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The Landfilling of Municipal Solid Waste and the Sustainability of the Related Transportation Activities

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Abstract: The management of municipal solid waste is a crucial issue to address as we move toward the decarbonization of urban contexts. Not by chance, this sector plays a relevant role in the Covenant of Mayors program, whereby municipalities are called to design their own Sustainable Energy Action Plans (SECAPs). However, despite new regulations strongly pushing the recycling and reuse of materials contained in municipal waste, many cities still use large landfills. As part of the overall environmental pressure exerted by these urban systems, the transport of waste from collection points to landfills or treatment facilities must be considered in order to correctly assess the full environmental burden of waste management. To this aim, in this paper, the Ecological Footprint method is applied to the municipal solid waste management system of the city of Palermo (Sicily). The results show that the impacts produced by the means of transport used, both in the status quo and in the assumed enhanced scenario (with less municipal waste disposed to landfills in favor of recycling), are significant compared to those caused by the other segments of the waste management system. The concept of a "saved footprint" is also introduced here, in order to properly compare the two scenarios.

1. Introduction

The European Union (EU) considers improving the management of municipal solid waste [1] as one of its main environmental and health objectives, with this approach being in line with its strategy for smart, sustainable, and inclusive growth [2] and its policy framework for climate and energy [3]. Within this frame of reference, municipalities applying to the EU Covenant of Mayors (CoM) for Climate and Energy initiative [4] are required to define their Sustainable Energy Action Plans (SEAPs) and Sustainable Energy and Climate Action Plans (SECAPs) to be submitted as part of the 2030 Agenda. To implement these action plans, integrated approaches are preferably required in order to comprehensively assess mitigation and adaptation strategies [5,6] and solutions [7] to counteract climate change. In particular, regarding the aim of improving the livability of the urban context both in environmental and health terms, the reduction of CO_2 emissions resulting from anthropogenic activities is one of the main objectives to be achieved under the CoM program. For example, one must consider the repercussions that urban pollution, especially related to transport [8], has on the indoor air quality of buildings, particularly those used for public services around which the social life of citizens gravitates [9].

Among the sector objectives of the aforementioned environmental action plans, municipal solid waste (MSW) management is one of the most relevant. In fact, since the growing demographic is leading to increasing waste production, the adequate assessment of waste generated by domestic and commercial activities represents a key factor in guiding cities

(and towns) towards the formulation of appropriate technologies, strategies, and policies aimed at this sector.

On this subject, a detailed study on the influence of environmental policies on waste treatment in 41 OECD and/or EU countries [10] and a measurement of the environmental performance in the treatment of MSW in EU-28 [11] have been conducted in order to assess the effectiveness of such policies and identify the most sustainable practices that could be successfully implemented. MSW can, in fact, be considered either as an opportunity, being a significant source of raw materials/energy, or as a threat, a cause of pollution, if not properly managed [12]. For this purpose, coupling the rising need for renewable energy sources with the requirements for increasing the shares of waste-recycled materials has proven to be a good example of waste-to-energy conversion technology [13]. In addition, promoting waste separation behavior among citizens by reducing psychological distances and improving environmental information campaigns could constitute an effective strategy to raise individual good practices [14].

Within this context, local administrators are looking for easy and reliable methods of analysis, aimed at ranking the planned policies (included in SEAPs), based on their effectiveness also from an environmental point of view.

In 2015, the European Commission promoted a group of laws to encourage the transition to a circular economy [15], in which the view of waste is reversed in the sense that used materials should not be disposed of, but should constitute a valuable resource to be put back into the production circuit. Waste management, in other words, is an important part of a circular economy, representing a nexus between waste generation and recycling, economic growth, and greenhouse gas (GHG) emissions [16,17]. This group of laws identifies criteria and steps to improve the efficiency of waste management and increase the amount of recycled material and reduce the amount going to landfills [1]. In particular, the proportion of waste for reuse and recycling is set to reach 60% by 2025 and 65% by 2030; in addition, by 2030, the fraction of waste disposable in landfills must be limited to 10%. Furthermore, reducing the shares of MSW sent to incineration and/or landfill, in favor of other more environmentally friendly options, can be considered a means to protect both the environment and human health, as well as promote the recycling of materials [18]. Nevertheless, almost 99% of what consumers buy is thrown away within six months [19], and as a result, a high number of landfills are still used in EU member states. Table 1 reports the situation in Europe (in the year 2018), where approximately 500,000 landfills were in service [20].

Table 1. Landfills in some countries of Europe.

Country	Number of Landfills	Share of Landfilled Waste on Total Waste Produced
United of Kingdom	24,000	36%
Belgium	4061	8%
Portugal	3589	38%
Germany	58,000	10%
Austria	5882	8%
Italy	40,000	23%
Greece	30,000	79%
Netherlands	4000	3%
Denmark	3200	6%
Finland	2600	11%
Sweden	6000	9%
Hungary	2730	60%

In Italy, in particular, 34% of waste is still landfilled, while 28% is sent for recycling, 18% is composted, and 21% is burned in waste-to-energy plants. Moreover, it should also be considered that recent analyses of the impact of the COVID-19 outbreak on waste cycle management [21,22] have shown an actual increase in the amount of non-recycled materials

due to sanitary needs and new safety consumption practices. Therefore, the increase in the quantity of recycled waste, in accordance with EU requirements [1], requires the constant updating of Waste Management Plans implemented by regional administrations [23].

In general, a municipal solid waste management system (MSWMS) can be divided into three macro sections: Gathering, transport from the collection points, and final treatment (including disposal). However, although the environmental sustainability of this important urban service has been widely addressed [24,25], more attention has been paid to the initial [26,27] or final stages of the chain [28–30], mostly based on the Life Cycle Analysis (LCA) approach. This latter method, in fact, has been used extensively to evaluate which environmental impact indicators are more important per waste flow [31,32], in order to assess whether recycling can be considered a good option for mitigating environmental impacts.

Conversely, little attention has been paid to the handling of waste from urban collection points to landfills. In this respect, although some works aimed at examining waste-related energy consumption [28], energy flows [33], and economic aspects [34] suggest that transportation is an important item in an MSWMS, only a few studies available in the literature show an assessment of the environmental and climate change impact [35,36] of transport vehicles used to collect and deliver municipal waste to the landfills and treatment points.

On the contrary, waste transport, which is a very significant segment of the whole waste management system, needs special consideration in order to correctly assess the overall impact of municipal waste treatment. For example, with reference to the waste disposal system of the city of Palermo (Italy), waste is transferred to landfills by lorries whose polluting emissions are not negligible since the transfer consists of a twelve-kilometer route. On the other hand, this urban circulation of trucks may be responsible for the delay in traffic flow, especially when it passes through the numerous ring roads that usually lead from the city to the landfill [37,38]. This delay indirectly translates into increased pollutant releases from the whole urban traffic system, as confirmed by data referring to other towns belonging to different geographic contexts. Maués et al. [39], referring to the second-largest city in the Brazilian Amazon, estimated GHGs emissions in CO_2-eq. from the transport of civil construction waste, finding a production of 40,440 kg CO_2/year for a waste volume of nearly 1244 m^3/month. Eisted et al. [40] report on GHGs emissions (kg CO_2-eq.) associated with the transport of 1 ton of waste for 1 km for four different modes of transport, that is road (e.g., by trucks and compaction trucks), rail (e.g., by trains), ocean (e.g., by oceanic ships and coasters), and inland water navigation (e.g., by barges). For instance, for the transport of waste by trucks, the potential contribution to global warming of 1 ton of waste indicated in the work ranged between 0.091 and 0.557 kg CO_2-eq. ton^{-1} km^{-1}, while for the transport of waste by trains based on diesel, it is estimated to be ranged from 0.002 to 0.058 kg CO_2-eq. ton^{-1} km^{-1} [40].

Therefore, in order to improve municipal waste management, thus meeting the objectives of the EU waste policy, the overall impact of MSWMSs on the environment should be properly considered by local administrators. Moreover, it is evident that, due to its intrinsic complexity and cross-cutting relation with several aspects of environmental quality control, integrated methods of analysis are needed to properly address this issue. Taking this into account, the availability of easy and reliable methods to assess the impact of MSWMSs becomes essential. Based on a review of the literature on the subject, the LCA methodology [41,42] is one of the most widely used methods for this aim. A comprehensive review of LCA studies applied to MWMSs is presented in [43,44]. However, such methods, although specifically oriented toward the singling out of the pressure exerted by a given system on the most relevant categories of the environmental impact, are not characterized by a single indicator of performance that embodies a synthetic environmental description of the system.

With the aim of bringing a contribution to cover this gap, in this paper, the application of the Ecological Footprint (EF) method [45] is proposed to evaluate different options regarding MSWMSs. In addition to its obvious connection with environmental issues, the EF method shows the advantage of treating energy-related issues with an integrated

approach that allows the evaluation of the energy consumption of a process (electrical and/or thermal), perfectly in line with the mission of SEAPs.

More specifically, the scope of the present research has been contextualized in the frame of the lack of current scientific literature properly considering the transportation phase in waste treatment. Therefore, in order to provide a contribution to overcoming this lack, we propose here the utilization of the integrated/holistic EF method for the evaluation of the environmental pressure exerted by a municipal waste system. The application of the method (apart from its validity in providing the environmental evaluation of the system by means of only a comprehensive indicator) has shown that this segment plays an important role in the whole environmental performance of the waste-handling system and therefore cannot be neglected.

The EF integrated sustainability indicator is, in fact, able, thanks to its formal calculation structure, to easily evaluate and compare not only the differences in terms of environmental impacts between, for example, the discharge of a given material and its recycling but also the contribution provided by the different phases of the same process.

2. Materials and Methods

2.1. The Ecological Footprint Approach

The EF is a general sustainability indicator that was firstly introduced by William Rees from British Columbia University [46], further developed by Mathis Wackernagel [47–49], and has gained great popularity worldwide due to its feasibility and ease of use [50].

The EF of a given activity is defined as the biologically productive areas of land and sea necessary to provide the resources that such activity consumes and to absorb the produced wastes. In other words, when adopting the EF approach, given human activity is evaluated in terms of the equivalent (bioproductive) land area of the planet that is required to sustain it. Moreover, according to the EF method, the weight of an anthropic activity not only affects the portion of land on which such activity is located, but it is also casually distributed on the entire Earth's surface through appropriate conversion factors, meaning that, in general, a given community may use more land than that actually available. As a result, when the bioproductive space needed is greater than that actually available, it means that the resource consumption rate of that activity is no longer sustainable.

To introduce a principle of compensation among exploitation and environmental pressure, in [48], the "legitimate portion of land", corresponding to the average amount of land belonging to each individual, is proposed. This quantity has been assigned a value of 2.13 ha per capita [51], corresponding to a circle with a diameter of 155 m.

In its general form, the EF considers a few specific ecologic items, namely soil, grasslands, built-up land, forests, productive marine areas, land for energy, and land for biodiversity. Obviously, the local efficacy of these bioproductive areas might differ from the predetermined mean global values [52]. Therefore, in order to effectively compare the footprints relating to diverse types of land, appropriate "equivalence factors" are proposed. Such factors are expressed as the ratio between the mean productivity of a bioproductive space's given category and the average world productivity. By doing so, the pertinent relevant productivity can be attributed to respective "local hectares".

It should be underlined that the ecological deficit is a real problem to be addressed and is no longer just a hypothesis. Indeed, since 2005, the demand for natural resources has exceeded the earth's regenerative potential by over 20% [53].

The above-reported considerations provide evidence of the importance of devoting adequate attention to the management of natural resources employed by human activities, and the treatment of municipal solid waste is undoubtedly one of the most relevant areas to be appropriately addressed.

2.2. Computing the Ecological Footprint of the Municipal Solid Waste Management System of Palermo

With reference to municipal waste and its disposal system, only a few estimates of its environmental impact through integrated assessment methods are present in the literature [54,55]; many of them analyze other types of waste, such as construction and demolition waste [56,57], municipal animal waste [58], and agricultural waste [59]. Therefore, to identify the role played by the waste transport phase on the environmental impact exerted by an MSWMS, it was decided to apply the EF method to the MSWMS of Palermo Municipality, in Sicily.

In addition, apart from the environmental assessment of Palermo's current waste disposal system, an improved scenario is considered as well. In particular, such an improved scenario, together with a reduction in the amount of solid waste sent to landfills (due to an improvement in the amount of recycled material), is also characterized by the use of less impactful means of transport to bring residual waste to the landfill and deliver recycled waste to the appropriate treatment platforms.

In more detail, the Integrated Waste Management Plan related to the so-called "Ambito Territoriale Ottimale" (ATO) PA3 was considered, which includes the city of Palermo and the small island of Ustica (Sicily, Italy) [23]. Figure 1 identifies the selected territorial area within the entire map of Sicily.
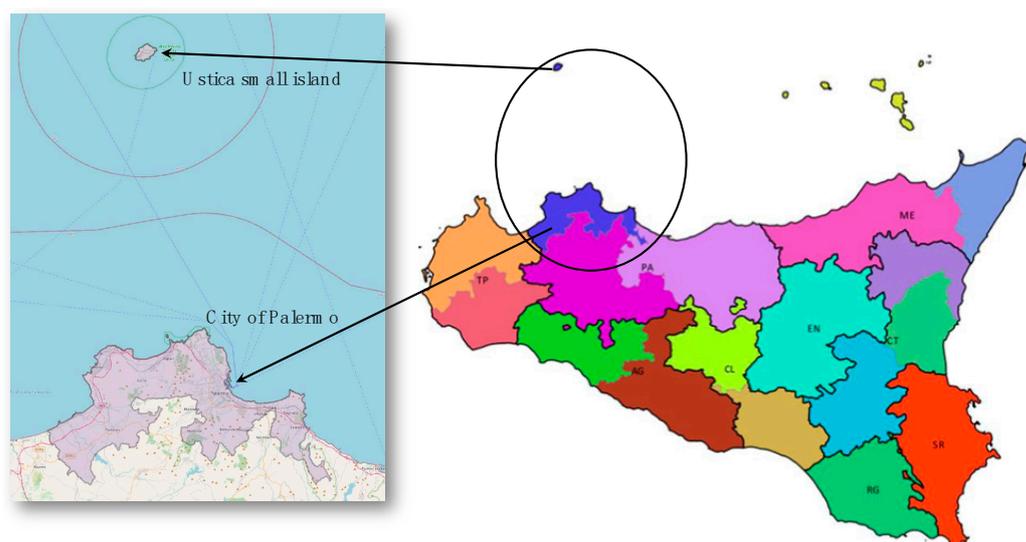

Figure 1. The "Ambito Territoriale Ottimale" (ATO) PA3, where the integrated waste management plan is implemented.

The actual total amount of waste produced annually is 470,827 tons, for a population of 683,794 inhabitants living on a territorial area of 160 km^2, including the city of Palermo (whose area is 151.5 km^2) and the small island of Ustica (whose area is 8.5 km^2) [23].

An improvement of the current waste management scheme is currently being analyzed to intercept approximately 37% of the recyclable materials produced in the area, namely paper and cardboard, glass, plastics, metals, and organic waste. In the present situation, only 7% of these materials are recycled. Table 2 shows the yearly quantities of materials contained in the urban waste of Palermo and the recycled quantities in the cases of 7% (actual situation) and 37% (foreseen situation) of recovery.

As aforementioned, the EF is expressed in terms of the bioproductive land area required for the entire urban waste management. "Land for energy" (SFP) and "built-up land" (ES) are the categories of ecological surface mainly involved in the application of the EF method in the present case, since soil, pasture, forest, and productive marine areas are not of interest of the analyzed waste system.

Table 2. Yearly production of recyclable materials in the cases of 7% and 37% recycling [23].

Material	Total (t/y)	7% Rec. (t/y)	37% Rec. (t/y)
Paper	79,279	5550	29,333
Glass	18,018	1261	6667
Plastic	54,054	3784	20,000
Metals	9009	631	3333
Organic	144,144	10,090	53,333

The three fundamental waste chain stages, i.e., collection, transport, and disposal, were considered separately in order to identify the EFs of each segment to usefully compare the relative performances.

The relationship used to evaluate the "land for energy" (SFP_i) for each ecological space (land) category is:

$$SFP_i = R_i \times CF_i \times QF_{SFP} \times C_{U,j} \tag{1}$$

where R_i is a parameter used to evaluate the impact of single stages or sub-stages (unit of measure x), CF_i is a conversion factor depending on the R_i parameter (tC/x or tCO$_2$/x), QF_{SFP} is the "land for energy" equivalence factor (-), $C_{U,j}$ is Carbon dioxide (CO$_2$) or only the Carbon (C) uptake rate (hectars/tC or hectars/tCO$_2$), i-subscript is the stage or sub-stage analyzed, and j-subscript is CO$_2$ or C.

Meanwhile, the formula used for the "built-up land" (ES) is:

$$ES_i = T_i \times QF_{ES} \times PF \tag{2}$$

where T_i is a parameter used to evaluate the impact of the single stages or sub-stages (unit of measure ha) and PF is the local productivity of each land category comparable with global averages.

With regards to the waste-gathering phase, "land for energy", SFP_G, is expected to sequester the CO$_2$ emissions related to the dumpster life cycle, while the "built-up land" is associated with the harvesting phase, ES_G, including the entire built-up space used by them. Hence, SFP_G can be evaluated with the following relation:

$$SFP_G = R_G \times CF_G \times QF_{SFP} \times C_{U,CO2} \tag{3}$$

where R_G ($= N_d \times M_d \times E_I$) is given as the product of the number of dumpsters (N_d), the quantity of material of which the dumpsters are made (M_d), and the energy intensity of such materials (E_I). CF_G is, in this case, the fossil fuels' carbon intensity and QF_{SFP} is the equivalence factor for forested land for energy. In the case reported in this work, the energy intensity E_I has been set as equal to 50 MJ/kg for plastic and 187 MJ/kg for galvanized aluminum [60], QF_G is assumed to be 1.17 [49], and the carbon sink rate $C_{U,CO2}$ is 0.192 ha/kgCO$_2$ [51].

Meanwhile, ES_G, which mainly refers to the area of urban land occupied by bins, can be assessed with the following relation:

$$ES_G = T_G \times QF_{ES} \times PF \tag{4}$$

where T_G is the total area occupied by the bins, QF_{ES} is equal to the real biocapacity of the country, and PF is equal to the local productivity of the built land category.

The assumption of the area occupied by the dumpsters as the "built-up" area might appear to be accounted for twice, given that the roadways are built-up areas themselves, but its calculation is justified because it is a portion of the roadway that is used exclusively for the waste collection service.

Most of the EF of the waste transportation phase of the MSWMS is attributable to the quantity of energy employed in building, maintaining, and powering the vehicles used to

transport waste. From these amounts of energy, it is possible to derive the associated CO_2 emissions and convert them into the relevant land area needed to sequester the emitted carbon. Rees and Wackernagel [48] provide a way to make a rough estimate of the energy needed to construct and maintain a vehicle, by means of an incremental percentage factor; that is, the increment of the energy required to fuel a vehicle of 15% for its construction and maintenance, plus a 30% additional rate for the construction and maintenance of the roads infrastructures. Hence, the land for the energy of road transportation, SFP_{TR}, can be calculated as follows:

$$SFP_{TR} = R_{TR} \times CF_{TR} \times QF_{SFP} \times C_{U,C} \tag{5}$$

where R_{TR} (=$F_C \times F_I \times BF$) is given as the product of the annual fuel consumption of the vehicles that make up the waste collection fleet (F_C), the fuel energy intensity (F_I), and the boosting factor, which roughly accounts for the embodied energy of the vehicles involved in transporting waste and building and maintaining the roads travelled (BF), CF_{TR} is the amount of carbon emitted for energy consumption, and QF_{SFP} is the equivalence factor for "land for energy". In this case , F_I is set as equal to 33.0 MJ/L for gasoline and 36.7 MJ/L for diesel fuel.

"Built-up land" must also be taken into account to establish the rate of road area attributable to waste transfer, and is given by:

$$ES_{TR} = T_{TR} \times QF_{ES} \times PF \tag{6}$$

where T_{TR} (=$P_{OR} \times S_S$) is given as the product of the statistical percentage (P_{OR}) of the street surface occupied by vehicles transporting waste in the considered system and the road area (S_S), while QF_{ES} and PF are the same as the parameters used in the case of the gathering system. The road surface area affected by waste transport has been estimated as almost 90% of the entire road system of the city of Palermo since, in the current configuration of the system, almost all urban roads are affected by the service. However, in reference to the waste transport phase, it must be taken into account that the small island of Ustica is part of the urban service provided by the Municipality of Palermo. Therefore, ships transporting waste from Ustica to the port of Palermo were also considered, i.e., the land for energy for waste transport by ship, SFP_{TS}:

$$SFP_{TS} = R_{TS} \times CF_{TS} \times QF_{SFP,\,SEA} \times C_{U,C} \tag{7}$$

where R_{TS} (=$D_{TS} \times W_{TS} \times 0.27$) is given as the product of the average covered distance (D_{TS}), the amount of waste transported annually by the plan's system (W_{TS}), and 0.27 is the ratio of the atomic weight of carbon to the molecular weight of CO_2. CF_{TS} is the mass of CO_2 emitted by an average-sized ferry per km traveled and per ton of product transported, as it was originally released by the Stockholm Environmental Institute [61].

The values of D_{TS}, W_{TS}, and CF_{TS} are approximately 75 km, 584 tons, and 10.5 gCO_2/km per ton of waste, respectively.

Meanwhile, with reference to the disposal of waste into landfills, this was analyzed in terms of related facilities, taking into account the amount of land area occupied and the consumption of primary energy (fuels) and electricity employed in their operational activities. The relevant surface types of bioproduction areas have been assessed in terms of land for energy and built-up land. In particular, the "land for energy" for the disposal phase in the case of electricity, SFP_{DE}, and thermal energy, SFP_{DF}, can be expressed as follows:

$$SFP_{DE} = R_{DE} \times CF_{DE} \times QF_{SFP} \times C_{U,C} \tag{8}$$

$$SFP_{DF} = R_{DF} \times CF_{DF} \times QF_{SFP} \times C_{U,C} \tag{9}$$

where R_{DE} (=$EL_C \times F_e$) is given as the product of the annual electricity consumption (EL_C) and the amount of fuel used for generating the unit of electric energy (F_e), while R_{DF} (=$TC \times F_t$) is given as the product of thermal energy (fossil fuel) consumption (TC) and the

amount of fuel used for generating the unit of thermal energy (F_t). The conversion factors (CF_{DE} and CF_{DF}) are the carbon rates with respect to the fossil fuel used.

The "built-up land" relevant to the disposal system, ES_D, can be calculated as follows:

$$ES_D = T_D \times QF_{ES} \times PF \tag{10}$$

where T_D is equal to the landfill surface.

3. Results

Once the single-impact components have been calculated, the overall EF value can be obtained by simply adding the *SFP* (ha) values associated with each individual waste management system phase for the Palermo–Ustica land context, as shown in Table 3.

Table 3. Ecological footprint (ha) of the current MSWMS.

	Gathering	Transportation	Disposal	Total
SFP (ha)	2740	3139	382	6261
ES (ha)	9	47	14	70
Total [*EF* = *SFP* + *ES*] (ha)	2749	3186	396	6331
Phases percentage (%)	43.42	50.33	6.25	100

As can be seen, the transport segment, which is usually underestimated, is the one causing the greatest impact on Palermo's current MSWMS. This rate, indeed, represents over half of the overall environmental impact of the urban management system for the considered municipality. Clearly, this result is affected by the specific distance travelled by the trucks to bring the gathered waste to the landfill; however, since landfills are often located far from city centers, municipal wastes are in any case subjected to some travel for their disposal.

This estimate is subjected to certain simplifying assumptions. In fact, for simplicity, the same recycling rate was assumed for all types of materials. Furthermore, following the approach reported in [49], it was also assumed that the ecological (saved) footprint per ton of recycled material (ha/t) is evaluated on the basis of the average values reported in Table 4. Since these data refer to global mean values, they may not perfectly fit the Palermo MSWMS situation. However, this simplified approach allows us to make a quick, albeit rough, estimate of the environmental performance of the recycling system; as more precise information becomes attainable, it will be possible, using the EF method, to improve the analysis accordingly.

Table 4. Average values of the ecological footprint for the considered materials [51].

Material	Paper	Glass	Plastic	Metals	Organic
EF (ha/t)	2.45	0.85	3.85	0.65	0.85

As previously reported, the municipal administration is currently revising the "Integrated Plan" in order to increase the quantity of recycled material up to 37% against the current value of 7%. Therefore, the new management system assumed will feature considerable enhancement of the recycling chain. This includes increasing the number of waste recycling bins, whereby some of them will be distributed along urban streets while others will be employed for door-to-door collection. Moreover, the waste transport will involve, in addition to the remaining non-recycled part, the newly selected dry materials (paper and cardboard, glass, plastic, metals and organic waste) that will have to be delivered to the newly designed technological treatment platforms. Finally, a new technological site is also planned for composting the organic portion of the recycled waste. Table 5 shows the carbon footprint of the upgraded MSWMS.

Table 5. Ecological footprint (ha) of the upcoming improved MSWMS.

	Gathering	Transportation	Disposal	Total
SFP (ha)	2588	2539	733	5860
ES (ha)	7	47	42	96
Total [*EF = SFP + ES*] (ha)	2595	2586	775	5956
Phases percentage (%)	43.57	43.42	13.01	100

4. Discussion

Initially, it is important to provide justification for the method adopted here and to contextualize its novelty in the current scientific panorama. Indeed, the approach chosen here differs from those mainly present in the literature in two ways. First of all, we aimed to highlight the role of the transport phase in an MSWMS. The application provided, which refers to the case of the large city of Palermo, in Sicily, confirms that it is not possible to neglect the transport phase when assessing the overall environmental impact of such systems. In this case, its relative weight was approximately 50% in the current situation and 43% in the improved service configuration. The other novelty in the current research landscape was the choice of the EF method for assessing the overall environmental impact of the municipal waste management system.

In fact, some studies have proposed the analysis of the environmental pressure exerted by such complex systems: Most of them have turned their attention to the LCA method [62–66]. This method, as it is known, provides a useful estimate of the potential environmental pressures exerted on some key impact categories, thus indicating the role played by the system under study on climate change. Other studies have focused on the carbon footprint of waste collection scenarios [35], but their approach, in addition to being based on the LCA method of vehicles and fuels used, was primarily geared toward assessing the weight of the vehicle fleet in relation to the national transportation landscape and not the relative weight of the transportation phase compared to the other phases of waste management. Furthermore, other studies, based on experimental investigations [67,68], have evaluated the effects due to the change of fuel of some vehicles of a fleet of trucks devoted to the waste gathering in the city of Milan, without going as far as the comparative evaluation of the waste transport phase with respect to the other phases of their management.

On the contrary, our aim was to provide an integrated and easily comparable assessment of the waste handling system, in order to also compare different scenarios of the same system by means of a single indicator. For this reason, we turned to the EF method, which, besides being widely used in the scientific community and having been applied to various systems and territorial areas, provides a holistic view of the environmental performance of a given system by assessing the area of the bio-productive land and bio-productive sea surface "sequestered" by that system.

The outcomes of our analysis showed that the valorization of the recycled fraction of municipal waste will improve the environmental performance of the entire system (as illustrated in Figure 2), but some considerations must be made about every single segment of the new waste management chain.

Firstly, the increase in the value of the "built-up land", particularly in the disposal segment, needs some clarification. In fact, the structural changes of interest in the existing condition are supposed to involve the installation of four new sites for the treatment of the recycled materials. In fact, the improvement of the "Integrated Plan" adds to the existing landfills, which represent the only disposal system at the moment, facilities for the composting, sorting, recovery, and treatment of bulky materials, which, of course, leads to an increase in the value of the built land of the system in the regime.

Even in this improved scenario, the contribution of waste transport to the environmental impact of the whole system is still significant, representing approximately 43% of the whole treatment chain. The differences can be essentially attributed to the change in the number and capacity of waste collection bins and the modification of the number

and typologies of vehicles that are intended to transport waste and recycled materials from the collection points to the new treatment sites. From a carbon footprint perspective, this new waste management system implies different fuel consumption by the vehicles, different types and amounts of materials, and the related embodied energy required for the construction of new garbage bins and new vehicles; and, finally, larger areas of built-up land for the allocation of new bins used by new vehicles along their routes.
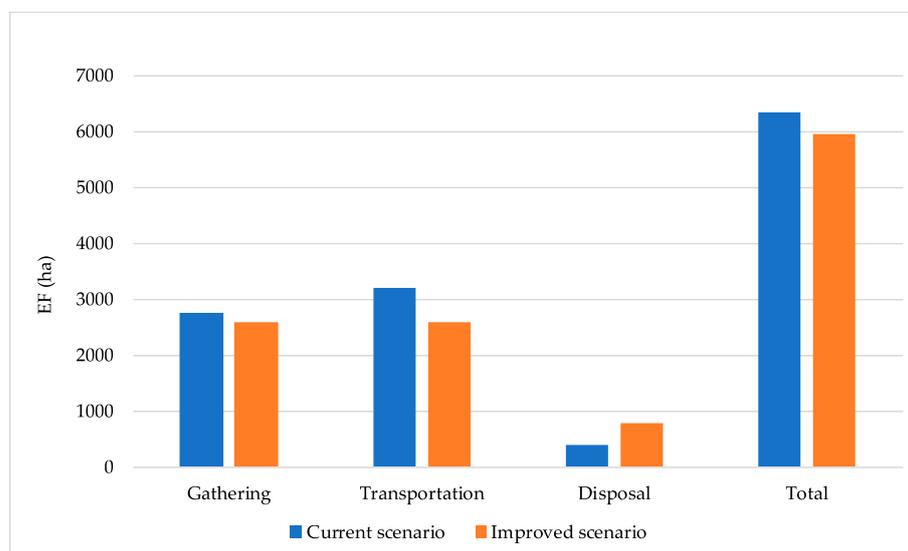

Figure 2. Ecological footprint, by phases, of current and improved scenarios.

In detail, the increase in the separated portion of waste and the corresponding decrease in its unsorted portion leads to a considerable modification in the typologies of vehicles required for waste gathering. Specifically, in this case, wider use of garbage bins, instead of dustbins, is required. Interestingly, the average fuel consumption for carried bins is approximately 9 km/L, compared to a value of only 1 km/L for garbage trucks.

However, some further considerations are necessary regarding this important phase of urban waste management. First of all, it is assumed that the distances covered by the trucks and ships for each run do not substantially change; moreover, it is assumed that the vehicles adopted in the new configuration of the system show the same average fuel consumption. Obviously, the fuel consumption of the remaining vehicles in the truck park is assumed to be unchanged. To summarize, the fuel consumption involved in the new scenario refers to three categories of vehicles: (a) The vehicles adopted for collecting the recycled materials, (b) the new vehicles introduced for non-specific gathering, and (c) the old remaining vehicles.

Moreover, it is assumed that the "built-up land" of the transportation segment involved in the movement of (recycled and non-recycled) waste does not change, considering that a comparable percentage of roadways travelled by vehicles can be rationally hypothesized for the ones operating in the current system and for those supposed to operate in the improved planned system.

With regard to the waste transport from the small island of Ustica to Palermo, currently carried out by ship, no changes between the current and the final improved conditions have been assumed. In fact, only the proportion between differentiated (expected increase) and undifferentiated (expected decrease) waste portions will be modified, but the overall annual quantity is supposed to remain unchanged and transported by the same ferry. Consequently, the annual quantity carried by the same ferry will remain almost the same. Therefore, the fuel consumption (hence, the related air pollutant emissions) will remain almost unchanged.

A comparison between the EFs of the improved and current systems is shown in Figure 3, broken down by the types of bio-productive land areas involved.
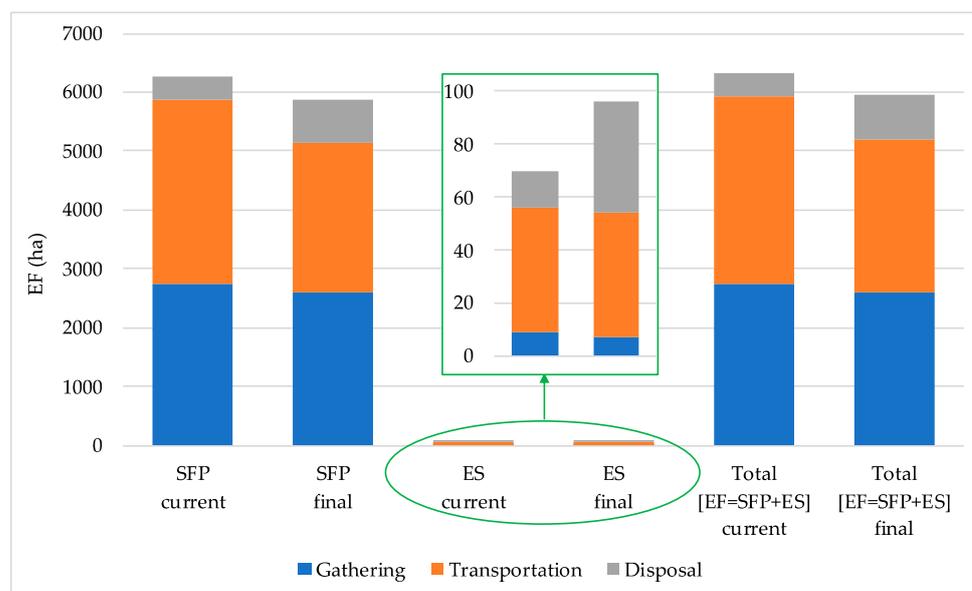
Figure 3. EFs, by land categories: Comparison between current and final improved scenarios.

However, apart from the calculation of the EF referring to the waste management system, both in the current and improved schemes, the EF saved by the increase in the amount of recycled material should also be considered. Table 6 summarizes the comparison of the saved footprints directly attributable to the change in the recycling performances of the system under both conditions.

Table 6. Saved footprint in the current situation and in the case of improved recycling.

Material	Total Content Theoretical EF (ha)	7% Rec. Saved EF (ha)	37% Rec. Saved EF (ha)
Paper	194,234	13,596	71,866
Glass	15,315	1072	5667
Plastic	208,108	14,568	77,000
Metals	5856	410	2167
Organic	122,522	8577	45,333

The so-called theoretical EF reported in Table 6 refers to the whole impact exerted by the recyclable materials contained in the gathered waste, including the quantity of virgin materials and the amount of energy needed to produce them, and does not take into account the EF produced by the landfill and its gathering and transportation systems. By increasing the amount of material attended to by recycling, the theoretical EF is obviously reduced, since no virgin material is used or processed to obtain "second life" materials. Therefore, with the actual 7% rate of average recycling, only 38,222 ha (of the total 546,035 ha) are saved, while with the enhanced recycling rate of 37%, this saved EF accounts for up to 202,033 ha. In other words, the whole impact of the materials present in the waste bulk is reduced to the values of 507,812 ha and 344,002 ha for the rates of 7% and 37%, respectively. Regarding the original (theoretical) impact of 546,035 ha of EF exerted by the materials, it must be observed that, although relevant, this figure should be compared with the total EF of Sicily, accounting for approximately 15,780,000 ha (computed on the base of the average EF of the Italian population, that is, approximately 3.11 ha/inh.), vs. a total physical surface of 2,570,200 ha of the island. Clearly, the bio-productive land involved in the production of the considered materials, strictly speaking, should not be totally imputed to the Sicilian territory, since the extraction, working processes, and transportation of these materials are likely based in other regions and/or countries. Nevertheless, this comparison is certainly

well representative of the strong environmental impact on the planet of the management of the waste, particularly when these materials are conferred to landfills, without any (or with a low rate of) recycling.

5. Conclusions

The applicative demonstration of the proposed EF method to the Municipality of Palermo has made it possible to easily highlight the weight of the waste transportation phase in the assessment of the environmental impact caused by an MSWMS. Such weight is significant since it resulted in an average of almost 50% of the entire waste management chain. Furthermore, in relation to the new improved scenario, in which the percentage of recycled waste is substantially higher, the weight of transport is still significant, being more than 40% of the whole impact. This suggests that deep consideration should be given to the way in which the waste movement is operated in a given management system. In fact, the number and type of trucks and bins should be properly designed, appropriately taking into account their environmental performance.

Beyond what emerges from this application to the city of Palermo, the EF method can certainly be replicated in different geographical situations and other cities. It is based, in fact, on a methodology, such as the ecological footprint, which is perfectly in line with the principles of sustainability envisaged by the Millennium Goals, which have general validity at a planetary level. Obviously, the replicability of the method to other Italian cities is made even more evident by the similarity of their regulations with those of Palermo.

Another outcome of the present work concerns the validation of the feasibility of the proposed EF method in capturing the pressure level exerted on natural resources, allowing a comparison between such an impact and the carrying capacity of the involved territory. The applicative demonstration presented here, regarding an integrated waste management system for the Municipality of Palermo and the small island of Ustica, has evidently shown that the computation scheme adopted for the EF model is rather easy to apply and should be easily managed by technicians. In fact, it was possible to analyze the MSWMS starting from just the data on energy consumption and material flows, by simply using some conversion factors and the related amount of embodied energy. Obviously, the reliability of the method is based on the correctness of the available data, whose consistency is not always guaranteed. This is actually the major limitation of the method.

Moreover, it must be emphasized that the proposed EF method does not make it possible to analyze and "capture" other important factors of the whole impact of a given system, for example, pollutant emissions, with the exception of CO_2, or social aspects, such as the level of employment assured by a given system or the level of human healthiness assured to workers and the population. Finally, it should also be underlined that it is impossible to analyze "collateral" phenomena related to the facilities, such as malodorous releases from landfills, the noise produced by sorting and recovery facilities, and, finally, social approval of the entire system by the involved stakeholders.

Conversely, while it is true that the use of several different indicators provides the ability to analyze, in detail, different aspects connected to the use of products and the management of systems, they often obtain disjointed results whose comparability is sometimes difficult. In this regard, the EF—besides confirming the important role of the transportation phase in the management of urban waste—has also proven, in this case, to be a valuable "joint" indicator. In fact, it would allow simple and effective analysis of the relationships among diverse ecological functions and the synergy between different kinds of pressures exerted on the natural environment, for example, biodiversity, land erosion, water scarcity, and CO_2 increases. Therefore, central governments and local administrations should be engaged in the systematic gathering of data relevant to performing the accurate analyses required by the EF method.

In conclusion, the scientific novelty of the work lies mainly in pointing out the importance of considering the waste transport phase in the overall assessment of the environmental performance of MSWMSs. This aspect, in fact, had only been scarcely mentioned in the

scientific literature of the sector. At the same time, the work has shown the practicability of the EF method in analyzing the environmental impact of waste movement, thus making it possible to achieve an integrated assessment, by means of a single indicator, of a system of great importance in the management of the services that municipalities are called upon to provide to their citizens.

Abbreviation

Parameter	Meaning	Unit
BF	Boosting energy factor for vehicles construction, maintenance and waste transportation	%
CF	Conversion factor	tC/x * or tCO$_2$/x *
C_U	Carbon uptake rate	ha/tCO$_2$ or ha/tC
D_{TS}	Average distance waste transportation by ship	km
EF	Ecological Footprint	ha
E_I	Energy intensity of materials	MJ/kg
EL_C	Annual electricity consumption	MJ
ES_D	"Built-up land" pertinent to the disposal system	ha
ES_G	"Built-up land" pertinent to the collection phase	ha
ES_{TR}	"Built-up land" pertinent to the waste transference	ha
F_C	Fuel consumption for running waste collection fleet	L
F_e	Amount of fuel used for generating the unit of electric energy	L/MJ
F_I	Fuel energy intensity	MJ/L
F_t	Amount of fuel used for generating the unit of thermal energy	L/MJ
M_d	Amount of materials of which bins are constituted	kg
N_d	Number of wheelie bins for the collection phase	-
PF	Factor of performance of the "built-up land"	-
P_{OR}	Statistical percentage of road surface occupied by garbage trucks	%
QF_{ES}	Factor of equivalence of "built-up land"	-
QF_{SFP}	Factor of equivalence of forested land for energy	-
$QF_{SFP,\,SEA}$	Factor of equivalence of land for energy for productive sea	-
SFP_{DE}	"Land for electric energy" for disposal phase	ha
SFP_{DF}	"Land for energy" (fossil fuel energy) for disposal phase	ha
SFP_G	"Land for energy" for collection phase	ha
SFP_{TR}	"Land for energy" for road transportation phase	ha
SFP_{TS}	"Land for energy" for transportation phase by ship	ha
S_S	Street surface occupied by carbage trucks from collection areas to the disposal points	ha
TC	Thermal energy consumption	MJ
T_D	Landfill surface	ha
T_G	Total surface occupied by bins	ha
W_{TS}	Amount of waste yearly transported by ship	tons

* where x is the unit of measure related to parameter *Ri* of Equation (1).

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