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Assessment of the Synergy between Recycling and Thermal Treatments in Municipal Solid Waste Management in Europe

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Abstract: In 2018, the production of Municipal Solid Waste (MSW) in EU-28 reached 250.6 Mt, with the adoption of different management strategies, involving recycling (48 wt %), incineration and thermal valorization (29 wt %) and landfilling (23 wt %). This work was based on the analysis of the baseline situation of MSW management in EU-28 in 2018, considering its progress in 2008–2018, and discussed the possible improvement perspectives based on a framework involving incineration and recycling as the only possible alternatives, specifically evaluating the capability of already-existing incineration plants to fulfill the EU needs in the proposed framework. The results of the assessment showed two main crucial issues that could play a pivotal role in the achievement of Circular Economy action plan targets: the need to increase the recycling quotas for specific MSW fractions through the separate collection, and therefore the improvement of definite treatment process chains; the optimization of the recovery of secondary raw materials from incineration bottom ash, involving the recycling of ferrous and nonferrous metals and the mineral fraction. Both issues need to find an extensive application across all member states to decrease the actual differences in the adoption of sustainable MSW management options.

Keywords: circular economy; incineration; municipal solid waste; recycling; thermal treatment; waste-to-energy

1. Introduction

Since the adoption of Waste Framework Directive (WFD) 2008/98/EC, considerable progress has been made in Municipal Solid Waste (MSW) management across the EU. The WFD defined the main pillars of modern MSW management, based on the 3 Rs (reuse, recycle and recovery): the waste hierarchy, setting an order of priority from the preferred option of waste prevention through preparing waste for reuse, recycling and energy recovery, with landfill disposal as the last option; the negative consequences of waste management towards the biosphere and established the principle of limiting the environmental impacts; recycling itself became a social priority. After 20 years, these measures lead to a transition to the actual Circular Economy (CE) EU policy, its waste management and recycling targets and related socioeconomic issues. MSW production in EU-28 exceeded 250 Mt in 2018 [1],

encompassing three main strategies: landfilling (23 wt %), thermal treatments (e.g., incineration and thermal valorization, 29 wt %) and recycling (48 wt %). The WFD was the main driver of change in MSW management operations in the EU in 2008–2018, enabling a 17 wt % reduction of landfilled waste and the increase of thermal treatments (13 wt %) and recycling operations (9 wt %, including part of thermal treatment residues) [1]. However, substantial differences still exist among the member states in MSW management and the relative significance of the three above-mentioned strategies [1]. On the one hand, northern countries rely on the existing incineration capacity, even if progress towards higher recycling quotas is noticeable. This fact might change the balance between the two strategies, thus disengaging and making available some of the existing incineration capacity at the national and European level. On the other hand, southern and recently acquired/candidate member states, having scarce or absent incineration capacity, still highly depend on landfilling.

MSW management practices, together with social indicators, were recently analyzed [2] to assess the environmental and CE performances of EU countries, recording the best results for northern member states, mostly committed to incineration and pro-environmental attitudes and stimulated social activity. Sweden was reported as the best-performing country [3] from the combination of reduction of waste generation rate, MSW management practices and related GHG emissions. Specific attempts to measure the progress of EU countries towards a CE through a set of indicators, with the aim to support the development of EU policies, were restrained by the lack of available data [4]. The mutual roles of MSW conventional waste-to-energy (WtE) processes and recycling in the CE were recently investigated considering specific key drivers (e.g., socioeconomic issues, environmental awareness, availability and cost of landfills, membership of EU and how long), demonstrating that even though WtE technologies are on a lower level in the waste hierarchy if compared with recycling, they play complementary roles and support the CE [5]. The lack of MSW sorting in some EU countries is a crucial issue, depending on the economic development and not related to the knowledge about waste generation [6], in achieving the CE targets defined by actual EU policies. It is well known that life-cycle thinking can support the choice of MSW management strategies related to the lowest impacts on the environment. MSW management was extensively analyzed and discussed in the framework of life-cycle analysis (LCA), pointing out the well-known limitations of the life-cycle approach in the lack of primary data and local specificity of the results (among the others [7,8], material recovery and incineration were often considered as alternatives [9] with sometimes controversial results); however, when recycling and thermal recovery were combined [10], or when thermal recovery is compared to landfill disposal [11], the environmental performances of the MSW management system resulted highly positive.

Based on the acknowledged positive performances of coupling recycling and thermal valorization as MSW management strategies, the novelty of this research relies on the proposal of a framework at the EU level involving recycling (i.e., waste treatment operations based on physicochemical and biological processes) and thermal valorization as the only possible options. The proposed framework, fully consistent with the CE EU policy, considers landfilling not as a direct perspective for MSW disposal but only as a final destination for minimized residual flows deriving from enhanced recycling and thermal valorization operations. The aim of this work is therefore not merely an analysis of MSW management in the EU context, already provided by the literature, but to present an alternative perspective in which landfilling plays a secondary role. A previous study [12] based on a GIS approach analyzed the MSW distribution across the EU and tried to identify the optimal location for new potential WtE installations. Considering that a new WtE installation could require at least 10 years of design and authorization to be ready to operate, and compared to the above-cited study [5], which investigated the main drivers for high recycling and incineration rates in EU countries, this work was specifically focused on the assessment of already-existing WtE plants and their capability to accommodate EU needs in the proposed framework. The analysis specifically considered 2018 (the most recent data available for EU member states on MSW management) and EU-28 because the United Kingdom could have a significant role in the European context, even after Brexit. Considering a virtuous scenario in which landfilling is no more a direct-access option, the whole MSW management system should

evolve towards an equilibrium between thermal treatments and recycling operations. Recyclables and secondary raw materials deriving from either biological routes or enhanced material recovery operations, also applied to incineration bottom ashes, in the next decade must find their spot in the market according to the Circular Economy EU strategy.

2. Methodology

The approach of the research involved a three-step methodology based on the following phases:

1. Analysis of the MSW management strategies in the period 2008–2018 to define the baseline situation and investigate the trends in the considered decade. The three options, landfilling, thermal treatments (incineration and thermal valorization) and recycling, were involved in the survey. It is useful to aggregate the adopted strategies into disposal through land deposition and landfilling, thermal treatments and recovery operations. In this work, the following definitions will be adopted, consistently with the WFD: landfilling (operations including D1 to D7 and D12), thermal treatments (operations including D10—Incineration and R1—Waste-to-Energy (WtE)) and recycling (operations including R2 to R11, *de facto* from R3 to R5). Socioeconomic parameters, such as population, population density, domestic gross product (GDP), were considered. This part of the research was mainly supported by Eurostat data [1,13,14].

2. Analysis of the EU incineration potential of bottom ash (BA) quantitative and qualitative features and management and a definition of the actual research gaps related to BA valorization. This part of the research was based on scientific literature and reference documents. The recently released BAT Reference Document for Waste Incineration [15] supplied the information related to the EU incineration potential that we analyzed according to two viewpoints. Firstly, we compared the amount of BA treated with the incineration capacity in the EU. Secondly, we evaluated the differences concerning BA treatment operations in the EU and their performances. The treatments were divided into in situ or ex situ, respectively, applied directly in the WtE plant or elsewhere. BA composition depends on the quality of the incinerated waste, highly variable on time and geographical area. Moreover, the outline of the incineration plant could also affect BA quality because the amount of organic material is related to the combustion temperature and to the waste retention time in the combustion chamber [16]. Although the evaluations on MSW composition are usually uncertain and incineration conditions depend on the specific plant design, it was possible to identify general BA qualitative features.

3. Definition of future perspectives considering a scenario at the EU level in which recycling and thermal valorization are the only possible strategies. Social issues, such as population and migration phenomena, were involved in the hypothesized trends. This part of the research was supported by Eurostat data [1,13,17] and official reports of EU agencies.

3. Results and Discussion

3.1. Municipal Solid Waste Management in the EU

Considering average MSW production in the EU and specific MSW amounts expressed as kg per capita between 2008 and 2018 [1] (Figure 1), a linear decline in the years following the 2007–2008 financial crisis can be noticed, whereas after 2013, the MSW amount increased again, even if at half of the precrisis drop rate, thanks to EU policies after the implementation of the WFD. These trends could be justified by the strong correlation that links population, economic development and the total amount of MSW produced in different countries [18]. In detail, the increase of the resident population in Europe in the considered decade from 500 to 512 M [13] and the economic development (measured as the gross domestic product (GDP) per capita and expressed in EUR, Figure 2) [14] both contribute to enhancing MSW production and the specific MSW amount. A recent study [19] demonstrated that a reliable prediction of waste disposal should also account for the rate of population change and the unemployment rate, especially during economic turndowns.

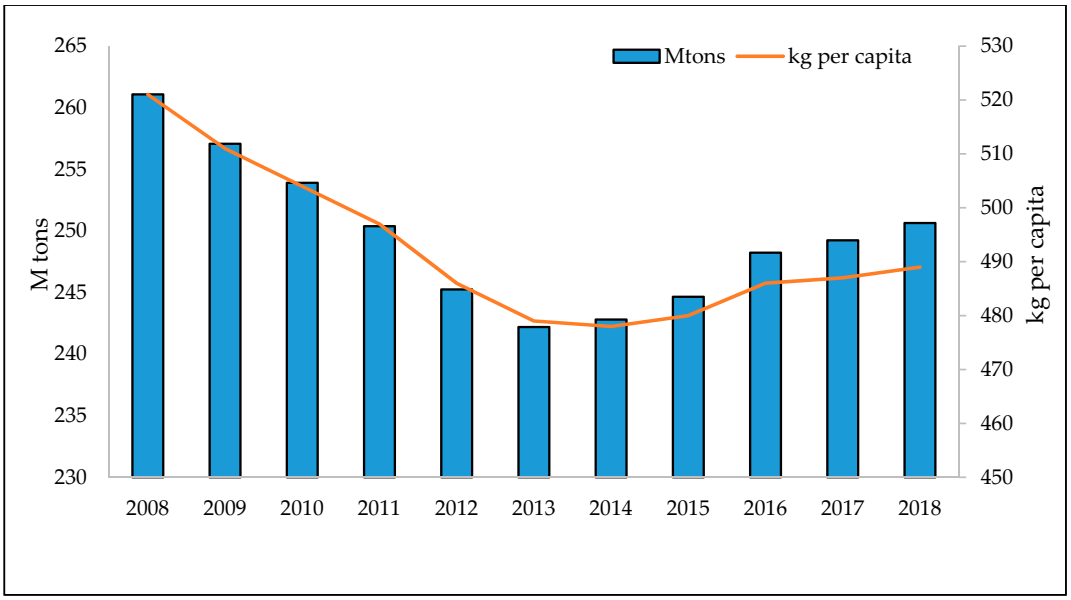

Figure 1. Municipal Solid Waste (MSW) produced in EU-28 in 2008–2018, in million tons and kg per capita [1].

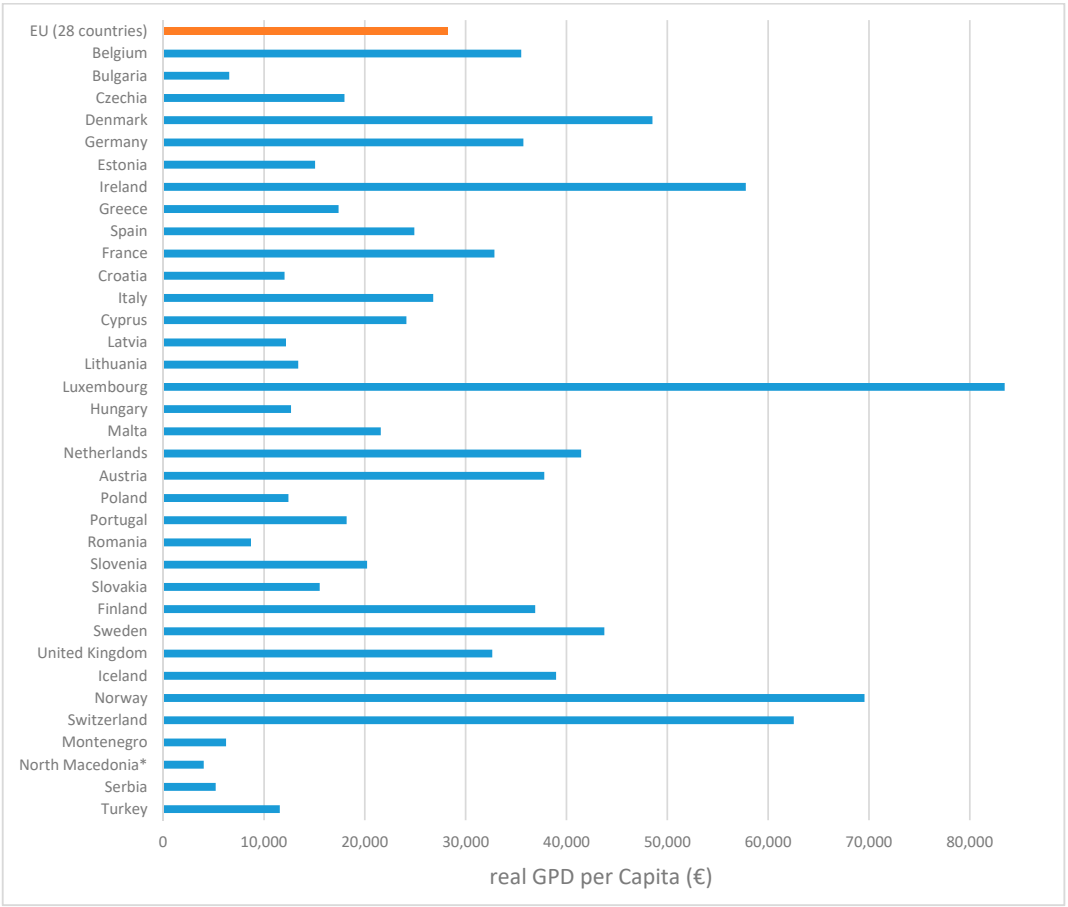

Figure 2. Economic development (measured as the gross domestic product (GDP) per capita, in EUR) of EU-28 member states in 2018 [14] (* 2018 value was not available for North Macedonia; therefore, the 2017 value is shown).

How is Europe dealing with this enormous amount of waste? The analysis of the average quotas for each MSW management strategy [1], studying their changes through the considered decade (Figure 3A), demonstrated a remarkable result of the policies adopted by the EU after the implementation of the WFD. A comparison between 2008 and 2018 (Figure 3B) showed a 17% reduction of the landfilled quota, counteracted by an increase of recycling (9%) and thermal treatments (13%). The same data can be tracked in a triangular diagram (Figure 4A), which makes evident that the member states exhibited a huge variability in MSW management operations (Figure 4B). Some countries are represented near one vertex of the ternary diagram (100% landfilling); other countries are found on the directly opposite side (70–80% thermal treatments and 40–70% recycling). Most northern and central countries (Austria, Belgium, Denmark, Finland, Germany, the Netherlands, Norway and Switzerland) apply policies to drastically minimize the landfilling of untreated MSW. Oppositely, countries still highly dependent on landfilling, over 70%, can be found (former Yugoslavia countries, Malta, Aegean countries, Romania). In between, the remaining countries are generally positioned in the region below 60% thermal treatments share. As a general statement, MSW management strategies are strongly related to economic development [20]; member states having a higher GDP, such as Germany and Sweden, prefer strategies based on recycling and WtE, whereas countries with a lower GDP mostly rely on landfill disposal.

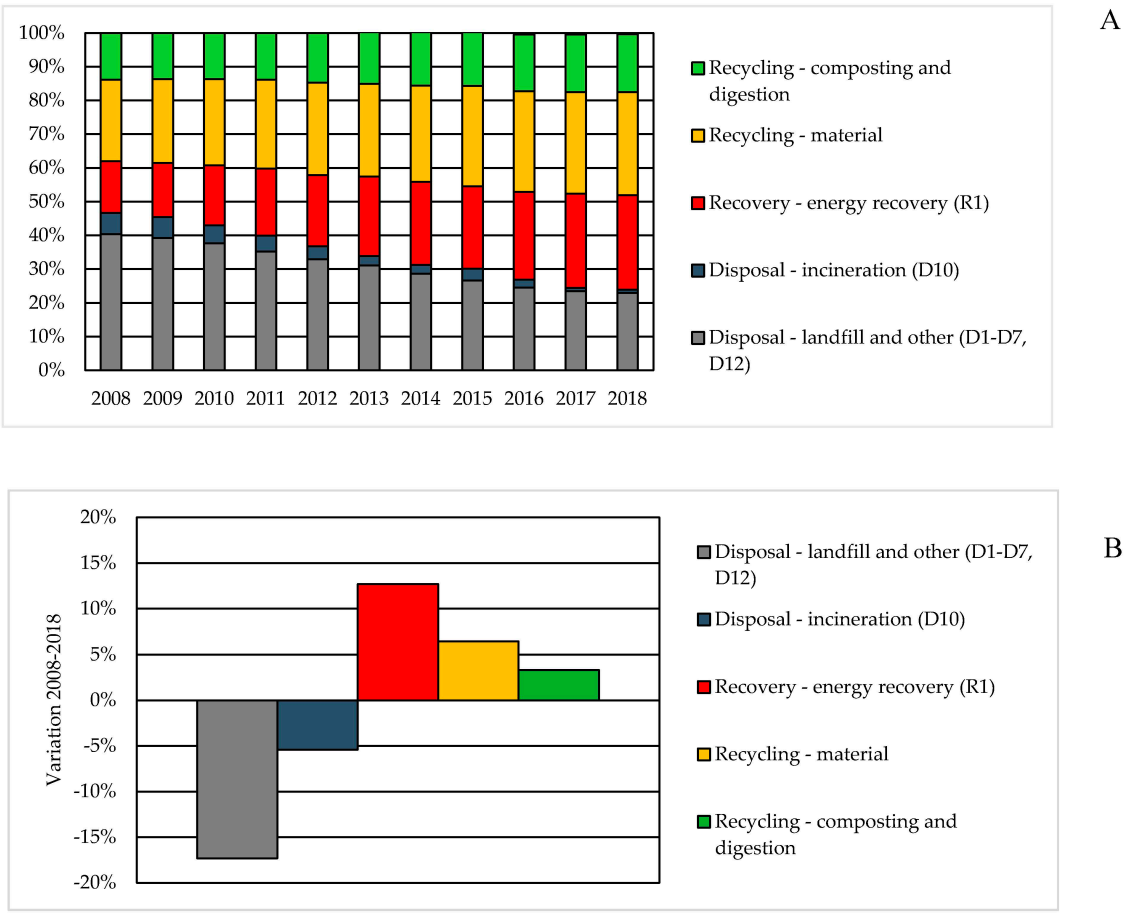

Figure 3. MSW management in EU-28 in 2008–2018: (**A**) historical evolution of waste management operations [1]; (**B**) net % variation of waste management operations between 2018 and 2008.

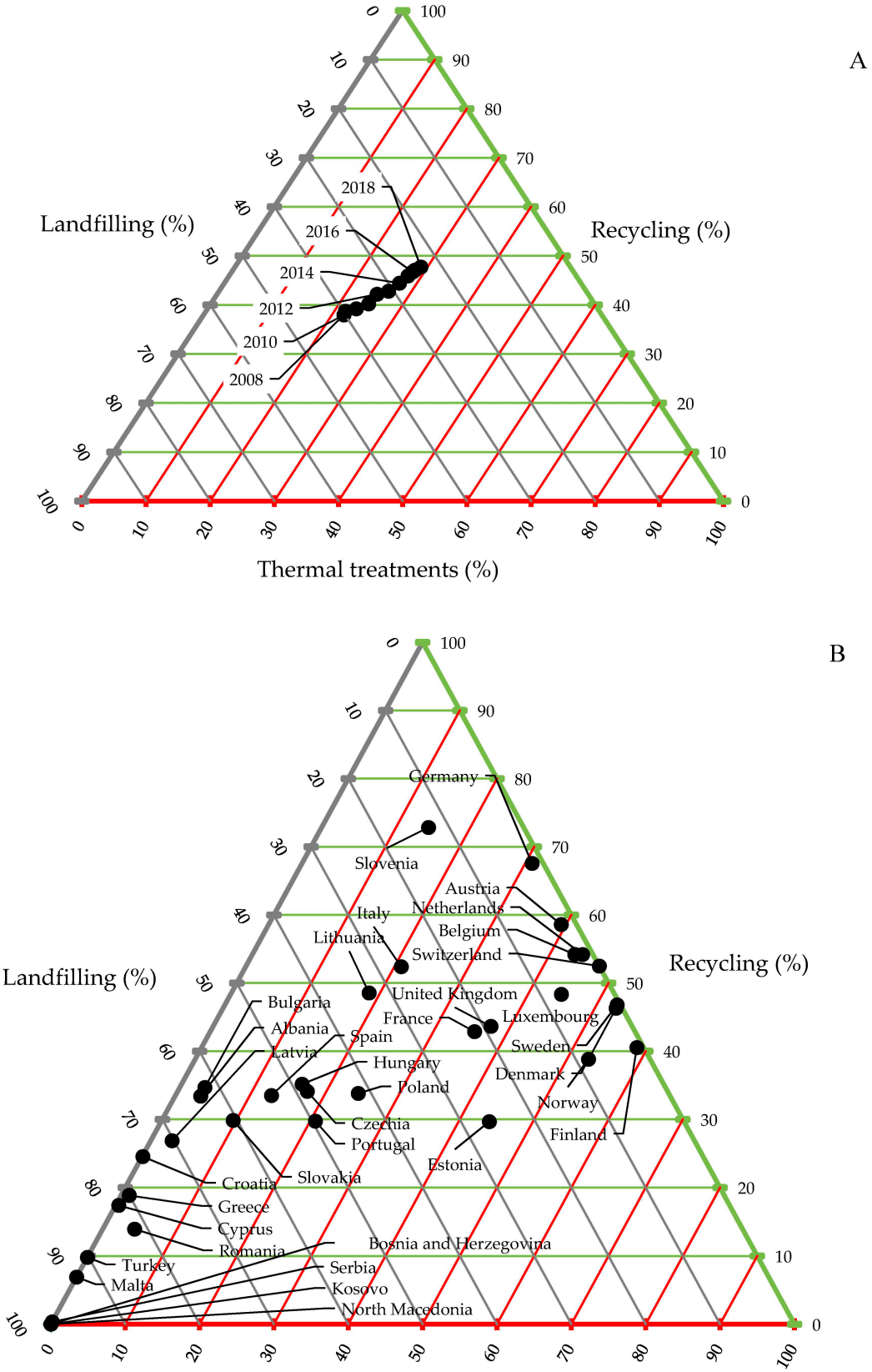

Figure 4. (**A**) MSW management operations in EU-28 in 2008–2018; (**B**) MSW management in member states in 2018 [1].

3.2. Bottom and Fly Ash Management in EU

3.2.1. Role of Thermal Treatments

As previously shown, the role of thermal treatments at the EU level is unquestionable. Considering the countries with almost zero landfilling (Figure 4B), it is evident that virtuous MSW management scenarios involve waste incineration, regardless of the achieved recycling quota. Member states such as Germany, Austria, the Netherlands, Switzerland and the Scandinavian countries reach 70% recycling quotas, and unrecyclable waste materials are treated almost completely in WtE plants [1]. Worthy of being mentioned is the case of Slovenia, which exhibits the highest recycling quota in Europe (73%), albeit the domestic treatment of generated MSW accounts for only 79%.

3.2.2. Bottom Ash Qualitative and Quantitative Features

Bottom ash (BA) is a granular material with particle size dimensions between 0.02 and 10 mm [21] and an average density equal to 950 kg/m^3. Hydraulic conductivity may vary between 10^{-9} and 10^{-4} m/s and moisture between 15 and 60 wt % depending on the quenching process [21]. The porous structure of BA determines its sorption capacity, specifically related to the fine fractions. Other physical features, such as shear resistance, freeze-thaw resistance and abrasion resistance, make it possible to recycle BA as building aggregate. Moreover, it is noticeable that elastic modulus results higher in BA that is not stabilized or "aged" [16].

BA is made of inert MSW fractions (glass, minerals, metals) and organic unburnt residues; refractory materials such as glass and ceramics may represent up to 20–30 wt % of BA, whereas the organic residue usually accounts for less than 4 wt %. Nonmineral components, specifically heavy metals, are more abundant in the fine fractions [22]. Specifically, BA is made of silica and calcium oxide, metal oxides and metals (ferrous scraps, aluminum, lead, zinc) and incombustible residues [23]. The metal content in BA is equal to about 8–10 wt % (6–7 wt % ferrous metals and below 2 wt % nonferrous metals, mainly aluminum) [23]. Considering an estimated yearly production of BA in the EU equal to 19 Mt [23], BA landfill disposal could imply a loss of 1.5–1.9 Mt/y of metals.

The mineralogical composition of BA after quenching consists of: a mineral fraction (about 60 wt %) made of quartz SiO_2, gehlenite $Ca_2Al_2SiO_7$, calcium carbonate $CaCO_3$, anhydrite $CaSO_4$ and ettringite Ca_6Al_2 $(SO_4)_3$ $(OH)_{12}$ $6H_2O$; an oxidized mineral fraction (5–13 wt %), including magnetic oxides such as goethite FeOOH, magnetite Fe_3O_4 and hematite Fe_2O_3; and metals/metal alloys such as aluminum, steel, copper and zinc [22]. Considering their composition, BA may be recycled through relatively easy processes and could be destined for a wide array of applications [24]; some, however, are limited by the high amount of metals that could be leached into the environment [22]. Therefore, BA is considered an environmental burden and an underexploited resource at the same time [25,26].

In 2018, 470 MSW thermal treatment facilities were in operation in the EU [15], mainly located in France, Germany, Italy, Denmark, Sweden and the United Kingdom. The new BREF (Best Available Techniques (BAT) Reference Document for Waste Incineration) on waste incineration [15] estimated the amount of BA produced by each EU member state in 2018, obtaining a total mass of 18.75 Mt, which is consistent with the value estimated by CEWEP (Confederation of European WtE plants) (19 Mt/y) [23]. Differences can be either related to the inclusion of industrial waste and the use of a lower BA share (i.e., only 20% of the incoming waste mass instead of 25%). From the catalog on waste incineration facilities in Germany [27], based on 58 WtE plants, around 25% of the incoming waste mass became bottom ash, regardless of the size of the facility. These results are consistent also with the new BREF on Waste Incineration [15], which reported a bottom ash production of 150–350 kg/t of MSW.

3.2.3. Bottom Ash Treatment

After incineration, BA is usually quenched through wet or dry processes [28,29] and aged for 3–8 weeks to achieve an overall stabilization of the mineral components [30]. BA treatment aiming at the efficient recovery of secondary raw materials is by now common and extensively adopted in Germany, Austria, the Netherlands, Switzerland and the Scandinavian countries [31], whereas other EU countries combine recovery and landfill disposal [32]. Recovery perspectives for BA mostly involve metals and the mineral fraction, recycled as building material or adsorbents [33]. The presence of metals (such as oxides or scraps) hinders BA recovery as inert material [22], with specific reference to potential leaching in the environment; therefore, the optimization of metals recovery could be pivotal to simultaneously achieve the recovery of high-value fractions and the improvement of the quality of the mineral fraction [33]. Another strategy to limit metals leaching risk consists of the application to BA of further thermal treatments, which may involve volatilization of metal compounds at 1000 °C [20] or metal stabilization through vitrification [34] or sintering [35]. Currently, the main application of BA, if not landfilled, is the recovery as a secondary raw material in building material production (e.g., for road construction) [36] or in concrete [37]. This specific perspective is favored by the fact that aggregate cost depends on the distance between quarries and building works; MSW incineration plants are usually located near urban areas where building materials are mostly requested [32]. Even if it was estimated that BA recovery as inert aggregate could hypothetically substitute only 0.6 wt % of primary aggregates in the EU market, the diversion of BA from the total waste flow destined to landfills would imply a 7–8 wt % reduction of such flow annually [38].

The most complete information dataset of BA treatment is available in the new BREF on Waste Incineration [15]. According to this work, the reported capacity for BA treatment (e.g., the sum of the capacities of the plants found in the new BREF, equal to about 8.4 Mt/y) is less than half of the amount of BA produced in the EU (see Section 3.2.2). This means that for the remaining quota, there is no information or, arguably, no treatments are applied. Furthermore, it can be also seen that in the new BREF, the existence of thermal treatment plants is reported in only 12 member states, whereas 20 countries apply thermal treatments to at least 10 wt % of produced MSW.

Comparing BA treatment operations in the EU and their performances, recovery involved 6.31 wt % ferrous metals and 1.70 wt % nonferrous metals, in agreement with the EU bottom ash factsheet published in 2016 [23]. Moreover, we observed that the amount of ferrous metals recovered in situ was higher (7.06 wt %, calculated from 12 plants) compared to ex situ BA treatment (5.71 wt %, calculated from 11 plants). This can be explained from the fact that incineration facilities generally include gross magnetic separation applied to BA before further processing [15], therefore depleting the content of ferrous metals in the BA treated ex situ. Contrarily, the recovery of nonferrous metals resulted higher in ex situ facilities, which strongly rely on the optimization of the recovery of this high-value fraction to enhance revenues. Considering the above-mentioned metals recovery values from BA (6.3% ferrous metals, 1.7% nonferrous metals) and the difference between the EU incineration capacity and the declared BA production, we estimated that about 800,000 tons of metals were lost in 2018. This could lead to lost revenues roughly corresponding to at least 37–47 M EUR/y, considering the average scrap values on the current market (about 600 EUR/t for steel, 500 EUR/t for aluminum and 3600 EUR/t for copper). The nonferrous metals contained in BA could contribute up to 85% of their economic value [39]. The recovery of metals from BA is generally achieved by means of modular unit operations combined in different treatment outlines [22,40]. As most recovery plants are focused on the recovery of the metallic fraction of BA, magnetic and Eddy current separators are, respectively, present in 100% and 95% installations. Obviously, the use of screens follows in the ranking (91% plants), since the use of magnetic and Eddy current separators requires a narrow particle size distribution to increase their separation performances [39,41]. The other two separation stages mostly applied are manual sorting (normally involving the coarser fraction, 67% plants) and the separation of the light fractions, such as plastics and unburned materials, via wind sifters or aeraulic separators (63% plants) [22].

Although extensive treatment for metals recovery can be nowadays considered state-of-the-art, some uncertainties remain about the exploitation of the fine and mineral fractions of BA. Well-known problems are related to the management of the fine fraction, which concentrates hazardous BA components [22]. The relative amount of the fine fraction depends on the technological level of the waste incineration treatment. Countries having extensive knowledge on incineration processes, such as Germany, the Netherlands, Belgium, Denmark, Austria and Finland, usually define a particle size cut for the minimum dimension of BA destined to recovery at 2 mm [31], and considering the average particle size characteristics of BA, fines could account for up to 40–50 wt %. Landfill disposal of BA fine fraction implies a high risk of leaching metals into the environment and, at the same time, the loss of secondary raw materials (most of the metals embedded in the fines are not recovered) and a potential economic and environmental revenue.

The second open issue about BA valorization is its safe inclusion as a substitute aggregate for construction without environmental drawbacks. Different approaches and evaluation measures are adopted in the EU for this issue. Considering Germany, which has the primate in the reported BA treatment facilities [27], the main uses of the mineral fraction are for road and subpavement base construction, highway embankment construction, the backfilling of mine voids, the construction of noise barriers, substitute aggregate for concrete production, the construction of certain landfill elements or disposal by landfilling. These uses encompass the general trend in the EU [15], in which the main destination for the residual mineral aggregates is road construction (74% of cases), followed by landfilling operations (47%), for which is not specified where the use is for its construction or during landfilling operations. However, the discriminant for the above-mentioned BA treatment options is still a nonunified, country-based regulation. It is nowadays well known that most existing legislations are based on leaching limits rather than total content limits [42].

3.2.4. Fly Ash Features and Management

Apart from BA, thermal treatments produce fly ash (FA) that accounts for 3% of the total incinerated material [43], leading to an estimate of 2.25 Mt produced in EU-28 in 2018.

Chemical elements redistribute during MSW combustion according to their specific volatilization capacity: elements with higher boiling points are diverted in BA, whereas volatile elements are released as gases or condense on the surface of FA particles [44]. Therefore, the main BA components are SiO_2, CaO, Al_2O_3 and Fe_2O_3, whereas FA is richer in light elements such as Na, Cl [45], heavy metals such as Cd, Zn, Pb, Hg, Cu, Cr and Ni and organic pollutants such as polychlorinated dibenzo-p-dioxins and furans [46] (Figure 5). Moreover, FA composition seems strongly dependent on the air pollution control devices installed in the incinerator, especially in terms of metal content, as FA collected through bag filters present concentrations of Na, Zn, Cd, Sb and Pb one order of magnitude higher than the samples deriving from water spray-cooling tower, and the latter concentrate more V and Hg compared to bag filtered fly ash [45].

Similarly to BA, FA often undergoes "aging," usually through water washing, phosphation and carbonization, all aimed to stabilize leachable potentially toxic elements (PTEs); however, low efficiencies are observed in the stabilization of Zn, Cd and Sb that, despite complying with the thresholds set by the European Landfill directive for acceptance in nonhazardous waste landfill, limits their reuse application in construction industry [47].

Compared to BA, FA recycling in civil engineering applications is more challenging due to concern about PTE leaching. The final destination of FA traditionally consists of backfilling or landfilling; regardless, they require treatment through thermal processing, water extraction or cement stabilization in order to comply with legislation limits for hazardous material disposal [48]. Different strategies have been studied to recycle FA [49] in glass, cement or ceramic manufacturing and as green mining resources for Zn, P, Cu and rare earth elements; however, concern arose about air pollution and PTE leaching and the economic viability of metal recovery. Cement stabilization is the most common FA management strategy in the EU [48]; however, it requires great amounts of cement to immobilize

PTEs and it causes massive CO_2 release during the cement manufacturing process. Considering the mentioned critical issues related to FA management, the framework proposed in this work focused specifically on BA valorization.

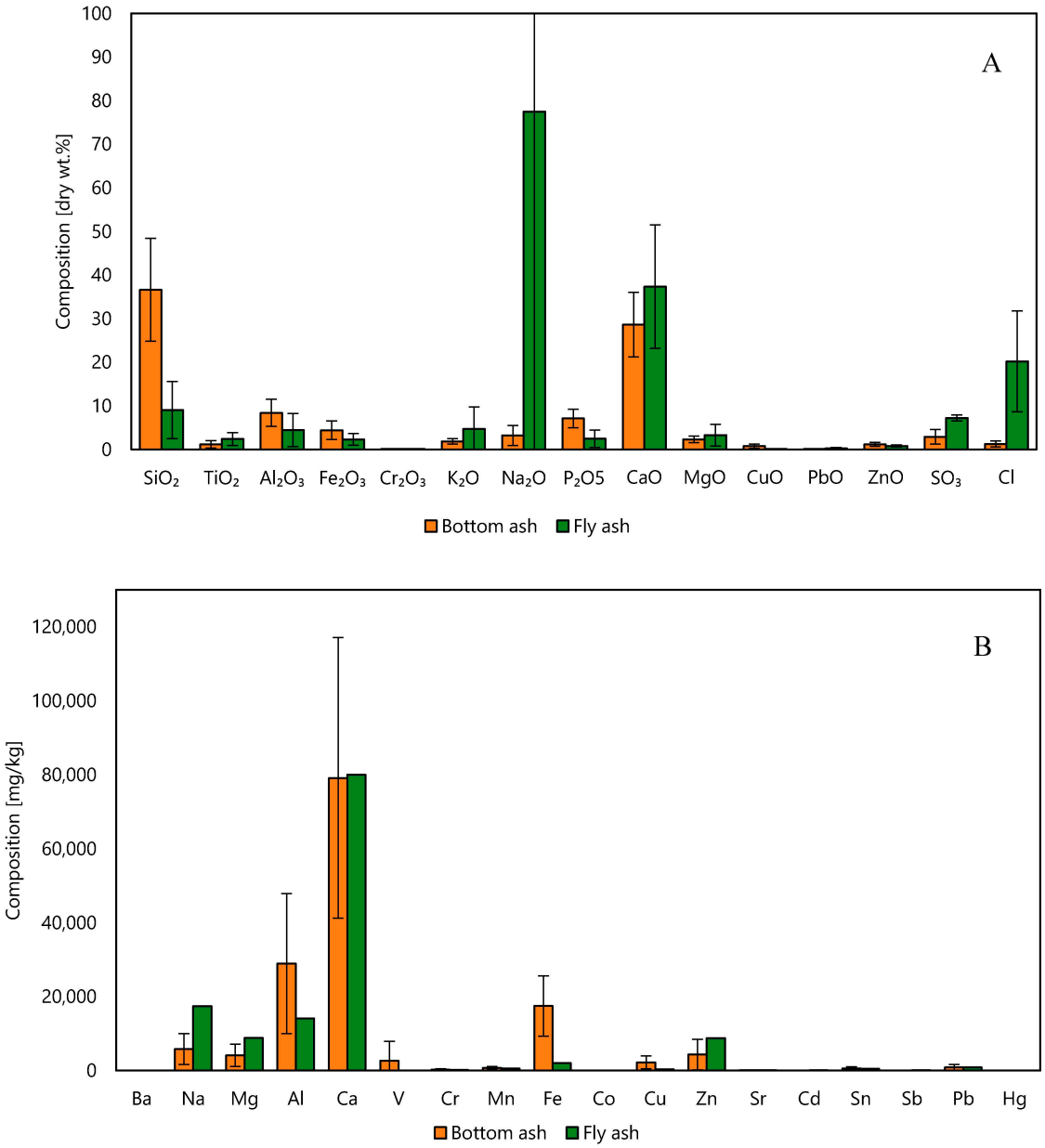

Figure 5. Composition of bottom and fly ash [45]: (**A**) minerals and (**B**) metals.

3.3. Future Perspectives in a "Recycling and Thermal Treatments Only" Scenario

On the grounds of the performed analysis of MSW management at the EU level and the extremely interesting perspectives and possible improvements of BA management, this work hypothesized a future framework for MSW management based exclusively on recycling (through mechanical and biological routes) and WtE treatment, considering landfilling only as the final destination for minimized residual flows deriving from enhanced recycling and thermal valorization operations. The proposed MSW management framework is based on the following main assumptions:

- Total MSW amount estimated for 2030 was calculated considering specific waste generation in 2018 (489 kg per capita) [1];
- The estimated population by 2030 was expected as 524 M [17]. Calculations also considered the Eurostat projection data involving higher migration phenomena and the consequent increase of the population to 531 M;
- The achievement by 2030 of the EU targets set for landfilling (10% MSW) and recycling (65% MSW, with 25% thermal treatments) [50].

The main outcome of this evaluation is that the highest swap of treatment quotas from 2018 to 2030 is from landfilling to recycling (Table 1). In detail, the role of thermal treatments is not likely to drastically decline (only 3%), whereas recycling significantly increases (18%). However, it should be observed that the very last step from the 10% to "zero-landfilling" target was already mostly reached in 2018 by means of thermal treatments in Austria, Belgium, Germany, the Netherlands, Sweden and Denmark (Figure 4B).

Table 1. MSW management in EU-28: actual situation and future perspectives related to the application by 2030 of a "recycling and thermal treatment only" framework.

	2018 (Actual Situation)		**2030 (Baseline Projections)**		**2030 (Higher Migration)**	
Population (residents)	512,372,000		524,000,000		531,000,000	
MSW generated (t)	250,642,000		255,188,000		258,597,000	
Landfilling (t)	56,743,000	(23 wt %)	25,518,800	(10 wt %)	25,859,700	(10 wt %)
Thermal treatments (t)	72,701,000	(29 wt %)	63,797,000	(25 wt %)	64,649,250	(25 wt %)
Recycling (t)	121,198,000	(48 wt %)	165,872,200	(65 wt %)	168,088,050	(65 wt %)

Another point worth mentioning is the rearrangement of the existing incineration capacity within the member states in the next future. Communication 34/2017 of the European Commission [51] stated that a balance between new infrastructures aimed at recycling and a careful analysis of existing incineration capacity, coupled with waste shipping possibilities, is highly necessary. In 2014, the EU incineration capacity for mixed MSW was 81.3 Mt [52]; therefore, adopting the proposed MSW management framework, the existing EU incineration capacity could fulfill the requirements for thermal treatments. However, careful planning, also based on LCA and considering cross-border shipments of waste, is necessary [50]. This point becomes even more relevant while observing that the available incineration capacity is unevenly distributed in the EU at the moment, where only five countries (Germany, France, the Netherlands, Sweden and Italy, considering that the UK no longer belongs to the EU) own three-quarters of the European incineration capacity, considerably limiting the available routes for waste shipments.

4. Conclusions

This work analyzed the actual state-of-the-art of MSW management in the EU considering 2018 data, the most recently available in Eurostat. Even with relevant heterogeneity within single-member states, in the last decade, a reduction of about 16% of the average landfilled quota, counteracted by an increase of recycling and thermal treatments (9% and 11%, respectively) were observed. Thermal treatments proved unquestionable and virtuous waste-management scenarios, regardless of the recycling quota achieved. Considering future scenarios related to the achievement of CE targets in 2030, the requirements for thermal treatments might still be fulfilled from the already-existing incineration capacity, which resulted mostly concentrated in a limited number of countries. Therefore, an overall assessment of the economic and environmental facts considering cross-border waste routes is highly necessary.

BA treatment could play without any doubt a strategic role in the achievement of CE targets, even if a wide variance of management operations and their performances was observed at the European level. Although extensive treatment processes for metal recovery from BA can be nowadays considered mature technologies, the exploitation of the mineral fraction remains an open question because of technical limitations, even if its recovery as a secondary raw material in building applications was widely reported. The main findings of this work will serve as a preliminary study to be further verified and validated through the application of standardized BA treatment procedures at different latitudes in Europe. A detailed and univocal regulation framework related to BA management is urgently needed, and this issue is currently one of the main barriers to closing the loop of BA management according to the EU strategy on CE.

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