechnol4020023/s1, Table S1: Environmental impact categories and normalization factors for European Inhabitants Equivalent; Table S2: LCIA characterization results; Figure S1: Scheme of the Haase MBT plant; Figure S2: Scheme of the Entsorga MBT plant; Figure S3: Scheme of the ArrowBio MBT plant; Figure S4: Scheme of the Global Renewables MBT plant; Figure S5: Scheme of the Ecodeco MBT plant; Figure S6: Scheme of the Herhof MBT plant; Figure S7: Scheme of the Linde MBT plant; Figure S8: MFA result in Sankey diagrams of Haase MBT plant; Figure S9: MFA result in Sankey diagrams of Entsorga MBT plant; Figure S10: MFA result in Sankey diagrams of ArrowBio MBT plant; Figure S11: MFA result in Sankey diagrams of Global Renewables MBT plant; Figure S12: MFA result in Sankey diagrams of Ecodeco MBT plant; Figure S13: MFA result in Sankey diagrams of Herhof MBT plant; Figure S14: MFA result in Sankey diagrams of Linde MBT plant; Figure S15: Contribution of operational product output, energy output, and energy input on the LCIA results for each MBT plant.

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