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Comparative LCA of Alternative Scenarios for Waste Treatment: The Case of Food Waste Production by the Mass-Retail Sector

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Abstract: Food waste is one of the most important issues taken into account by the European Union due to its negative environmental, economic and social impacts. The treatment of food waste through recycling processes represents a solution for food waste minimisation. Concerning, in particular, the retail sector, it is necessary to define strategies for retail-oriented sustainable food waste management. The aim of this study is to compare the potential environmental impacts related to five scenarios (landfill, incineration, composting, anaerobic digestion and bioconversion through insects) for the disposal/treatment of food waste produced by a mass retail company operating in Messina (Italy) through the application of the Life Cycle Assessment method, in order to find the best treatment solution. Results based on the treatment of a functional unit of 1 tonne of food waste show that the bioconversion scenario represents the most preferable solution considering all of the impact categories analysed through the CML 2 baseline 2000 method, except for Global Warming, for which higher environmental performances are connected to the anaerobic digestion scenario. The incineration and the bioconversion scenarios show the highest environmental benefits when the production of alternative energy sources and valuable materials is evaluated through the inclusion of the avoided productions in the analysis.

Keywords: food waste; Life Cycle Assessment; mass-retail; supermarkets; alternative scenarios; landfill; incineration; composting; biogas; bioconversion

1. Introduction

Food waste (FW) is one of the most significant problems taken into account by the European Union and the international scientific community in recent years. Gustavsson et al. [1] estimated that the amount of global food waste and loss is about 1.3 billion tonnes per year, equivalent to one third of food produced globally for human consumption. In particular, the amount of food wasted in the EU-28 is about 88 million tonnes per year (equivalent to 173 kg per capita), when considering both edible food and the inedible parts associated with food [2]. The increasing attention paid to FW issues is mainly due to its negative environmental, economic and social impacts [3,4]. For instance, the greenhouse gas (GHG) emissions related to the food wasted during the production phase were estimated to be about 2.2 Gt CO_2 equivalent (eq) in 2011 [5], while the costs associated with the wastage were around 143 billion Euro per annum in the EU-28 [2]. In this context, the reduction of FW and the optimisation of its management is a priority for the European Commission, which is working to achieve a significant reduction in FW by 2020 by means of joint actions, in order to obtain a minimisation of loss and waste throughout the whole food supply chain [6]. The growing awareness of the need for sustainable strategies for the FW management hierarchy is driving, on the one hand, towards an increase in research activities oriented towards waste prevention, which should be the most preferable solution [7]; and on the other, towards an increasing consideration of FW treatment at the disposal/recycling stage.

1.1. Food Waste: A Life Cycle Perspective

Considering a life cycle perspective, it is important to highlight that FW production is not only related to one single stage, but is a phenomenon that includes all levels of food chain [8]. In particular, according to Stenmarck et al. [2], the largest contribution to FW production in the EU-28 is due to the household sector (46.5 million tonnes per year), followed by the processing stage (16.9 million tonnes per year). Furthermore, even if the primary production sector causes the highest environmental impact in terms of the whole life cycle of the food chain [9], it contributes less to FW production, providing about 9.1 million tonnes per year and contributing 11% to the total wasted food in the EU-28.

In contrast, the lowest FW production, from a life cycle perspective, is connected to the wholesale and retail sectors, which cause about 5 million tonnes per year, corresponding to 5% of the total amount of FW produced in the EU-28. Nevertheless, these sectors show the highest contribution in terms of edible food wasted (about 83%) and a high economic loss equivalent to 2768 Euro per tonne of edible FW [2]. In addition, the retail sector is directly connected to the consumers that represent the last step in the food supply chain, and who are the main contributors to household production of FW (about 53%) [2,3,10,11].

Due to this, it is necessary to define strategies for retail-oriented sustainable FW management, considering that the mass retail sector presents particular features that are not involved in the other sectors or, in particular, at the household level. Indeed, mass retail companies (MRCs) can be directly involved in the selection of the best practices for FW's collection and transport as well as for its treatment, creating new business opportunities for FW utilisation following a circular economy approach. Furthermore, the MRCs are directly involved in the quantitative and qualitative analysis of FW produced and this may allow a more detailed assessment of the FW management strategies. In this context, the analysis of different treatment systems for FW produced by the mass retail sector should be taken into account considering a life cycle thinking perspective.

1.2. Life Cycle Assessment Studies in a Food Waste Context

Notarnicola et al. [12] highlighted that the Life Cycle Assessment (LCA) method is able to offer an important contribution to the analysis of FW management, allowing the proposal of environmentally-friendly solutions (e.g., using recovered nutrients as fertilizers) or improving management options along the whole production chain in a circular economy context. The LCA method has been widely adopted in recent years to analyse FW management activities (e.g., [4,13–17]).

For instance, Salomone et al. [4] applied LCA in order to assess the FW bioconversion process into compost (to be used as fertilizers) and dried larvae (to be adopted as fishmeal) by the action of the *Hermetia illucens* insect (Black Soldier Fly). The main results underscored the fact that the bioconversion process contributed 30.2 kg CO_2 in Global Warming Potential (GWP), 215.3 MJ in Energy Use, and 0.661 m^2a in Land Use per 1 tonne of FW.

Caputo et al. [16] adopted the Food Chain Model and the LCA method in order to analyse all the steps of the food chain, and to assess the environmental impacts with the aim of proposing a means of sustainable development related to the organisation of food demand and supply in an institutional food system, considering the food production, processing, consumption, and waste management at the local level. In particular, the study focused attention on the quantification of the energy sources in the food supply chain. Results showed that the main sustainable strategies were connected to the utilisation of seasonal, less energy-intensive, locally-sourced products. Furthermore, the authors underlined that a possible solution to manage FW may be represented by its conversion into energy sources, such as biodiesel and bio-methane.

Schott et al. [13] carried out a review analysis of nineteen existing LCA studies on food waste management in order to propose a general overview of the GWP related to different treatment systems, and to identify decisive factors that may cause changes in the impacts. The main results highlighted several methodological differences, in particular connected to the selection of system boundaries and variation in the input data adopted to assess similar processes. In addition, the changing in GWP results is mainly related to the assumptions made in relation to the background system (e.g., assumptions related to the interaction of the waste management system with the background energy system and/or bio-system).

Regarding the household sector, different LCA studies were implemented. For example, Naroznova et al. [18] assessed the GWP impacts based on a treatment of the proportions of individual materials found in organic household waste in Denmark, comparing anaerobic digestion and incineration systems. Results highlighted that anaerobic digestion allowed a GWP reduction when FW (and, in particular, animal and vegetable fractions, as well as kitchen towels) were treated.

In addition, Bernstad and la Cour Jansen [19] carried out an LCA study in order to analyse the environmental impacts (positive or negative) related to the management of the household's FW produced in a residential area in Malmö (Sweden), comparing three different treatment systems (decentralised composting, centralized anaerobic digestion and incineration) and including in the analysis the use of the resources obtained by the treatment processes. GWP results showed that biogas digestion caused the main environmental benefits, in particular when biogas is adopted as substitute for the electricity coal power source.

A literature analysis conducted using the keywords "Life Cycle Assessment", "food waste" and "supermarket" or "retail" in Science Direct and Web of Science (WoS) databases in April 2017 underscored that only four LCA studies related to FW produced at the retail level were published between 2000 and 2017 in international scientific journals: Brancoli et al. [11] and Scholz et al. [20], Eriksson and Spångberg [21] and Eriksson et al. [22]. Furthermore, the literature analysis confirmed that the assessment of the environmental impacts related to the FW produced by the mass retail sector through the LCA method is a recent issue, since all four studies were carried out in the last two years.

Brancoli et al. [11] analysed the FW produced at a supermarket in Sweden in order to categorise and quantify the FW fractions, to assess which portions present the highest environmental impacts, and to propose alternative treatment processes to the systems currently adopted. Results underscored that bread had the largest contribution in terms of mass and economic costs, as well as in environmental impact, especially when ozone depletion, freshwater ecotoxicity and resource depletion were assessed. Regarding GWP impacts, the main contribution came from beef waste. The analysis of environmental impacts related to alternative treatment scenarios showed that the production of biogas through a pre-separation of the FW from its packaging and the utilization of bread waste for feed production were the most preferable solutions.

Scholz et al. [20] applied LCA in order to assess the Carbon Footprint (CF) of FW coming from different departments of Swedish supermarkets. The products' CF was calculated using the results from previous studies. The analysis highlighted that the main contribution to the CF came from fruit and vegetable departments, followed by meat departments.

Two similar LCA studies have been carried out by Eriksson and Spångberg [21] and Eriksson et al. [22]. The authors performed, in both studies, comparative LCAs between different food products treated by means of various systems in order to assess the CF or energy use. The main results of these studies highlighted that the best waste management scenario, as well as reductions in GHG emissions or in primary energy use, can be directly related to the type of food products treated.

Instead, the literature overview underscored that many LCA studies focusing on FW management have been performed, but only four are directly related to the mass-retail channel. Furthermore, even if different treatment systems for FW were investigated and compared (e.g., landfill, composting, etc.), some hypotheses have been less rigorously evaluated, such as the bioconversion process, which, in accordance with Salomone et al. [4], may represent an attractive solution for FW treatment. Lastly, the four LCA studies on FW at the retail level focus on the assessment of FW management scenarios within a specific local food-chain or with a regional contextualisation (relating in particular to Sweden), but none of them aim at the identification of proper strategies for FW management directly related to a specific MRC, considering, in particular, collection and transport activities.

In this context, the aim of this study is to compare the potential environmental impact related to five different scenarios (landfill, incineration, composting, anaerobic digestion, and bioconversion into compost and feed through the action of the insect *Hermetia illucens*) for the disposal and recycling of FW produced by an MRC operating in Messina (Italy), using the LCA method. Furthermore, this study allows, on one hand, identification of the system with the lowest environmental impact in order to support the MRCs in deciding on the adoption of sustainable FW management and treatment strategies; while on the other hand, adding environmental information useful for the evaluation of new business opportunities for FW treatment and utilisation.

2. Materials and Methods

The assessment of the potential environmental impacts related to five different scenarios of disposal/treatment of FW produced by an MRC operating in Messina (Italy) is carried out by means of the Life Cycle Assessment (LCA) method. The LCA method is a standardized tool that allows the assessment of the potential environmental impact associated with a product, process, or service throughout its entire life cycle, from raw material extraction and processing, through manufacturing, transport, use and final disposal [23]. In accordance with ISO standards [24,25], an LCA study is structured of four iterative phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

The assessment is carried out through a comparative LCA, that means that the comparison of the environmental profiles of different systems is made on the basis of equivalent functions. In particular, two FW disposal scenarios (representing the two options actually implemented by the investigated MRC) are compared with alternative hypothetical treatment scenarios, in order to evaluate how the results change when alternative FW treatment processes and an optimised localisation of treatment facilities are considered.

2.1. Goal and Scope Definition

The goal of this study is to assess the potential environmental impact associated with the treatment of FW produced by a MRC operating in Messina (Italy), comparing five different scenarios. The LCA method is applied to analyse both disposal scenarios (landfill—scenario 1; and incineration—scenario 2) and alternative scenarios for the recycling/recovery of the organic fraction (composting—scenario 3; production of biogas—scenario 4; and production of compost and feed through the action of the insect *Hermetia illucens*—scenario 5). Thus, this research is carried out in order to find the system with the lower environmental impacts, helping the mass retail company to select sustainable practices for the treatment of FW.

System boundaries (Figure 1) include all the direct and indirect activities involved in the management of FW produced by the MRC, from FW collection at supermarkets to its final treatment. In this context, three main phases were investigated:

1. Collection—transportation of FW and its packaging from 12 retail stores of the MRC to the landfill and incineration plant through the collection centre (in scenarios 1 and 2), or transportation from the stores to the unpacking plant (for scenarios 3, 4 and 5), is considered;

2. Pre-treatment—FW fraction is separated from its packaging in order to carry out the treatment in the subsequent phase. This phase is only necessary for scenarios 3, 4 and 5; and
3. Treatment—FW is treated in the different plants under investigation (landfill, incinerator, composting, anaerobic digestion and bioconversion).

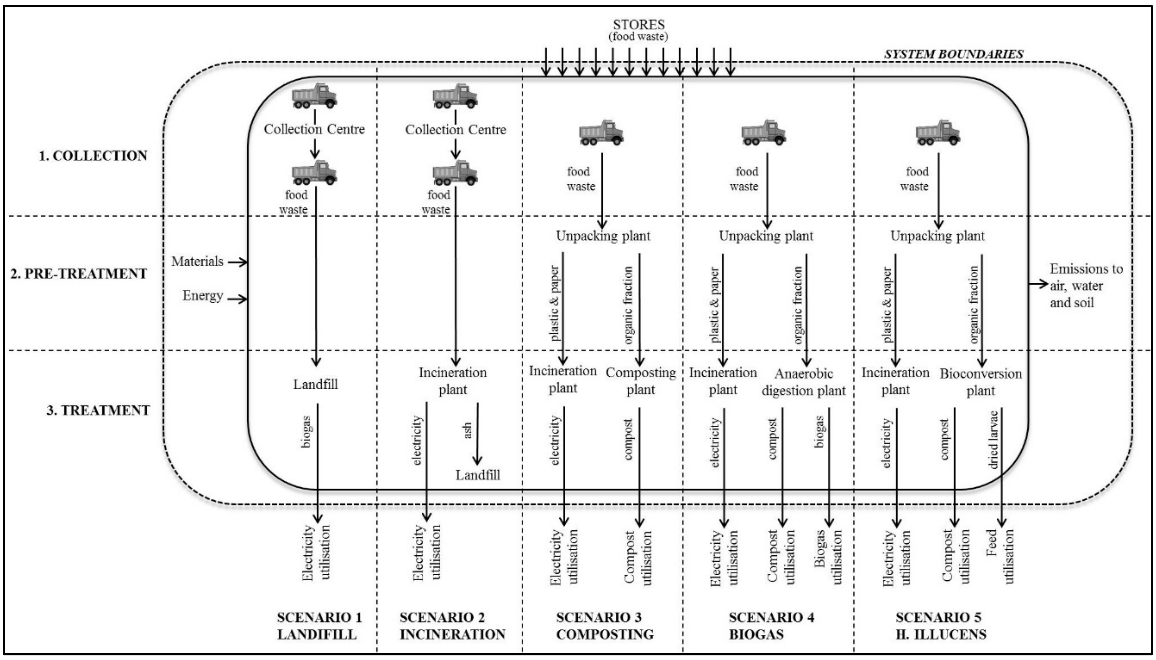

Figure 1. System boundaries.

Furthermore, the avoided production of different energy sources and materials was also included in the system boundaries. The inclusion of avoided products means that FW treatment processes allow for the avoided production of conventional products and thereby a negative contribution to the environmental impacts. The treatment of packaging materials (plastic and paper) separated during the pre-treatment phase was assumed to be equal for each scenario (incineration with energy recovery). The utilisation of the products obtained from the treatment processes was not included in the system boundaries because these are outside the scope of this study.

In order to design the different scenarios, some estimations and assumptions were made. Firstly, a localisation in the same area at an average distance (about 30 km) among the supermarkets of the MRC is supposed for the de-packing and recycling/recovery plants in order to optimise the collection and transport of FW. Secondly, two plants situated in the Province of Messina (Italy) are considered for the localisation of the landfilling and the incineration systems, even if they were actually inactive (Figure 2). Finally, since the data related to the treatment phase is obtained from the international literature, the composition of FW sent to the treatment plants is assumed to be the same as was analysed in the baseline studies.

In accordance with other authors [4,26,27] who have implemented LCA studies related to FW management, a functional unit (FU) of 1 tonne of FW to be treated was selected in order to carry out the comparison between the investigated scenarios.

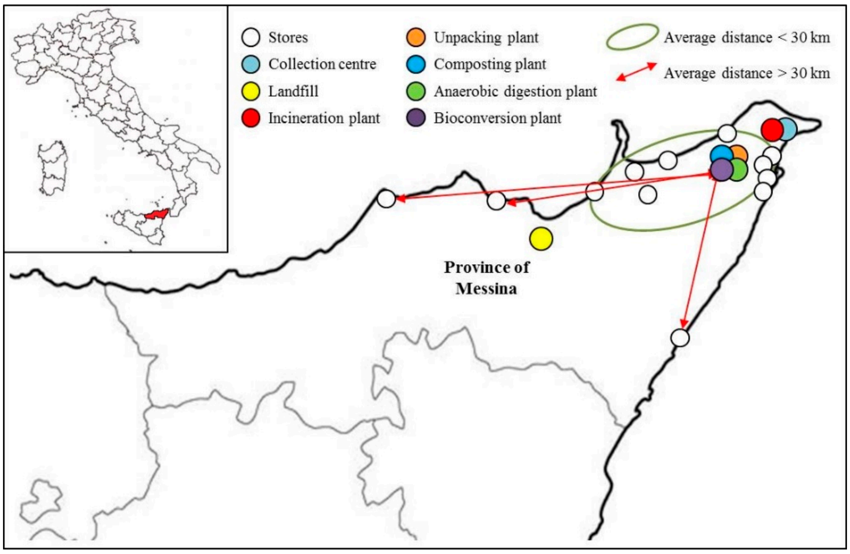

Figure 2. Localisation of the supermarkets/treatment plants and average distance for food waste transportation.

2.2. Inventory Analysis

Foreground data refer to the amount and transport of FW and its packaging, for which primary data were collected through specific questionnaires and direct interviews. Data were collected in 2015, and the total amount of the FW and its packaging produced by the 12 MRC stores was 112.77 tonnes, for which 98.7% was composed of the FW fraction and 1.3% was represented by the packaging fraction. The FW is mainly composed of fruits and vegetables, followed by meat and fish, deli products and dairy and cheese products (Figure 3). The average moisture content of the FW is about 75%.

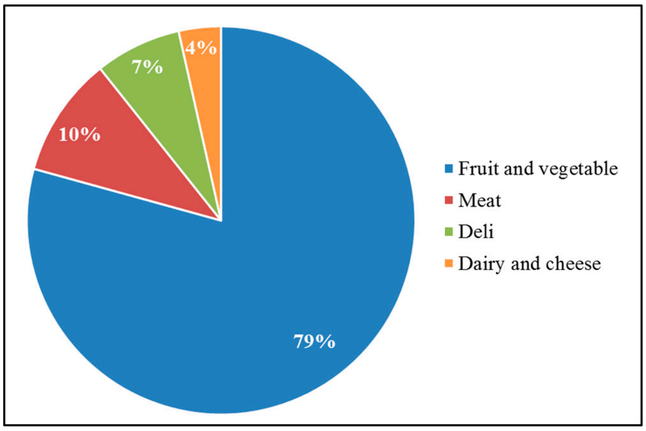

Figure 3. Percentage composition of the food waste produced by the MRC stores.

Background data refer to secondary data obtained from the international literature and databases. In particular, data related to the pre-treatment phase, concerning the amount of electricity adopted during the unpacking process, are estimated using the data from Atritor Company [28]. In addition, previous LCA studies are used in order to collect the inventory data related to the hypothetical treatment plants in phase 3: Mendes et al. [29] for landfill and incineration, Righi et al. [30] for composting and anaerobic digestion, and Salomone et al. [4] for the bioconversion process.

The inventory (Table 1) includes foreground data and background data.

Table 1. Main input and output data related to the functional unit of 1 tonne of FW to be treated.

	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		Landfill	**Incineration**	**Composting**	**Biogas**	***H. illucens***
Input						
Transport	tkm	90.3	90.3	19.9	19.9	19.9
Electricity	kwh	665	161	145	89	68
Diesel	kg	0.8	5.8	0.5		
Natural gas	m^3		11			
Chemicals inorganic	kg		10			
Auxiliary materials	kg		2		0.1	
Water	kg					61
Output						
Electricity	kWh	166	564			
Compost	kg			210	220	335
Biogas	Nm^3				85	
Dried larvae	kg					30

In scenario 1, which represents the most common treatment system adopted in the local context under investigation, the disposal of FW with its packaging is sent to landfill. Data related to the electricity and diesel consumption as well as the direct emissions due to waste treatment are considered. Furthermore, the production of biogas and the 30% energy recovery efficiency are assumed.

In scenario 2, the incineration of FW and its packaging by means of a mass-burn incinerator and the recovery of heat and electricity with an energy efficiency of 15% are assumed. The inventory data include substances, electricity and natural gas utilisation during the process. The direct emissions and the transportation and disposal of the ashes in the landfill are also included in the analysis.

In scenario 3, the FW fraction obtained by the unpacking process is treated by means of a composting plant in order to produce compost to be used as fertilizer. The amount of compost obtained by the process represents about 21% of the initial quantity of FW treated. Data connected to water, electricity and diesel consumption, as well as the emissions and the leachate disposal are considered.

In scenario 4, FW without its packaging is sent to an anaerobic digestion plant in order to obtain both biogas and compost. The biogas is combusted in a Combined Heat & Power (CHP) unit in order to produce electricity. The plant efficiency allows producing 85 Nm^3 of biogas (converted in 175 kWh of electricity) and 220 kg of solid digested matter from 1 tonne of FW. Inputs and outputs related to the system include materials, electricity and water consumption, and the direct emissions due to the treatment process.

In scenario 5, after the unpacking process (as in scenarios 3 and 4), FW is treated in a bioconversion plant through the action of the *H. illucens* insect in order to produce compost and dried larvae to be used, respectively, as fertilizer and a possible source for fish feed formulation. In particular, the insects are fed with FW and after the bioconversion process and the related production of the bio-digested (compost), *H. illucens* larvae are dried in order to produce feed. The waste reduction efficiency of the plant is about 67% and data related to materials, water and electricity consumption, and direct emissions are considered in the inventory analysis.

International databases are adopted in order to include the inventory data regarding raw materials and energy sources [31,32] as described in Table 2.

Table 2. Data sources related to the international databases.

Scenario	Phase	Process	Data Source
Landfill	Collection	Transport, lorry, 7.5–16 tonnes, EURO4/RER U	Ecoinvent [31]
	Pre-treatment	None	None
	Treatment	Diesel, at refinery/RER U	Ecoinvent [31]
		Electricity, high voltage, at grid/IT U	Ecoinvent [31]
		Electricity, medium voltage, at grid/IT U (AvPr) [1]	Ecoinvent [31]
Incineration	Collection	Transport, lorry, 7.5–16 tonnes, EURO4/RER U	Ecoinvent [31]
	Pre-treatment	None	None
	Treatment	Electricity, high voltage, at grid/IT U	Ecoinvent [31]
		Electricity, natural gas, at power plant/IT U	Ecoinvent [31]
		Diesel, at refinery/RER U	Ecoinvent [31]
		Chemicals (inorganic)	Ecoinvent [31]
		Auxiliary materials	Ecoinvent [31]
		Electricity, medium voltage, at grid/IT U (AvPr) [1]	Ecoinvent [31]
Composting	Collection	Transport, lorry, 7.5–16 tonnes, EURO4/RER U	Ecoinvent [31]
	Pre-treatment	Electricity, high voltage, at grid/IT U	Ecoinvent [31]
	Treatment	Diesel, at refinery/RER U	Ecoinvent [31]
		Electricity, high voltage, at grid/IT U	Ecoinvent [31]
		Urea (AvPr) [1]	Ecoinvent [31]
Biogas	Collection	Transport, lorry, 7.5–16 tonnes, EURO4/RER U	Ecoinvent [31]
	Pre-treatment	Electricity, high voltage, at grid/IT U	Ecoinvent [31]
	Treatment	Electricity, high voltage, at grid/IT U	Ecoinvent [31]
		Electricity, natural gas, at power plant/IT U (AvPr) [1]	Ecoinvent [31]
		Urea (AvPr) [1]	Ecoinvent [31]
H. illucens	Collection	Transport, lorry, 7.5–16 tonnes, EURO4/RER U	Ecoinvent [31]
	Pre-treatment	Electricity, high voltage, at grid/IT U	Ecoinvent [31]
	Treatment	Electricity, medium voltage, at grid/IT U	Ecoinvent [31]
		Tap water, at user/RER U	Ecoinvent [31]
		Transport, lorry 3.5–7.5 tonnes, EURO4/RER U	Ecoinvent [31]
		Urea (AvPr) [1]	Ecoinvent [31]
		Soy meal (AvPr) [1]	LCA Food DK [32]

[1] Avoided Product (AvPr).

Due to the production of new valuable materials and energy sources through the FW treatment, the avoided production of similar conventional products was also considered in the present study (Table 3). The avoided products are selected in accordance with the previous studies used to include the inventory data related to phase 3. The reference substances for the avoided production are calculated considering the content of total nitrogen for the compost, the amount of electricity produced from the biogas combustion for the anaerobic digestion, and the content of protein for the dried larvae. Furthermore, mineral fertiliser (urea) and electricity are assumed to be replaced by compost and biogas, while the dried larvae are considered to be a substitute for soy meal.

Table 3. Recycled materials/energy sources and quantification of the avoided products related to the functional unit of 1 tonne of FW to be treated.

Scenario	**Recycled Materials/Energy Sources**			**Avoided Products**		
	Material	**Unit**	**Amount**	**Material**	**Unit**	**Amount**
Landfill	Electricity	kWh	166	Electricity	kWh	166
Incineration	Electricity	kWh	564	Electricity	kWh	564
Composting	Compost	kg	210	Urea	kg	9
Anaerobic digestion	Biogas	Nm^3	85	Electricity	kWh	175
	Compost	kg	220	Urea	kg	9.4
Bioconversion	Compost	kg	335	Fertilizer (N)	kg	50
	Dread larvae	kg	30	Soy meal	kg	28

2.3. Life Cycle Impact Assessment

SimaPro 8 software [33] is used to perform the analysis. The Life Cycle Impact Assessment (LCIA) has been carried out by means of CML 2 baseline 2000 method [34] in order to obtain a higher level of detail allowing to develop a detailed environmental picture of each scenario, considering ten different impact categories and the respective characterisation factors: Abiotic Depletion (ADP), Acidification (AP), Eutrophication (EP), Global Warming (GWP100), Ozone Layer Depletion (ODP), Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FAETP), Marine Aquatic Ecotoxicity (MAETP), Terrestrial Ecotoxicity (TETP), Photochemical Oxidation (POCP). Furthermore, Energy Use (EU) (Cumulative Energy Demand method [35,36]) and Land Use (LU) (CML 2001 method [37]) impact categories were also assessed, according to other LCA studies related to the specific field of FW management. In the present study only the compulsory phases of the LCA method according to ISO 14,044 [25] are implemented.

3. Results and Discussion

In this section, characterization results related firstly to the five scenarios without the inclusion of the avoided products are shown. Then, results with the inclusion of avoided production are evaluated. The inclusion of the avoided products in the analysis allows an understanding of what potential environmental benefits may be connected with the substitution of a valuable substance or energy source produced by the treatment process with a related conventional material or energy source. In this context, the results of the comparison between the scenarios in which the energy recovery represents the main products obtained by the treatment of FW (scenarios 1, 2 and 4) is shown first, then the comparison between systems with recovery of valuable materials, such as compost (scenarios 3 and 5), is analysed.

3.1. Characterisation Results without Avoided Product

The comparative analysis of the five scenarios excluding the avoided products (Table 4) underscores the fact that the highest potential environmental loads are related to landfill and incineration scenarios in all the impact categories, while the lower load is connected to *H. illucens* scenario, except for the global warming impact category, for which the biogas scenario shows the lowest impacts. Analysing each scenario, results highlight that the percentage contribution to the potential environmental impacts for each category ranges from 80.8% for photochemical oxidation to 48% for ozone layer depletion in scenario 1, from 35.7% for global warming to 8.1% for photochemical oxidation in scenario 2, from 12.9% for acidification to 4.9% for global warming in scenario 3, from 7.6% for fresh water aquatic ecotoxicity to 2.8% for global warming in scenario 4, and from 6.4% in terrestrial ecotoxicity to 2.4% for photochemical oxidation in scenario 5.

The potential advantages related to the treatment of FW by means of the bioconversion process (scenario 5) in all impact categories except for global warming are mainly due to the lower electricity consumption in the treatment phase which contributes less than 1.8% to the total impacts when compared with other scenarios. An in-depth analysis of GWP impacts shows that biogas and *H. illucens* scenarios, which present lower impacts, contribute 66.1 and 71 kg CO_2 eq per FU, respectively. In particular, the main potential impacts associated with the biogas scenario are due to the use of electricity in the pre-treatment and treatment phases, which contributes 78.9%, while, in the *H. illucens* scenario, the highest impacts are related to electricity consumption and to GHG emissions during the bioconversion process in the treatment phase, which contribute 56.4% and 24.2%, respectively, to the total GWP impacts. Furthermore, the analysis underscore the fact that the potential environmental impacts related to the composting scenario are lower than landfill and incineration scenario, and higher than the biogas and *H. illucens* scenarios in all impact categories analysed. In particular, regarding the GWP, the composting scenario shows a value of 99.2 kg CO_2 eq, and the highest impacts are due to the consumption of electricity during the treatment phase, contributing 51.9%. In addition, the treatment of the packaging material through the incineration system in scenarios 3, 4 and 5 shows lower potential environmental impact. For example, the contribution to the GWP impact is 10.5% in the composting scenario, 15.8% in biogas scenario, and 14.7% in *H. illucens* scenario. The EU results show that the lowest contribution to the total impacts is connected to the *H. illucens* scenario which shows a value of 772.62 MJ per FU, while the highest impact is related to the landfill scenario (6874.4 MJ), for which the main contribution to the EU impact category is due to the electricity consumption (94.5%) during the treatment phase. Furthermore, the biogas scenario shows the best environmental performance in terms of LU (0.47 m^2a per FU), followed by the *H. illucens* scenario (0.89 m^2a per FU). On the contrary, the highest LU impacts are connected to the landfill scenario, which contributes to the impacts for 3.18 m^2a per FU.

Table 4. Comparison between the scenarios without the inclusion of the avoided products (functional unit 1 tonne of food waste to be treated).

Impact Category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
		Landfill	Incineration	Composting	Biogas	*H. illucens*
Abiotic depletion	kg Sb eq	2.91	1.54	0.65	0.42	0.33
Acidification	kg SO_2 eq	1.99	0.88	0.50	0.29	0.22
Eutrophication	kg PO_4^- eq	0.85	0.21	0.11	0.06	0.05
Global warming	kg CO_2 eq	1243.98	822.67	99.28	66.07	71.02
Ozone layer depletion	kg CFC-11 eq	3.40×10^{-5}	2.01×10^{-5}	7.75×10^{-6}	5.03×10^{-6}	4.02×10^{-6}
Human toxicity	kg 1.4-DB eq	93.83	41.05	20.82	13.32	10.64
Fresh water aquatic ecotox.	kg 1.4-DB eq	55.64	20.65	12.26	7.77	6.11
Marine aquatic ecotoxicity	kg 1.4-DB eq	133,965.36	49,607.83	29,476.41	18,608.93	14,609.60
Terrestrial ecotoxicity	kg 1.4-DB eq	0.95	0.49	0.21	0.14	0.12
Photochemical oxidation	kg C_2H_4 eq	2.97×10^{-1}	2.97×10^{-2}	1.79×10^{-2}	1.43×10^{-2}	8.97×10^{-3}
Energy use	MJ	6874.40	3480.82	1543.14	982.36	772.62
Land use	m^2a	3.18	1.24	0.70	0.47	0.89

The analysis of each phase (collection, pre-treatment and treatment) is shown in Figure 4. Results underscore the fact that the assumption regarding localisation in the same area at an average distance among all stores of the MRC for the unpacking and the recycling/recovery plants allows an optimisation of transport activities, since the collection phase presents the lowest impacts compared with the pre-treatment and treatment phases. For instance, analysing the GWP impacts related to the *H. illucens* scenario, phase 1 contributes 6.2%, while phase 2 and phase 3 contribute 44.4% and 49.4%, respectively. Regarding the recycling/recovery scenarios, and in particular the anaerobic digestion and bioconversion systems, Figure 4 underlines the fact that the contribution of the pre-treatment phase is higher than the collection and treatment phases in all impact categories, except for photochemical oxidation in the biogas scenario and global warming in the *H. illucens* scenario. The contribution of phase 2 ranges from 44% for photochemical oxidation to 56.8% for marine aquatic ecotoxicity in scenario 4, and from 44.3% for GWP to 72.4% for marine aquatic ecotoxicity in scenario 5. The main potential environmental impacts connected to phase 2 are due to the consumption of electricity during the unpacking process. It is important to underscore that the pre-treatment phase was not evaluated in scenarios 1 and 2, since FW was sent to the landfill and to the incineration plant with its packing fraction.

For each scenario and each phase, the main hotspots are always represented by energy consumption processes, highlighting that a key issue on which the strategies of retail-oriented FW management should focus on are strongly related.

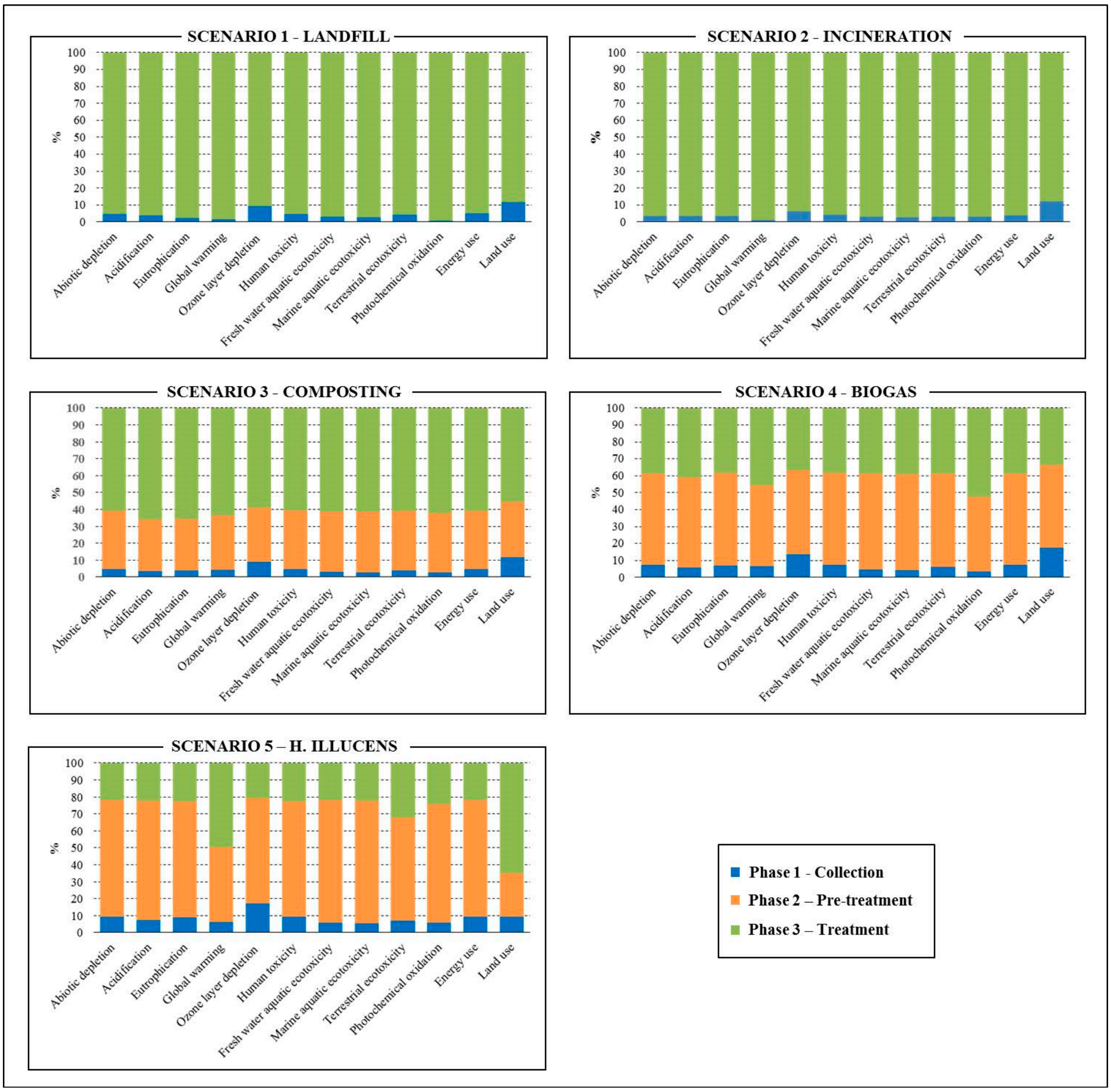

Figure 4. Characterisation results of the five scenarios: contribution analysis of the three main phases investigated (without the inclusion of the avoided products).

3.2. Characterisation Results with the Inclusion of Avoided Product

Results with the inclusion of the avoided production underscore a higher reduction of the potential environmental impacts when compared with the results excluding the avoided products (Table 5). In particular, the highest advantages are connected with the incineration, biogas and *H. illucens* scenarios, for which all of the impact categories show a high negative contribution to the impacts. Instead, the avoided production of a conventional electricity source, corresponding to the electricity obtained from the biogas produced in the landfill scenario, results in fewer benefits in terms of potential environmental impacts, since the percentage variation is from 45.26% in terrestrial ecotoxicity to 6.54% in photochemical oxidation.

Table 5. Comparison of the characterisation results related to the functional unit of 1 tonne of FW to be treated, with and without avoided products (AvPr).

Impact Category	Unit	Scenario 1—Landfill			Scenario 2—Incineration			Scenario 3—Composting			Scenario 4—Biogas			Scenario 5—*H. illucens*		
		Without AvPr	**With AvPr**	**%** [1]	**Without AvPr**	**With AvPr**	**%** [1]	**Without AvPr**	**With AvPr**	**%** [1]	**Without AvPr**	**With AvPr**	**%** [1]	**Without AvPr**	**With AvPr**	**%** [1]
Abiotic depletion	kg Sb eq	2.91	2.21	↓23.83	1.54	−0.81	↓152.83	0.65	0.36	↓44.85	0.42	−2.57	↓717.00	0.33	−1.01	↓408.58
Acidification	kg SO_2 eq	1.99	1.51	↓24.01	0.88	−0.74	↓184.98	0.50	0.38	↓24.60	0.29	−0.23	↓179.16	0.22	−1.28	↓681.51
Eutrophication	kg PO_4^- eq	0.85	0.75	↓12.05	0.21	−0.14	↓163.86	0.11	0.07	↓34.52	0.06	−0.04	↓162.99	0.05	−0.19	↓492.76
Global warming	kg CO_2 eq	1,243.98	1146.40	↓7.84	822.67	491.13	↓40.30	99.28	59.25	↓40.32	66.07	−299.46	↓553.26	71.02	−419.61	↓690.81
Ozone layer depletion	kg CFC-11 eq	3.40×10^{-5}	2.63×10^{-5}	↓22.61	2.01×10^{-5}	-6.08×10^{-6}	↓130.28	7.75×10^{-6}	5.96×10^{-6}	↓23.11	5.03×10^{-6}	-3.49×10^{-5}	↓793.79	4.02×10^{-6}	-3.80×10^{-6}	↓194.54
Human toxicity	kg 1.4-DB eq	93.83	69.32	↓26.13	41.05	−42.24	↓202.90	20.82	2.08	↓90.02	13.32	−33.29	↓350.04	10.64	5.33	↓49.88
Fresh water aquatic ecotoxicity	kg 1.4-DB eq	55.64	41.50	↓25.41	20.65	−27.38	↓232.58	12.26	7.38	↓39.81	7.77	0.68	↓91.22	6.11	3.80	↓37.87
Marine aquatic ecotoxicity	kg 1.4-DB eq	133,965.36	99,913.94	↓25.42	49,607.83	−66,084.95	↓233.21	29,476.41	15,618.24	↓47.01	18,608.93	−1,724.67	↓109.27	14,609.60	11,948.60	↓18.21
Terrestrial ecotoxicity	kg 1.4-DB eq	0.95	0.52	↓45.26	0.49	−0.98	↓300.99	0.21	0.00	↓101.06	0.14	−0.15	↓208.35	0.12	0.06	↓53.18
Photochemical oxidation	kg C_2H_4 eq	2.97×10^{-1}	2.78×10^{-1}	↓6.54	2.97×10^{-2}	-3.64×10^{-2}	↓222.74	1.79×10^{-2}	1.32×10^{-2}	↓26.14	1.43×10^{-2}	-1.70×10^{-2}	↓219.14	8.97×10^{-3}	-2.25×10^{-2}	↓351.28

Notes: [1] The percentage variation is calculated assuming the results related to the scenarios "without AvPr" as 100%.

Comparing the three scenarios with energy recovery (landfill, incineration, biogas), the characterisation results (Figure 5) underscore the fact that the lowest environmental loads are related to scenario 2 in all impact categories except for abiotic depletion, global warming and ozone layer depletion, in which the biogas scenario shows the highest advantages. Specifically, the higher performance connected with the incineration system is due to the substitution of conventional electricity with the energy recovered during the FW treatment, while the potential impacts related to the biogas scenario are −2.57 kg Sb eq per FU in abiotic depletion, −299.46 kg CO_2 eq per FU in GWP, and -3.57×10^{-5} kg CFC-11 eq per FU in ozone layer depletion, respectively. The reduction of the potential environmental impacts connected with scenario 4 are mainly due to the substitution of the electricity conventionally produced from natural gas with the electricity produced through the combustion of the biogas produced during the FW treatment, which contributes to the reduction of the impacts by −0.763 kg Sb eq per FU in terms of abiotic depletion, −92.3 kg CO_2 eq per FU in terms of GWP, and 1.01×10^{-5} kg CFC-11 eq per FU in terms of ozone layer depletion, respectively. Instead, the highest contribution to the impacts is related to the landfill scenario for which the replacement of a conventional energy source with the electricity obtained by the disposal and treatment of FW does not allow a higher reduction of the potential environmental impacts.

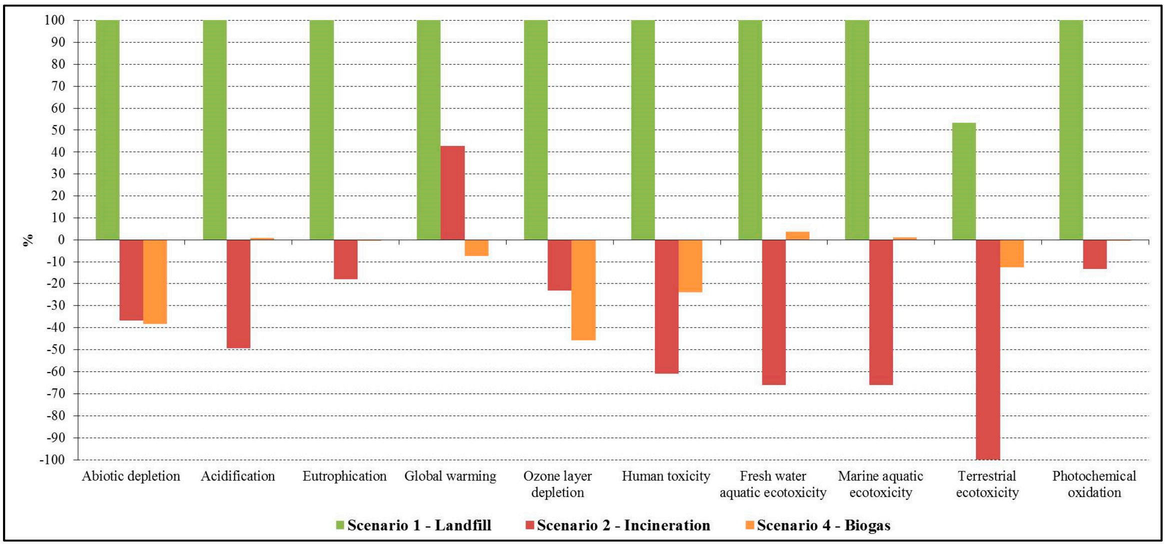

Figure 5. Comparison among the energy-recovery scenarios including the avoided products (characterisation results per 1 tonne of FW to be treated).

The analysis of EU and LU impacts related to scenarios 1, 2 and 4 (Table 6) underscores the fact that the main potential environmental benefits are related to the avoided production of conventional electricity, substituted by the electricity obtained through the incineration of the FW and its packaging, allowing a reduction in EU and LU of 2085.10 MJ and −1.26 m^2a, respectively. Environmental benefits are also related to the biogas, considering, in particular, the EU (−1658.47 MJ per FU) impact category, and are mainly due to the replacement of electricity by natural gas with the electricity produced through the combustion of the biogas obtained during the anaerobic digestion process, contributing about 94% to the reduction of the EU impacts. On the contrary, the landfill scenario shows the highest environmental impacts in both EU and LU, when compared with incineration and biogas scenarios.

Table 6. Energy use (EU) and land use (LU) results related to the landfill, incineration and biogas scenarios with the inclusion of the avoided products.

Impact Category	Unit	Scenario 1	Scenario 2	Scenario 4
		Landfill	Incineration	Biogas
Energy use	MJ	5236.21	−2085.10	−1658.47
Land use	m^2a	2.44	−1.26	−0.14

Regarding the two scenarios with material recovery, composting (scenario 3) and bioconversion through *H. illucens* (scenario 5) allow obtaining compost as a primary valuable material by means of the composting and bioconversion treatment of the FW fraction. Furthermore, the bioconversion process also allows the production of protein (dried larvae) to be used for fishmeal formulation. The results of the comparative analysis (Figure 6) highlight that scenario 5 presents higher potential environmental advantages than scenario 3 in all impact categories. This is due to the replacement of conventional fertilizers with the compost produced by the bioconversion process (scenario 5), which allows a reduction of the potential environmental impacts for −164 kg CO_2 eq per FU, for example, for the global warming impact category. The substitution of conventional fish feed, such as soy meal, with the dried larvae, produced during the bioconversion process, provides a lower contribution to the environmental benefits, for example by about 25.7 kg CO_2 eq per FU in the global warming impact category.

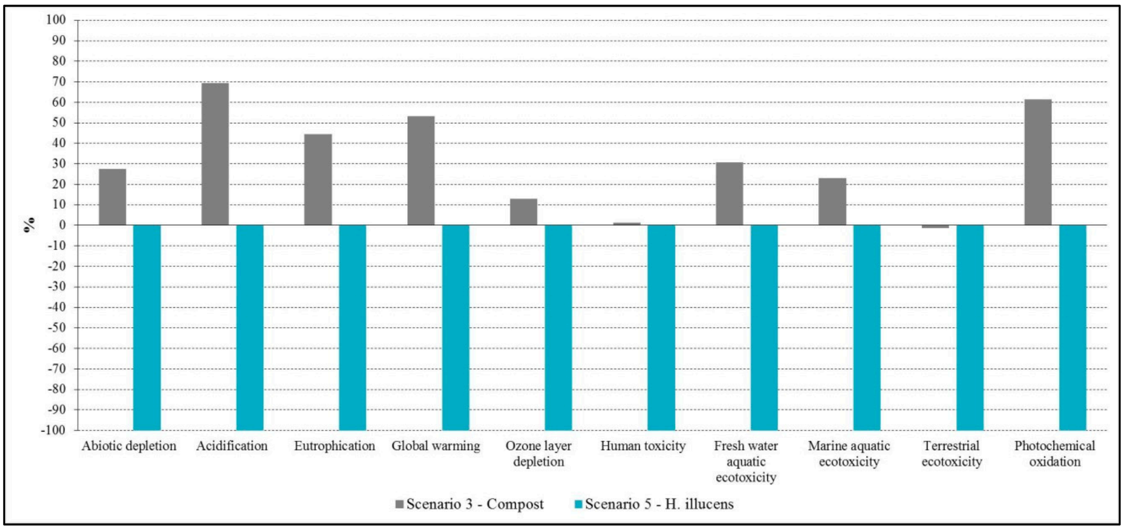

Figure 6. Comparison between the material-recovery scenarios including the avoided products (characterisation results per 1 tonne of FW to be treated).

Regarding the EU and LU impacts related to comparison between the compost and *H. illucens* scenarios (Table 7), the results underscore that the highest negative contribution to the potential environmental impacts is connected to scenario 5, which allows a reduction of −2698.11 MJ per FU in terms of EU, and −1.88 m^2a per FU in terms of LU. The main environmental benefits are due to the replacement of conventional fertilisers with the compost produced by means of the bioconversion of the FW. The composting scenario shows the highest EU and LU impacts and the avoided production of urea does not allow negative contribution in both of the investigated impact categories.

Table 7. Energy use (EU) and land use (LU) results related to the composting and *H. illucens* scenarios with the inclusion of the avoided products.

Impact Category	Unit	Scenario 3	Scenario 5
		Composting	***H. illucens***
Energy use	MJ	875.24	−2698.11
Land use	m^2a	0.18	−1.88

Lastly, the avoided production of conventional electricity due to the energy recovery during the incineration of the packaging materials results in the lowest environmental benefits in scenarios 3, 4 and 5, considering all the impact categories. For example, the contribution to the GWP impact is less than 9.5%, in all the scenarios.

4. Conclusions

The comparison of different scenarios for the disposal or recycling of FW produced by a mass retail company operating in Messina (Italy) through the application of LCA method has been performed in order to propose the most preferable treatment solution in terms of potential environmental impacts. To the authors' knowledge, this is the first LCA study that compares different FW treatment scenarios at the retail level, including in the system boundaries of the bioconversion process through the action of *H. illucens* insects. The results underscore the fact that the main environmental impacts are connected to the landfill and incineration scenarios, while the best environmental performances are related to the *H. illucens* scenario in all impact categories, except for GWP in which the anaerobic digestion treatment shows the lowest environmental impacts. The percentage contribution of the bioconversion treatment ranges from 6.4% in terrestrial ecotoxicity to 2.4% in photochemical oxidation, while the GWP related to the biogas scenario is 66.07 kg CO_2 eq per FU. Furthermore, the localisation in the same area, at an average distance among all sale points of the MRC, of the unpacking and the recycling/recovery plants allows an optimisation of the transports during the collection phase. This underscores the fact that the utilisation of an organised transport network can allow higher environmental performance. Including the avoided production of conventional energy sources in the analysis and comparing the scenarios that allowed the production of alternative energy sources (landfill, incineration and biogas scenarios) through the treatment of FW, the incineration scenario showed higher environmental benefits followed by the biogas scenario which presented significant advantages with respect to the abiotic depletion, global warming and ozone layer depletion impact categories. This is in accordance with different authors [29,38], who underscored the higher environmental benefits related to the incineration treatment with energy recovery. Results also highlighted that, comparing the scenarios which allow the production of valuable materials, such as compost (composting and *H. illucens* scenarios) and feed (*H. illucens* scenario), the bioconversion process showed higher environmental performances then the composting process in all impact categories. This highlights the fact that the treatment of FW through the bioconversion process can be an efficient solution.

The results of the study have some limitations connected with the influence of some of the analysis choices, such as the impact category selected to carry out the analysis or the type of alternative products obtained during the treatment process, accounted as avoided productions. In addition, FW and packaging composition could directly cause changes in the treatment process as well as in the efficiency of the plants, considering, in particular, the landfill and incineration scenarios. Furthermore, although the LCA is a non-site-specific method, the results of an analysis regarding FW treatment could change in consideration of a different region where different diet could allow the production of different FW. In this context, the efficiency of the treatment process can be directly related to the characteristic of the FW, such as moisture content or lower heating value. Lastly, this study accounted for the data from a small number of MRC stores (12) and analysed only five treatment scenarios, thus more stores and treatment systems should be included in a further analysis.

Anyhow, the results could be efficiently used to identify some best practices that the MRC may include in its sustainable FW management strategy. In addition, since the assumptions are also related to the hypothetical localisation of the treatment plants, further studies should be oriented to the analysis of the costs related to the installation of the most preferable systems in the mentioned area, and to transport activities, through the application of the Life Cycle Costing method. This would allow supporting the MRC to achieve two of the three pillars related to the sustainable development, considering both environmental and economic issues connected to the specific context of the FW management.

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References

1. Gustavsson, J.; Cederberg, C.; Sonesson, U.; van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste: Extent, Causes and Prevention*; FAO: Rome, Italy, 2011; ISBN: 978-92-5-107205-9.
2. Stenmarck, Å.; Jensen, C.; Quested, T.; Moates, G.; Buksti, M.; Cseh, B.; Juul, S.; Parry, A.; Politano, A.; Redlingshofer, B.; et al. FUSIONS—Food waste data set for EU-28. New estimates and environmental impact. In *European Commission's Project. Reducing Food Waste through Social Innovation*; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2016; ISBN: 978-91-88319-01-2.
3. Papargyropoulou, E.; Lozano, R.; Steinberger, J.K.; Wright, N.; Ujang, Z. Bin The food waste hierarchy as a framework for the management of food surplus and food waste. *J. Clean. Prod.* **2014**, *76*, 106–115. [CrossRef]
4. Salomone, R.; Saija, G.; Mondello, G.; Giannetto, A.; Fasulo, S.; Savastano, D. Environmental impact of food waste bioconversion by insects: Application of life cycle assessment to process using Hermetia illucens. *J. Clean. Prod.* **2017**, *140*, 890–905. [CrossRef]
5. Porter, S.D.; Reay, D.S.; Higgins, P.; Bomberg, E. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. *Sci. Total Environ.* **2016**, *571*, 721–729. [CrossRef] [PubMed]
6. European Commission. *Preparatory Study on Food Waste across EU 27*; European Commission: Brussels, Belgium, 2010; Volume 33, ISBN: 978-92-79-22138-5.
7. European Parliament. Directive 2008/98/EC of the European Parliament and the Council of 19 November 2008 on Waste and Repealing Certain Directives. Available online: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32008L0098 (accessed on 17 January 2017).
8. Zaman, A.U. Identification of key assessment indicators of the zero waste management systems. *Ecol. Indic.* **2014**, *36*, 682–693. [CrossRef]
9. Notarnicola, B.; Salomone, R.; Petti, L.; Renzulli, P.A.; Cerutti, A.K.; Roma, R. *Life Cycle Assessment in the Agri-Food Sector: Case Studies, Methodological Issues and Best Practices*; Springer: Cham, Switzerland, 2015; ISBN: 978-3-319-11940-3.
10. European Union. *Combating Food Waste: an Opportunity for the EU to Improve the Resource-Efficiency of the Food Supply Chain*; Special Report No 34 (EN); European Court of Auditors (ECA)—European Union: Luxembourg, 2016; ISBN: 978-92-872-6416-9.
11. Brancoli, P.; Rousta, K.; Bolton, K. Life cycle assessment of supermarket food waste. *Resour. Conserv. Recycl.* **2017**, *118*, 39–46. [CrossRef]
12. Notarnicola, B.; Serenella, S.; Assumpció, A.; McLarend, S.J.; Saouterb, E.; Sonesson, U. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *J. Clean. Prod.* **2017**, *140*, 399–409. [CrossRef]

13. Schott, A.B.S.; Wenzel, H.; la Cour Jansen, J. Identification of decisive factors for greenhouse gas emissions in comparative life cycle assessments of food waste management—An analytical review. *J. Clean. Prod.* **2016**, *119*, 13–24. [CrossRef]
14. Carlsson, M.; Naroznova, I.; Møller, J.; Scheutz, C.; Lagerkvist, A. Importance of food waste pre-treatment efficiency for global warming potential in life cycle assessment of anaerobic digestion systems. *Resour. Conserv. Recycl.* **2015**, *102*, 58–66. [CrossRef]
15. Kondusamy, D.; Kalamdhad, A.S.; Kondusamy, D.; Kalamdhad, A.S. Pre-treatment and anaerobic digestion of food waste for high rate methane production—A review. *J. Environ. Chem. Eng.* **2014**, *2*, 1821–1830. [CrossRef]
16. Caputo, P.; Ducoli, C.; Clementi, M. Strategies and tools for eco-efficient local food supply scenarios. *Sustainability* **2014**, *6*, 631–651. [CrossRef]
17. Bernstad, A.; la Cour Jansen, J. Review of comparative LCAs of food waste management systems—Current status and potential improvements. *Waste Manag.* **2012**, *32*, 2439–2455. [CrossRef] [PubMed]
18. Naroznova, I.; Møller, J.; Scheutz, C. Global warming potential of material fractions occurring in source-separated organic household waste treated by anaerobic digestion or incineration under different framework conditions. *Waste Manag.* **2016**, *58*, 397–407. [CrossRef] [PubMed]
19. Bernstad, A.; la Cour Jansen, J. A life cycle approach to the management of household food waste—A Swedish full-scale case study. *Waste Manag.* **2011**, *31*, 1879–1896. [CrossRef] [PubMed]
20. Scholz, K.; Eriksson, M.; Strid, I. Carbon footprint of supermarket food waste. *Resour. Conserv. Recycl.* **2015**, *94*, 56–65. [CrossRef]
21. Eriksson, M.; Spångberg, J. Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarkets. *Waste Manag.* **2017**, *60*, 786–799. [CrossRef] [PubMed]
22. Eriksson, M.; Strid, I.; Hansson, P.A. Carbon footprint of food waste management options in the waste hierarchy—A Swedish case study. *J. Clean. Prod.* **2015**, *93*, 115–125. [CrossRef]
23. Guinée, J.B. Handbook on life cycle assessment, operational guide to the ISO standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [CrossRef]
24. International Organisation for Standardisation (ISO). *ISO 14040:2006. Environmental Management—Life Cycle Assessment—Principles and Framework*; International Standards Organisation: Geneva, Switzerland, 2006.
25. International Organisation for Standardisation (ISO). *ISO 14044:2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; International Standards Organisation: Geneva, Switzerland, 2006.
26. San Martin, D.; Ramos, S.; Zufía, J. Valorisation of food waste to produce new raw materials for animal feed. *Food Chem.* **2016**, *198*, 68–74. [CrossRef] [PubMed]
27. Ahamed, A.; Yin, K.; Ng, B.J.H.; Ren, F.; Chang, V.W.C.; Wang, J.Y. Life cycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives. *J. Clean. Prod.* **2016**, *131*, 607–614. [CrossRef]
28. Atritor. Available online: http://www.turboseparator.co.uk/ (accessed on 10 January 2017).
29. Mendes, M.R.; Aramaki, T.; Hanaki, K. Comparison of the environmental impact of incineration and landfilling in São Paulo City as determined by LCA. *Resour. Conserv. Recycl.* **2004**, *41*, 47–63. [CrossRef]
30. Righi, S.; Oliviero, L.; Pedrini, M.; Buscaroli, A.; Della Casa, C. Life cycle assessment of management systems for sewage sludge and food waste: Centralized and decentralized approaches. *J. Clean. Prod.* **2013**, *44*, 8–17. [CrossRef]
31. Ecoinven Centre. *Ecoinvent Data v2.0 Final Reports Ecoinvent*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
32. Nielsen, P.H.; Nielsen, A.M.; Weidema, B.P.; Dalgaard, R.; Halberg, N. LCA Food Database. 2003. Available online: www.lcafood.dk (accessed on 17 January 2017).
33. PRè Consultant. *Simapro 8*; PRè Consultant: Amersfoort, The Netherlands, 2010.
34. CML. *CML 2 Baseline 2000*; Centre of Environmental Science: New Delhi, India, 2000.
35. Verein Deutscher Ingenieure (VDI) Cumulative energy demand terms, definitions, methods of calculation. In *VDI-Richtlinien 4600*; Verein Deutscher Ingenieure: Düsseldorf, Germany, 1997.
36. Frischknecht, R.; Jungbluth, N.; Althaus, H.J.; Bauer, C.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Köllner, T.; et al. *Implementation of Life Cycle Impact Assessment Methods*; Final Report Ecoinvent 2000 No. 3; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.

37. Guinée, J.B.; Gorée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; de Koning, A.; van Oers, L.; Wegener Sleeswijk, A.; Suh, S.; de Haes, H.A.U.; et al. *Life Cycle Assessment: An Operational Guide to the ISO Standards: Characterization and Normalization*; Ministry of Housing, Spatial Planning and the Environment and Centre of Environmental Science: Leiden, The Netherlands, 2001.
38. Arena, U.; Mastellone, M.L.; Perugini, F. The environmental performance of alternative solid waste management options: A life cycle assessment study. *Chem. Eng. J.* **2003**, *96*, 207–222. [CrossRef]