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Combined Use of an Information System and LCA Approach to Assess the Performances of a Solid Waste Management System

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Abstract: A municipal solid waste information system, named W-MySir, is utilised to acquire high-quality data to implement an attributional life-cycle assessment (LCA) focused on the evolution of the environmental performances of municipal solid waste management in a specific area. The main aim was to investigate how this combined approach can be used for monitoring progress of the management scheme toward important targets, such as being CO_2-neutral, increasing the circularity of the service, and planning a transparent approach to cost evaluation. The analysis was applied to the municipality of Procida, one of the three islands of Naples Bay (Italy), and focused on the last ten years of activity of the local solid waste service. The results of the life cycle impact assessment are reported in terms of the main impact categories. They indicate a positive evolution of the environmental performances, with improvements of up to 140% for global warming potential. The positive results are mainly due to the large increase in household source separation and separate collection in Procida during the period under analysis, together with the availability of a more integrated and sustainable regional system of solid waste management. Further improvements may be achieved through better performance at the sorting and remanufacturing stages of dry recyclable fractions and the availability of anaerobic digestion units to produce biomethane from organic fractions of municipal solid waste. The combined approach indicates potential further benefits for both the tools: LCAs could provide reliable results in shorter times; information systems could offer a wider spectrum of services for monitoring and planning waste management systems in a sustainable way.

Keywords: waste information system; waste traceability; life-cycle assessment; sustainable waste management; improved communication

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Citation: Ardolino, F.; Parrillo, F.; Di Domenico, C.; Costarella, F.; Arena, U. Combined Use of an Information System and LCA Approach to Assess the Performances of a Solid Waste Management System. *Appl. Sci.* **2023**, *13*, 707. https://doi.org/10.3390/app13020707

Academic Editor: Apostolos Giannis

Received: 30 November 2022
Revised: 28 December 2022
Accepted: 29 December 2022
Published: 4 January 2023

1. Introduction

W-MySir is an information system for waste traceability, provided since 2005 by Microambiente srl (https://wmysir.com/, accessed on 30 December 2022), which received the support of Conai, the Italian National Packaging Consortium (www.conai.org/en, accessed on 30 December 2022), for implementation in some Italian regions. The system provides comprehensive free information to local administrations, private companies, and citizens. It follows the pathways of the different fractions of municipal solid waste (MSW), each identified by its European waste code (EWC). This traceability is coupled with analytical quantification of waste streams, identification of selected treatment plants, and a series of other types of data and information that enable citizens and local administrations to obtain a continuous and complete picture of the current state of MSW management. Data obtainable from the W-MySir platform are all certified values coming from authorities (mainly the technical offices of various municipalities). The information system processes the data, making them available in the same format, producing figures and tables to make them more readable, and allowing comparisons between different years of management and different categories of solid wastes. The platform is largely utilised by municipalities to monitor the quantitative and qualitative degree of separate collections in their area of competence. It is also used to ensure compliance with Italian and European laws by producing all the required reports related to MSW management. The system is currently adopted in a large part of the south of Italy (in almost all the municipalities of the Campania and Calabria regions and in the majority of those of the Puglia region).

The scientific literature highlights the crucial role of high-quality data to develop reliable life-cycle assessment (LCA) studies, particularly in the waste-management sector [1–3]. Data contained in the W-MySir platform appear particularly suitable to support this kind of study, which the European Union considers to be the best way to quantitatively assess the environmental performance of a good or service [4]. W-MySir provides certified data about amounts gathered by municipal waste streams, the related percentages for separate collection, the number of journeys specifically made for each EWC, together with other information related to the transport (e.g., distance covered, type of vehicle, its identification, shipping certificate, company name) and destination (e.g., location, type of treatment). These data can also be used as a reliable basis to assess, from a life-cycle perspective, the performances of different MSW management scenarios related to different areas in a specific time, or to the same area at different time intervals. In other words, data obtainable from W-MySir, when properly processed, can be combined with the LCA procedure to provide a comprehensive understanding of an existing waste-management system, and to identify possible areas for further improvement. If the focus is on a specific municipality, data related to different years can also be used to analyse the evolution of the WM system, to quantify its environmental performances, and to evaluate whether the adopted criteria have produced the expected results. Figure 1 schematically describes the flow of data between the W-MySir platform and the proposed LCA case study, which refers to municipal solid waste management in 2011 and 2021 in the municipality of the island of Procida, one of the three islands (together with Ischia and Capri) of Naples Bay. An example of the data types that can be provided by the information system is reported in the tables and diagrams of ANNEX A.

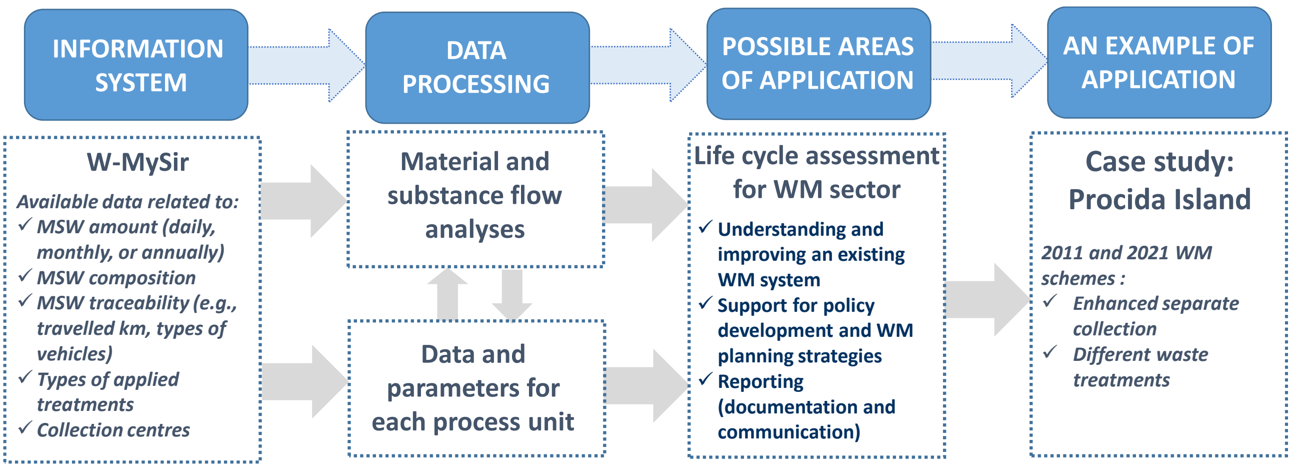

Figure 1. Data flows between the solid waste information system and the proposed LCA study.

The proposed case study represents a typical application of LCA in integrated waste management, which Christensen et al. [5] described as "Reporting (documentation and communication)", meaning being able to provide "comprehensive quantification of recovered materials and energy and of the potential impacts on the environments including loads and savings. This can be based on specific yearly data and as such provide quantitative information for annual reporting and thereby provide a basis for monitoring progress toward future targets, for example of being CO_2-neutral". The paper aims to highlight the importance of information systems in assessing the performances of waste management services. It describes how a well-structured and updated information system can support a municipality in a series of activities relating to monitoring and planning. The proposed combined use with LCAs can provide local government (municipality, but also larger districts) decision-makers with reliable and comprehensive data. These could be used to quantify the sustainability of their own waste-management scheme, but also to design and incorporate further improvements aimed at optimising overall environmental performance.

2. A Case Study for the MSW Management of the Procida Island

2.1. The System under Analysis and the Functional Unit

The study utilised an attributional, process-based approach, meaning that it accounted for impacts that directly relate to the system under analysis and to its activities. The standard guidelines of ISO 14044 [6] were used as a main reference. The stage of "Goal and Scope Definition" identified the "*system to be studied*" as the management scheme of the Procida municipality, starting from waste separate collection through to the recovery of secondary resources and the disposal of residues. The "*function of the systems under analysis*" was the management of solid waste generated in Procida in 2011 and 2021 (Figure 2) and gathered by a separate collection system. The focus was on the main waste streams, those concerning the organic fraction (namely, biowaste), dry recyclables (paper, plastics, metals, and glass), and unsorted residual waste (URW, to be sent for thermal treatment or landfilling). This excluded some minor waste streams (less than 10% of MSW, as shown in ANNEX A), such as bulky waste, WEEE, and textiles, the management of which is determined according to national criteria and is not affected by the performances of a local management scheme. The aim was to investigate the potential improvement achieved by the waste management scheme adopted over the last 10 years, with particular attention to end-of-life packaging of interest for Conai. The "*functional unit*" was the treatment of one tonne of MSW collected in Procida, following the suggestion of [5], with the aim of monitoring management and technology improvements, without the possible effects of different waste-generation rates.

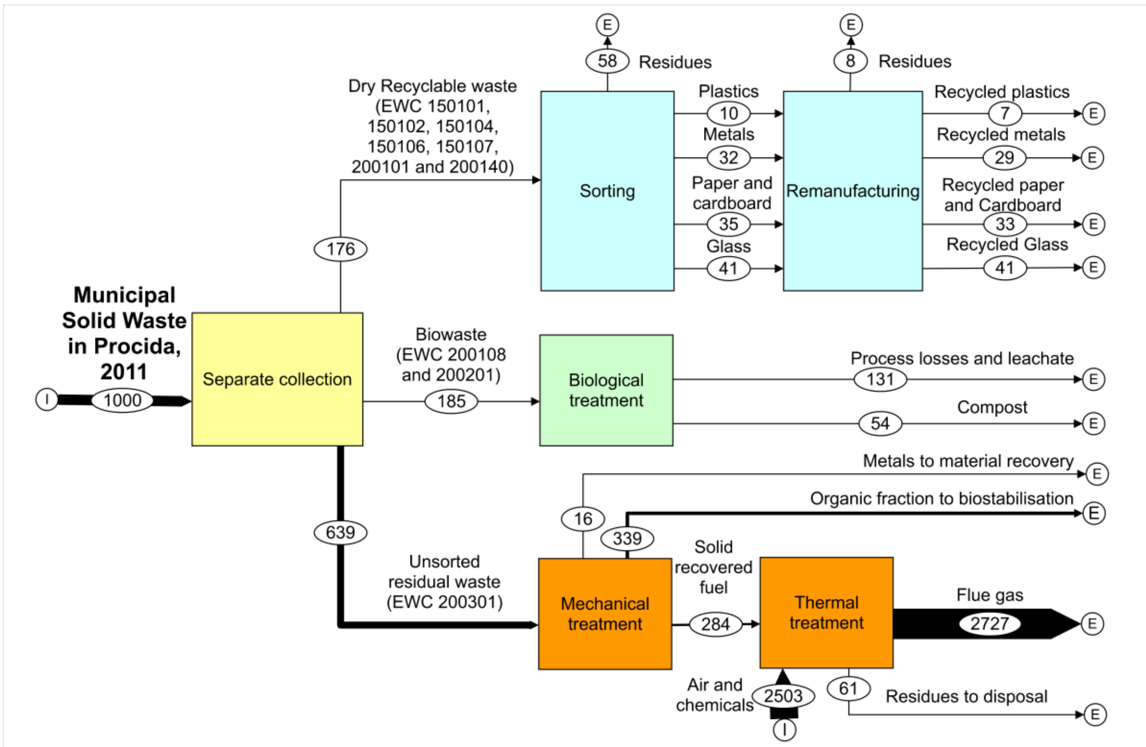

Figure 2. *Cont.*

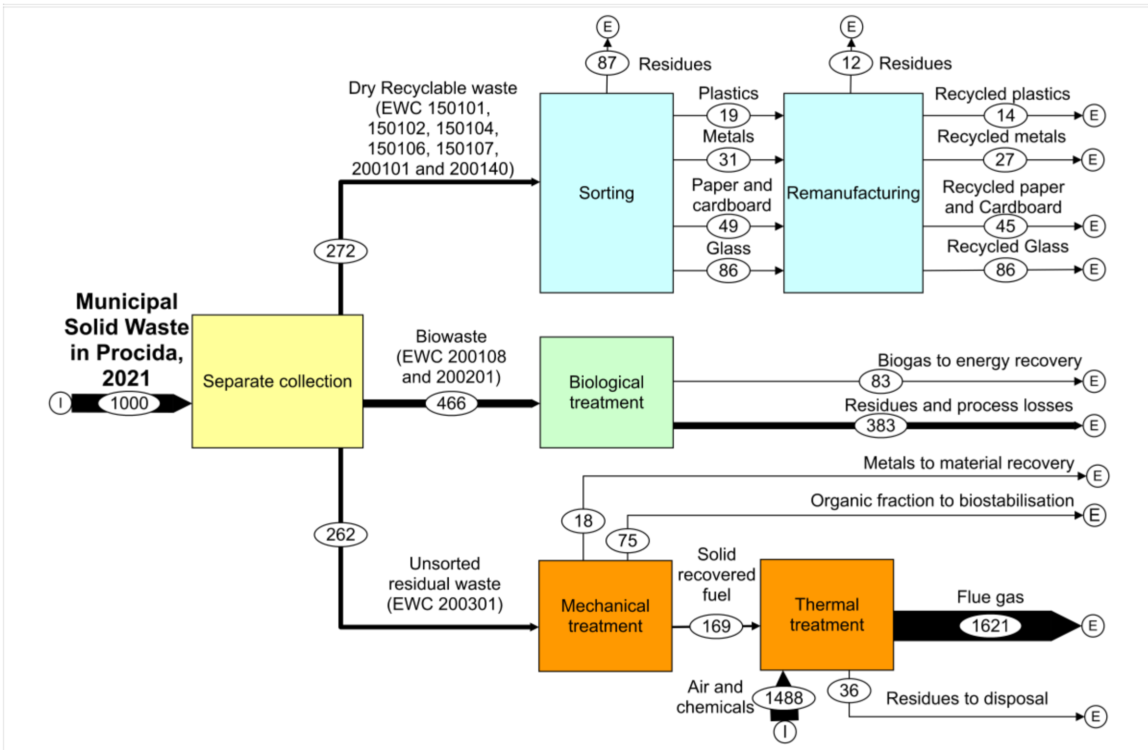

Figure 2. Quantified flow sheet of MSW management in Procida in 2011 (**top**) and 2021 (**bottom**), with reference to functional unit. Data are expressed in kg. EWC: European waste code; I: import; E: export. Data Source: W-MySir [7].

The reference composition as obtained is reported in Figure 3, starting from the compositions of all the separately collected waste streams (as available on W-MySir) and that of URW (obtained by combining the composition of URW in input to the waste-to-energy (WtE) unit active in Campania [3], coupled with the separation efficiencies of the material recovery facility, MRF, active in the same regional area [8]). Most of data were acquired by the W-MySir platform, with the support of Conai, who provided data related to the selection and remanufacturing residues of the main recycling chains, indicating that the "*quality of data*" was quite high. Moreover, an extended analysis of scientific and technical studies was carried out to estimate and compare all the direct and avoided environmental burdens. The Ecoinvent databank v.3.6 [9] was used to quantify the indirect burdens, while those related to the infrastructures were not considered.

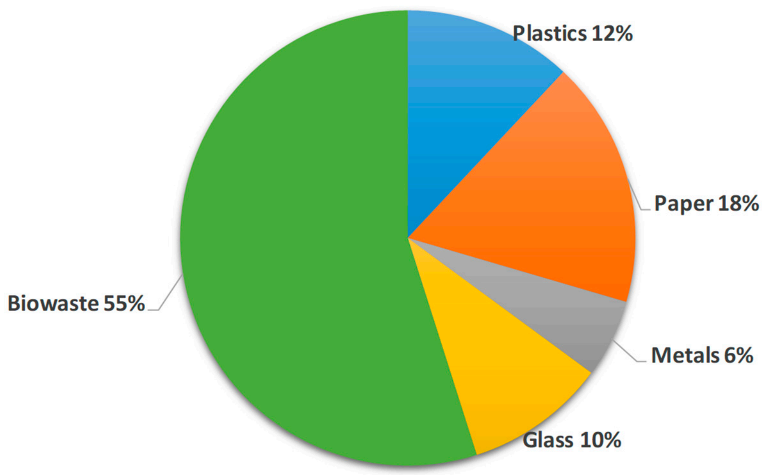

Figure 3. Reference composition for the functional unit of the study. Adapted from: W-MySir [7].

The system expansion methodology (also known as the "avoided burdens method") was used to solve the "*allocation problem*". In other words, as performed in previous studies [10], the products that were replaced on the markets by the obtained co-products (e.g., recycled plastics, metals, glass, and paper, as well as recovered energy) were identified and their substitution was included in the model. The study evaluated the substitution potential γ of an available market product with a recovered resource as the product of four parameters: $\gamma = U \cdot \eta \cdot \alpha \cdot \pi$, as recommended by Vadenbo et al. [11]. These parameters are the potential physical amount of the secondary resource (U); the recovery efficiency of this resource (η), depending on the waste treatment option; the substitutability (α), representing the functionality of the recovered resource with reference to the conventional resource; and the market response (π), which is the share of secondary resource that can effectively substitute the conventional product already available on the market. The Italian electricity mix of 2011 and 2020 was utilised to evaluate the avoided burdens related to the exported electricity [12]. Impact 2002+ [13] was used as the "*LCIA methodology*", while the software package used was SimaPro© 9.4 [14]. The study is valid with respect to the specific conditions and hypotheses described above.

2.2. Life Cycle Inventory

The life cycle inventory (LCI) stage was carried out by coupling Procida management data provided by W-MySir with literature data and parameters for each process unit. The information system provided data about Procida's MSW amount and composition and indicated the types of adopted process units (Figure 2), also quantifying the related distances. These data, together with those available in the scientific literature for units operating in the area of interest, were processed by means of material flow analysis to quantify all the environmental burdens.

Dry recyclable waste. The management of separately collected dry recyclable waste (including plastics, glass, paper, metal) requires several stages of sorting and remanufacturing and involves different input compositions, sorting and remanufacturing efficiencies of each material, as well as substitutability factors for the recovered fractions [15], as reported in Table 1. These input parameters were utilised, together with quantified flow sheets, to estimate environmental burdens related to the management of separately collected dry recyclable waste, which includes material and energy supply as well as recovered resources, as reported in Table 2. National average data about waste compositions and efficiencies of the sorting and remanufacturing phases were obtained from official reports published by the network of consortia belonging to Conai, which coordinates the management of all types of Italian packaging wastes [16–20]. These data were then coupled with those from the literature [21–23] when necessary.

Table 1. Input parameters utilised together with quantified flow sheets to estimate the environmental burdens related to management of separately collected dry recyclable waste.

Separately Collected Fraction	Input Composition to Sorting	Sorting Efficiency	Input Composition to Remanufacturing	Remanufacturing Efficiency	Substitutability
Plastics [1]					
Plastic packaging	90%	60%	-	-	-
Other fractions	10%	-	-	-	-
PET	-	-	35%	81%	0.95
HDPE	-	-	9%	88%	0.91
LDPE	-	-	18%	59%	0.91
PP	-	-	8%	66%	0.83
PS	-	-	1%	66%	0.79
Mixed plastics [2]	-	-	29%	-	-

Table 1. *Cont.*

Separately Collected Fraction	Input Composition to Sorting	Sorting Efficiency	Input Composition to Remanufacturing	Remanufacturing Efficiency	Substitutability
Paper [3]					
Paper and cardboard packaging	49%	95%	-	-	-
Other fractions	51%	-	-	-	-
Paper to testliner	-	-	56%	95%	0.9
Paper to newspapers	-	-	44%	90%	0.94
Glass [4]					
Glass	100%	90%	100%	100%	1
Metals [5]					
Fe	82%	83%	83%	88%	1
Non-Fe	18%	94%	17%	94%	0.9

[1] Corepla [16] and Conai [24] provided data for input compositions to sorting and remanufacturing phases, together with those related to sorting efficiencies; data from [21,22] were used for remanufacturing efficiencies and substitutability factors, respectively. [2] They include PET, polyolefins, and stirenics. It was assumed to be composed of 49% PET, 13% HDPE, 25% LDPE, 11% PP, and 2% PS. [3] Comieco [17] provided data for input composition to sorting phases and sorting efficiencies; data from [22] were used for input composition to remanufacturing, remanufacturing efficiencies, and substitutability factors. [4] Coreve [18] provided data for input compositions to sorting and remanufacturing phases, together with those related to sorting and remanufacturing efficiencies; data from [22] were used for the substitutability factor. [5] Ricrea [19] and Cial [20] provided data for input compositions to sorting and remanufacturing phases, together with those related to sorting efficiencies; data from [22] were used for remanufacturing efficiencies and substitutability factors.

Table 2. Direct and avoided burdens related to management of separately collected dry recyclable waste. Data Source: [16–23].

	2011 and 2021			
	Plastics	**Glass**	**Paper**	**Metals**
Dry Recyclable Waste in, kg	1000	1000	1000	1000
Direct Burdens				
Sorting				
Electricity, kWh	34	7	15	55
Diesel, kg	2	-	-	-
Heat, MJ	-	-	-	271
Residues, kg	462	97	532	151
Re-processing				
Electricity, kWh	327	31	252	390
Heat, MJ	18.84	4157	1740	1237
Water, kg	973	-		-
Diesel, kg	-	-	7.5	0.2
Sodium hydroxide, g	439	-	-	252
Methane, MJ	498	-	-	-
HDPE, kg	-	9.82	-	-
Quicklime, kg	-	-	-	307
Sodium chloride, kg	-	-	-	1.8

Table 2. *Cont.*

	2011 and 2021			
	Plastics	**Glass**	**Paper**	**Metals**
Hydrated lime, g	-	-	-	625
Nitrogen, g	-	-	-	508
Residues, kg	132	-	34	92
Air emissions				
CO_2 non fossil, kg	-	-	73	-
CO_2 fossil, kg	-	-	150	-
CO non fossil, g	-	-	0.3	-
CO fossil, g	-	-	17	0.02
N_2O, g	-	-	72	-
CH_4 fossil, g	-	-	31	-
CH_4 non fossil, g	-	-	0.2	-
SO_2, g	-	-	61	52
AVOIDED BURDENS				
Avoided PE production, kg	127	-	-	-
Avoided PET production, kg	203	-	-	-
Avoided PP production, kg	34	-	-	-
Avoided PS production, kg	5	-	-	-
Avoided glass production, kg	-	903	-	-
Avoided newspaper production, kg	-	-	173	-
Avoided testliner production, kg	-	-	225	-
Avoided steel foils, kg	-	-	-	600
Avoided aluminium billets, kg	-	-	-	141

Organic fractions. The management of biowaste separately collected in Procida greatly improved over the last ten years, moving from exclusive utilisation of aerobic composting processes (in 2011) to the adoption of anaerobic digestion (AD) with production of energy or, in some cases, biomethane (in 2021). The aerobic process is carried out in bio-cells tunnels, with a residence time of 45 days, necessary to produce about 300 $kg/t_{biowaste}$ of compost used for landfill capping. The exhaust gases from bio-cells are treated in a biofilter to remove odorous substances and pollutants before their release into the atmosphere, while leachate generated is sent to an external treatment plant [8]. The anaerobic digestion process is implemented in a continuous-flow, stirred-tank reactor working under wet and mesophilic conditions (37–39 °C) and having a treatment capacity of 35,000 $t_{biowaste}/y$. It produces about 140 $m^3{}_N/t_{biowaste}$ of biogas, containing 50.8$\%_{vol}$ of CH_4, 44.6$\%_{vol}$ of CO_2, and 4.6$\%_{vol}$ of other compounds, which is sent to a combined heat and power (CHP) unit, having conversion efficiencies of 38% for electricity and 45% for thermal energy [25]. The environmental burdens deriving from biowaste management are shown in Table 3, quantified for both the process units starting from the same reference composition, as reported in ANNEX B.

Table 3. Direct and avoided burdens related to management of separately collected biowaste (EWC 200108 and 200201). Data Source: [8,25].

	2011	2021
	Composting	**Anaerobic Digestion**
Input, kg	1000	1000
Direct Burdens		
Consumptions		
Water, kg	528	10
Diesel for general plant activities, L	0.96	0.3
Electric energy, kWh	53	-
Residues		
Solid residues to landfill, kg	-	153
Solid digestate to landfill, kg	-	156
Leachate to treatment, kg	74	-
Air emissions	from biofilter	from CHP and biofilter
NOx, g	-	336
CO, g	-	278
TOC, g	-	38
VOC, g	484	-
PM, g	35.3	3.1
SO_2, g	-	41.3
H_2S, g	15.5	-
HCl, g	-	6.4
Hg, g	2.6	0.01
HF, g	-	0.58
NH_3, g	16.7	8.55
Cd + Tl, g	-	0.03
PCDD/DF, g	-	3.7×10^{-9}
PHA, g	-	0.09
Sb, g	-	0.04
As, g	-	0.04
Co, g	-	0.04
Cr, g	-	0.04
Mn, g	-	0.07
Ni, g	-	0.07
Pb, g	-	0.04
Cu, g	-	0.04
Vn, g	-	0.04
Heavy metals, g	18.8	-
Mercaptans, g	2.6	-
Aldehydes, g	2.6	-
Ketones, g	5.9	-
Amine, g	2.6	-
Fat volatile acids, g	3.3	-
Biogenic CO_2 from biogas combustion, kg	-	262
Water emissions from liquid digestate treatment		
COD_{max}, g	-	47
BOD_5, g	-	15
Suspended solids, g	-	3
NH_4, g	-	1.8
AVOIDED BURDENS		
Electric energy exported to the grid, kWh	-	154
Compost used for landfill capping, kg	290	-

Unsorted residual waste. The management of URW includes a mechanical stage aimed at producing a solid recovered fuel (SRF) to be sent to a combustion-based WtE plant. Residues from the mechanical stage, the amount of which (Figure 2) is strictly related to the URW composition, as quantified starting from W-MySir, include the organic fraction sent for biostabilisation and metals sent for material recovery. The last generation WtE plant of Acerra, for which primary data are available in the literature [3], has received SRF from the Campania region since 2010 and recovers electric energy from their combustion as well as materials from bottom ashes treatment applied in recent years. The WtE unit has a waste-treatment capacity of more than 700,000 t_{SRF}/y and a thermal capacity of 340 MW_t. It is equipped with a moving grate furnace and has a net electric recovery efficiency of 26%. The air pollution control (APC) system includes a semi-dry scrubber, two fabric filter baghouses, and a selective catalytic reactor for the efficient abatement of acid gases, micro-pollutants and NOx, before the release of cleaned flue gases into the atmosphere. Generated solid residues include bottom ashes, which were sent for disposal in 2011, but were treated for recovery of metals and inert materials in 2021, fly ashes and APC residues, which are disposed of in exhausted salt mines in both scenarios. The environmental burdens deriving from the thermal treatment of SRF are shown in Table 4, quantified by considering different waste compositions of reference, as reported in ANNEX B, together with life-cycle inventory of the preliminary mechanical stage.

Table 4. Direct and avoided burdens related to management of solid recovered fuel obtained from unsorted residual waste (EWC 200301). Data Source: [3].

	2011	**2021**
Input, kg	1000	1000
Consumptions		
NH_3, kg	2	2
Hydrated lime, kg	7.3	7.3
Activated carbon, kg	0.5	0.5
Mixed reagent [1], kg	0.7	0.7
Water, kg	306	306
Diesel, kg	0.58	0.58
Auxiliary fuel, kg	3.5	3.5
Air emissions		
Biogenic CO_2, kg	493	526
Fossil CO_2, kg	758	1040
CO, g	65	65
NOx, g	469	469
NH_3, g	8	8
HF, g	1	1
HCl, g	13	13
SOx, g	6	6
Hg, g	0.0045	0.0045
Cd + Tl, g	0.00244	0.00244
Metals (Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V), g	0.0593	0.0593
Dust, g	2.7	2.7
VOC, g	1.1	1.1

Table 4. *Cont.*

	2011	2021
Benzene, g	0.8	0.8
Zn, g	0.054	0.054
PCDD/DF, I-TEQ, mg	6.7×10^{-7}	6.7×10^{-7}
PCB, WHO-TEQ, mg	1.15×10^{-7}	1.15×10^{-7}
PHA, mg	7.9×10^{-4}	7.9×10^{-4}
Solid residues		
Bottom ashes, kg	165	165
Fly ash + APC residues kg	49	49
AVOIDED BURDENS		
Electric energy exported to the grid, kWh	842	1110

[1] Mixed reagent is 75% hydrated lime ($Ca(OH)_2$) and 25% activated carbon.

Transportation stage. Finally, the environmental burdens of the transportation stage were quantified based on data provided by W-MySir, which included distance covered, type of vehicles, and the destination for each waste stream, as reported in Table 5.

Table 5. Environmental burdens related to transportation stages for all waste streams. Source: W-MySir [7].

	2011	2021
Transported waste, kg	**1000**	**1000**
Total transportation by sea, tkm	**13**	**13**
Total transportation by road, tkm	**116**	**146**
Which comprises:		
URW to mechanical treatment for SRF preparation, tkm	*34.5*	*7.9*
SRF to WtE, tkm	*8.5*	*3.4*
Separated metals/biowaste to recovery/biostabilitation, tkm	*17.7*	*4.6*
Biowaste to biological plants, tkm	*46*	*117*
Dry materials to sorting + remanufacturing plants, tkm	*8.8*	*13.6*

LCI results. Quantified LCI for treatment of each waste stream enabled a first comparison between Procida MSW management in 2011 and 2021 to be performed, based on the amounts of separately collected waste streams and those sent for ultimate disposal in landfill (Figure 4). The Procida 2021 scenario showed an increase in separate collection (of up to 74%), mainly due to the increased quantity of collected biowaste and, to a lesser extent, of plastics and glass. Improvements were also achieved in terms of reduced waste sent to WtE or for ultimate disposal in landfill, mainly related to the higher separate collection and material recovery from bottom ashes (which reduced residues from thermal treatments).

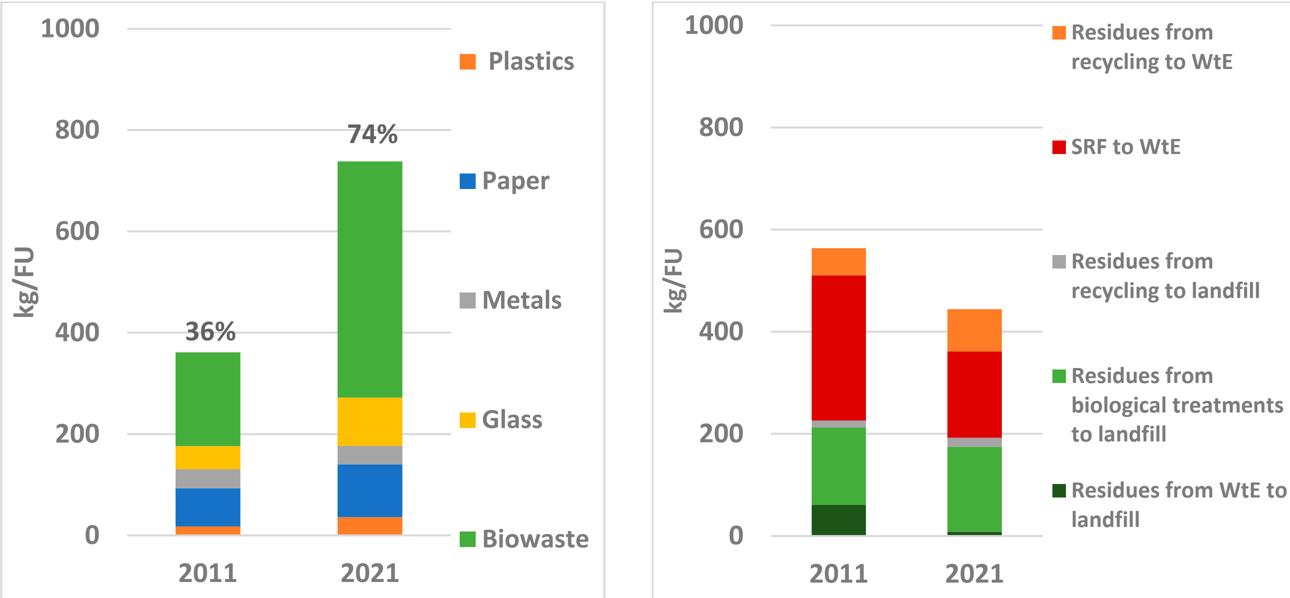

Figure 4. Comparisons between amounts of separately collected waste streams in Procida in 2011 and 2021 (**left**), and amounts sent to thermal treatments or disposal in landfill in the same years (**right**). Data source: W-MySir [7].

2.3. Life Cycle Impact Assessment

Data reported in the LCI section were used as input to the life-cycle impact assessment (LCIA) stage, which quantifies the potential impacts related to the main midpoint categories, those of global warming (GW), non-carcinogens (NC), respiratory inorganics (RI), non-renewable energy (NRE), and land occupation (LO). Figure 5 reports the normalized results (expressed as "person*year", i.e., the average impact in a specific category caused by a person during one year in Europe), to enable comparison of data related to different impact categories.

Data indicate that the evolution of MSW management in Procida was very positive. All the contributions to impact assessment in 2021 were negative, i.e., they positively affected the environment. The potential impact of GW improved by 140%, moving from 0.005 to −0.002 person*year, mainly due to the alternative management option adopted for the separately collected organic fraction and to the increased quantity of materials sent to recycling. The implementation of anaerobic digestion in place of a composting process led to better performances due to the impacts avoided resulting from obtained energy recovery. The increased amounts of glass, metals, plastics, and paper sent to recycling imply greater benefits related to the avoided production of virgin materials. The increased amount of glass sent to recycling (from 45 kg to 95 kg for FU) was the main difference between the two scenarios, resulting in an improvement for GW. On the other hand, the direct impacts of plastics recycling were higher than the avoided impacts. This is explained by the increased necessity of thermal treatment for the residues coming from the sorting stages, which amounted to about 50% of the separately collected plastics (as shown in ANNEX C) and were largely composed of plastic waste not suitable for mechanical recycling. On the other hand, the higher quantity of plastics sent to recycling (from 18 kg to 36 kg for FU), together with the implementation of anaerobic digestion of the MSW organic fraction, improved the NRE potential by 56%, due to the avoided consumption of fossil resources. The higher amount of paper sent to recycling (from 75 kg to 104 kg for FU) was the main contributor to improvement of the LO category (of about 16%) due to the avoided production of virgin paper. Categories connected to human health were also remarkably enhanced. RI improved by 47%, from −0.021 to −0.031 person*year, again with a primary contribution of recycling chains. NC improved by 143%, from +0.008 to −0.003 person*year, due to the alternative management option for bottom ashes (recovery of inert and metals instead of landfill disposal). Transportation had a limited effect on the GW, NRE and RI categories, even though it showed improved performances for 2021 related to the adoption of a more modern vehicle fleet (use of Euro 6 trucks instead of Euro 3 trucks).

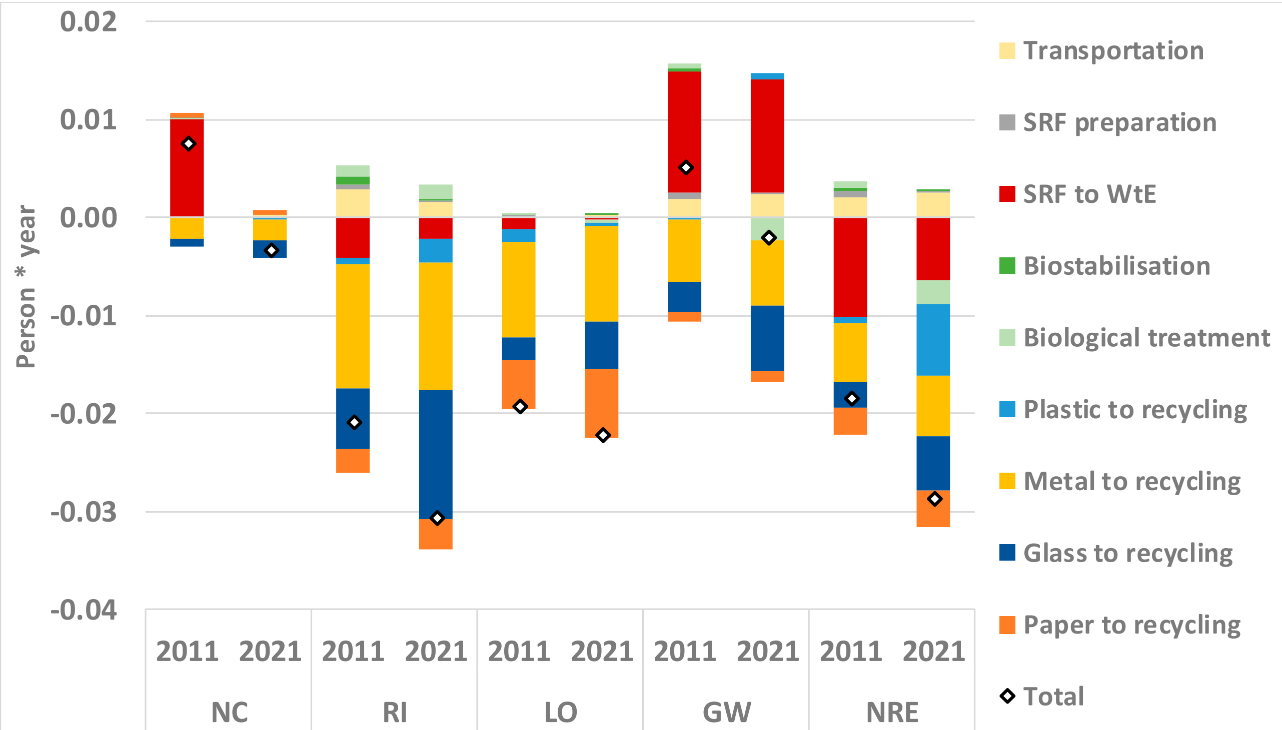

Figure 5. Life-cycle impact assessment for Procida's MSW management in 2011 and 2021, with the contributions of each specific stage. Results refer to the chosen functional unit ("the treatment of 1 tonne of MSW") and are normalised in "person*year" (the average impact in a specific category caused by a person during one year in Europe). NC = non-carcinogens; RI = respiratory inorganics; LO = land occupation; GW = global warming; NRE = non-renewable energy.

2.4. Interpretation

A sensitivity analysis was carried out by modelling two alternative scenarios for the Procida management scheme. The scenario "*Procida—Biomethane*" was defined according to which the organic fraction collected separately is sent to an anaerobic digestion plant aimed at recovering biomethane from biogas, which is sent to an upgrading unit instead of to the CHP. The LCI inventory was quantified based on data reported by [25], assuming the same anaerobic digestion plant utilised for the 2021 scenario but equipped with a three-stages membrane upgrading unit. Good performances in terms of CO_2 removal efficiency (of about 98%) and methane slip (lower than 1%) were obtained. This alternative strategy for biowaste management could be easily implemented in the near future since several AD plants for biomethane production have been active in Italy since 2020 because of the national legal framework, which provided incentives for plant operators [26].

The scenario "*Procida—EE Mix 2030*" assumes a future Italian electricity mix with larger percentages of non-fossil and renewable energy sources (from 51% to 43% with respect to 2020), mainly as a result of a higher share of wind energy (from 7% to 14% with respect to 2020) and a lower share of energy from natural gas (from 49% to 43%), as shown in ANNEX C. The future electricity mix (2030) was derived starting from that utilised for the 2021 base case scenario and considering national energy trends predicted by the European Community until 2050 [27].

These two sensitivity scenarios were implemented considering the waste composition and the share of separate collection defined for the Procida management scheme of 2021. These assumptions appear reasonable since the municipality showed rather stable conditions in terms of the quantity and composition of collected waste in recent years [7] due to the achievement of rates of separate collection greater than 70%—already higher than the value of 65% required by European legislation (ANNEX A). This enabled quantification of the sensitivity to change of a single assumption, neglecting other background conditions (such as the waste composition).

The sensitivity analysis results (Figure 6) showed that the implementation of scenario "*Procida–Biomethane*" could lead to further improvements for RI (7%), GW (171%) and NRE (3%), with reference to Procida 2021. These good performances were mainly related to the utilisation of biomethane for transportation use (with a vehicle fleet composed of 50% cars and 50% trucks), which replaces the production and utilisation of diesel for travelling the same distances, leading to avoided burdens greater than direct ones. The same scenario could lead to a worsening for LO (4%) due to the energy necessary for plant operations, which is provided by external sources in this AD configuration.

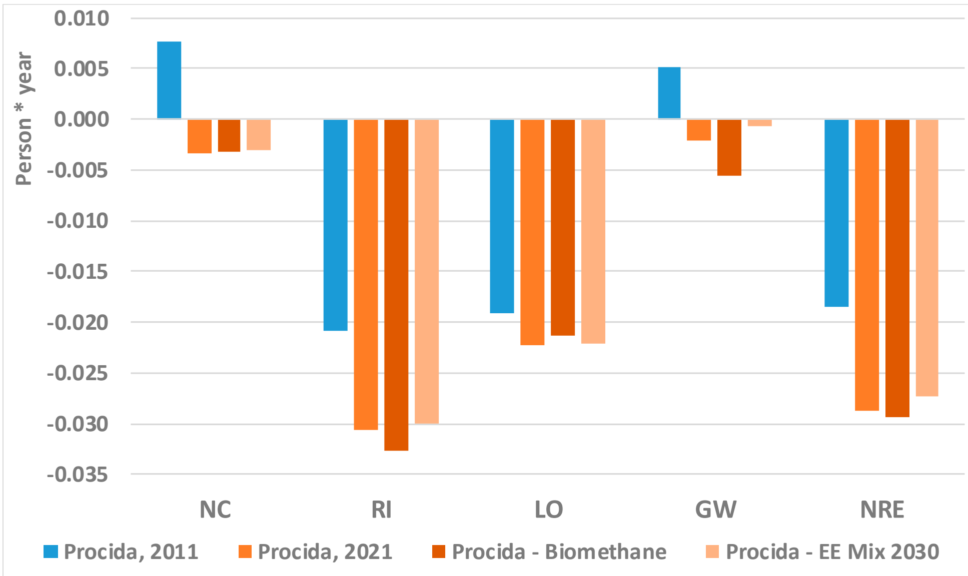

Figure 6. Results of sensitivity analysis scenarios, compared with those of base case scenarios. Results refer to the chosen functional unit ("the treatment of 1 tonne of MSW") and are normalised in "person*year" (the average impact in a specific category caused by a person during one year in Europe). NC = non-carcinogens; RI = respiratory inorganics; LO = land occupation; GW = global warming; NRE = non-renewable energy.

Again, with reference to Procida 2021, the scenario "*Procida—EE Mix 2030*" showed a worsening for the same categories, with values of up to 68% for GW. This is explained by the higher share of renewable energy sources, which have limited greenhouse emissions and lead to lower avoided impacts for AD and WtE plants. These results make the role of biomethane production from biowaste still more crucial. The scenario represents an efficient way to reduce fossil and non-renewable sources in the future when the energy mix will mainly comprise renewable sources.

3. Conclusions

An environmental LCA was implemented to investigate the evolution of MSW management in the Italian municipality of Procida island, based on high-quality data obtained from the W-MySir information system, which is widely used in the South of Italy. These data, together with those provided by Conai, or available in the scientific literature for units operating in the area of interest, were processed by means of material flow analyses to quantify the environmental burdens relevant to the LCA study.

The results quantify the improvement in the main impact categories, highlighting the great importance of the quantitative and qualitative increase of household source separation and collection over the last 10 years. The possibility of using a more integrated and sustainable management system is also crucial for all the pathways of sorted and unsorted wastes, including the recycling chains, biological treatments (particularly for the anaerobic digestion option), and thermal treatment (in highly efficient waste-to-energy units).

The role of the information system appears crucial in providing reliable high-quality data; it could provide a continuously updated databank for LCA studies. Future improvements to the platform will include the acquisition and processing of data for solid residues from the selection and remanufacturing stages, for innovative management options, together with those relating to the real role played by recycled products in the market.

The study demonstrates the importance of a well-structured and updated information system in supporting the activities of monitoring and planning of the waste management service of a community or larger districts. Its combined use with LCA can provide local governments with data for the reliable assessment of their waste management system and for the implementation of continuous improvements to its overall environmental performance. The combined approach appears advantageous for both the tools assessed: LCA studies could be more quickly implemented and provide further reliable results; information systems could offer more extensive and valuable services. This will help to monitor the sustainability of management systems and to plan for their evolution consistent with the principles of a circular economy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13020707/s1.

Author Contributions: Conceptualization, F.A. and U.A.; methodology, F.A.; software, F.A. and C.D.D.; validation, U.A.; investigation, F.A. and F.P.; data curation, F.P., F.A., F.C. and C.D.D.; writing—original draft preparation, F.A.; writing—review and editing, U.A.; visualization, F.P.; supervision, U.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: Annexes associated with this article can be found, in the online version.

Conflicts of Interest: The authors declare no conflict of interest.

List of Acronyms

AD	Anaerobic Digestion
APC	Air Pollution Control
BOD_5	Biochemical Oxygen Demand
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
EC	European Community
EU	European Union
EWC	European Waste Code
FU	Functional Unit
GW	Global Warming
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LHV	Low Heating Value
LO	Land Occupation
MFA	Material Flow Analysis
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
NC	Non-Carcinogens

NRE	Non-Renewable Energy
PCB	Polychlorinated Biphenyls
PCDD/DF	Polybrominated Dibenzo-p-Dioxins/Furans
PE	Polyethylene
PET	Polyethylene Terephthalate
PHA	Polycyclic Aromatic Hydrocarbons
PS	Polystyrene
RI	Respiratory Inorganics
SME	Small–Medium Enterprise
SRF	Second Recovered Fuel
TOC	Total Organic Carbon
URW	Unsorted Residual Waste
VOC	Volatile Organic Compounds
WM	Waste Management
WtE	Waste-to-Energy

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