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Life Cycle Assessment of Energy Production from Solid Waste Valorization and Wastewater Purification: A Case Study of Meat Processing Industry

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Abstract: The meat processing industry is a very energy-intensive and water-demanding industry that produces large amounts of solid and aqueous wastes. Therefore, methods for the effective treatment of the produced wastes have been studied in order to treat and reuse water within the industry and valorize the solid wastes for the production of energy and value-added products. The primary aim of this work is to evaluate the overall sustainability of energy produced from solid waste valorization and wastewater treatment in the meat processing industry via Life Cycle Assessment (LCA). For this purpose, the total environmental impact of a typical meat industry that utilizes conventional waste management methods (Scenario A) was evaluated and compared with two different industries with appropriate waste treatment/valorization processes. In the first studied valorization scenario (Scenario B), waste management is conducted using anaerobic digestion, composting, membrane bioreactors, and ultraviolet (UV) treatment, whereas in the second studied valorization scenario (Scenario C), aeration treatment, chlorination, and hydrothermal carbonization (HTC) are the selected treatment techniques. As expected, it is evident from this LCA study, that both Scenarios B and C exhibited a significantly improved environmental footprint in all studied indicators compared with Scenario A, with the reduction in certain environmental impact categories reaching up to 80%. Between the two studied alternative scenarios, the biggest improvement in the environmental footprint of the meat industry was observed in Scenario C, mainly due to the substantial quantity of the produced thermal energy. According to the results of the present case study, it is evident that the incorporation of appropriate methods in the meat industry can result in the efficient generation of energy and a significant improvement in the environmental footprint contributing to environmental safety and sustainability.

Keywords: Life Cycle Assessment; sustainability; waste valorization; energy production; wastewater treatment; meat processing industry

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1. Introduction

The meat processing industry is a continuously developing field that includes the utilization of large quantities of natural resources, such as water and energy [1]. As a result, the meat processing industry is accountable for severe environmental impacts (on air, water, and soil), which are constantly growing due to vast amounts of energy and water consumption, as well as waste production [2]. Moreover, the management and treatment of the produced wastes requires further consumption of energy and raw materials that can further burden the environmental footprint of the specific industry due to the high organic content of both solid wastes and wastewater [2]. However, the nature of the produced wastes provides a plethora of opportunities for treatment and valorization (water recycling and reuse, energy production, material recovery, etc.) [3].

Among several methods for the treatment and valorization of meat processing waste aiming at energy and production water reuse, the ones that have been selected as the most appropriate due to their efficiency in wastewater treatment and renewable energy production via waste valorization are the following: membrane bioreactor, aeration treatment, chlorination, ultraviolet (UV) treatment, anaerobic digestion, hydrothermal carbonization (HTC), and composting. A membrane bioreactor is a state-of-the-art alternative method for wastewater treatment that couples the biological process with membrane filtration. Specifically, it consists of a bioreactor tank, in which the biomass is degraded, followed by membrane filtration for the removal of microorganisms from the treated water [4]. Aeration treatment involves the addition of air into wastewater, thus allowing the biodegradation of organic compounds resulting in water decontamination [5]. UV treatment is an effective method for the disinfection of treated water, in which water is exposed to ultraviolet light resulting in the disinfection of hazardous pathogens, such as bacteria and viruses [6]. Chlorination is a reliable and efficient method used for water disinfection, which possesses the ability to efficiently oxidize a wide spectrum of organic and inorganic compounds as well as to eliminate any microbial hazards [7]. Anaerobic digestion constitutes an anaerobic fermentation process for solid wastes (wet), in which organic matter is efficiently degraded by microorganisms and converted into biogas [8]. Subsequently, the biogas is transferred into a biogas cogeneration (combined heat and transfer—CHP) unit and generates power (renewable) in the form of electricity and heat [9]. One other advantage of anaerobic digestion is derived from the fact that the solid residue of the process (digestate) can be utilized in composting, further increasing the circularity of the solid wastes [10]. Hydrothermal carbonization (HTC) involves the conversion of organic compounds through certain chemicals into structured solid fuels, which can subsequently be utilized for the generation of electricity and thermal energy [11]. The combination of several of the aforementioned methods in the treatment of wastewater and solid wastes produced during meat processing has the potential not only to reduce the total waste of the industry, thus improving the environmental footprint of the sector, but also to reuse the recovered water and produced energy within the industry, increasing to a degree self-sufficiency of natural resources and reducing the operating cost [12].

However, it is necessary to confirm the environmental benefits of the specific methods in comparison to the conventional existing ones. Life Cycle Assessment (LCA) is a verified tool, defined by the International Organization for Standardization (ISO 14040:2006) for assessing the environmental behavior of processes/products/services [13]. LCA takes into consideration the inputs, outputs, and potential environmental effects of a product system across its life cycle, and can pinpoint hot points and recommend improvements in the production process aiming at environmental sustainability [14]. LCA can be performed according to two different principal approaches, the attributional and the consequential methods. The first reports the environmental features of a current state system, while the latter, which is used in the present work, focuses on prognosticating the effect of changes in established procedures [15]. Additionally, the life cycle impact indicators can be quantified by various methods, including ReCiPE, EDIP, and CML, which frequently exhibit different impact categories, classification of inventory, and model characterization [14].

The primary aim of the present study was to evaluate the environmental sustainability of various treatment methods for wastewater and solid wastes utilized in meat processing industries. For this purpose, a conventional meat processing industrial line was first investigated to highlight the environmental impact of the specific sector and the necessity for efficient utilization of the wastes for energy production and wastewater purification. Subsequently, three different scenarios (Scenarios A, B, and C) for the treatment of wastewater and solid wastes were studied, the first consisting of conventional methods and the latter two of innovative ones, aiming at confirming the environmental benefits of the proposed methods for energy production and wastewater purification.

2. Materials and Methods

LCA study was performed following the recommendations proposed by the ISO 14040 recommendations series (14040:2006 and 14044:2006) [16]. ReCiPe 2016 (H, hierarchist) was selected as a method to perform the impact assessment, with its main objective being the transformation of Life Cycle Inventory results into a limited number of environmental impact scores using characterization factors. Finally, GABI ts software (v10.6.2.9, Sphera Solutions GmbH, Echterdingen, Stuttgart, Germany) was used for the calculation of the impact categories [16].

2.1. Goal

The goal of the LCA study was to determine the effect of the implementation of various wastewater and solid waste treatment methods for energy production in the conventional meat processing industry on different environmental impact categories. First, the environmental impact of the conventional meat processing industry was evaluated, using data obtained from existing references. Subsequently, to evaluate the effect of the benefits of incorporating novel methods for waste valorization and wastewater purification, three different scenarios were studied based on the literature, one with conventional treatment methods and the other two with innovative ones.

2.2. . . . and Scope

2.2.1. Product System

The case of the present work was based on the conventional meat processing industry, with the final products being various pork-meat products, including packaged and fresh meat. Figure 1 depicts the production processes and the involved flows. The main processing steps involved in meat processing include the following:

- Slaughter house;
- Scalding and hide removal;
- Evisceration;
- Trimming;
- Refrigeration and chilling;
- Cutting and deboning;
- Processing;
- Packaging of the final products.

The corresponding flows are highlighted in five different colors in order to be better classified. Light and dark red colors indicate the flows connected to steam and solid wastes, respectively. Flows related to condensate and wastewater are depicted in light and dark purple, respectively. Finally, green connects to the final product flows, and the blue color indicates the rest of the flows in the meat processing.

In the first studied scenario (Scenario A) for the wastewater and solid waste treatment (Figure 2), wastewater is transferred to a municipal wastewater treatment plant, and solid wastes are processed in landfilling. This scenario considers that the meat processing industry is not involved in any recycling treatment and/or valorization of its waste for energy production, which constituted the most common practice for several years.

In the second studied scenario (Scenario B), wastewater and solid wastes are treated on-site within the boundaries of the industry (Figure 3). Specifically, wastewater is first screened, processed in a membrane bioreactor, and finally treated with UV radiation. Therefore, the final product will be cleaned water that can be either recycled in the industry (decreasing freshwater consumption) or returned clean to the aquatic environment [4]. Solid wastes are treated in an anaerobic digester, with the resulting biogas (after CO_2 removal to increase the methane content) used for the production of electricity and heat via cogeneration [17]. The produced heat is recirculated to the anaerobic digester, while electricity is sold to the grid as renewable energy (for economic reasons). Finally, the digestate from the anaerobic digestion is transferred to a composting unit.

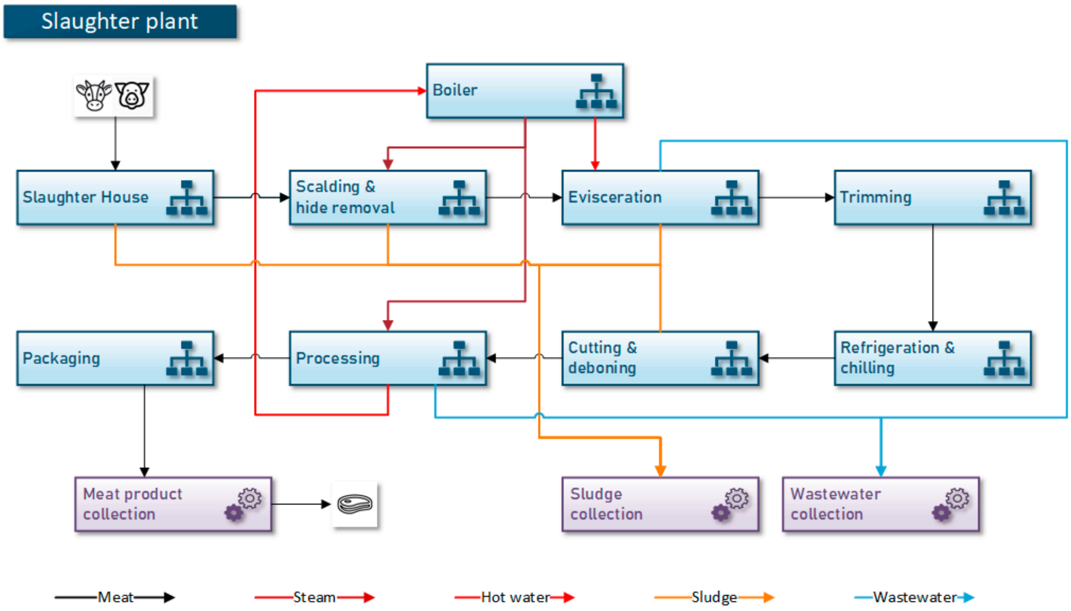

Figure 1. Production process flowcharts and main flows.

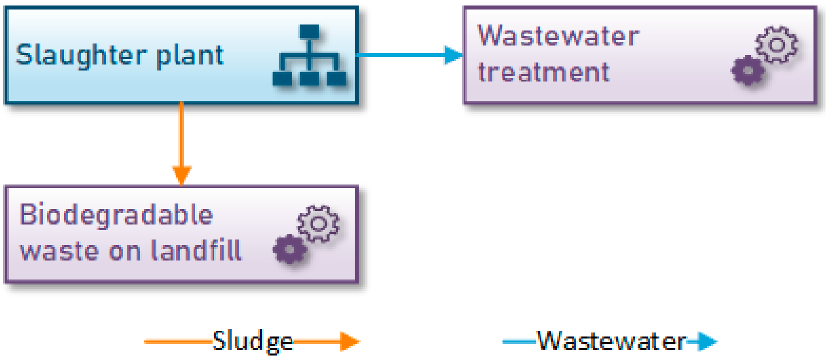

Figure 2. Wastewater and solid waste treatment, and main flows in Scenario A.

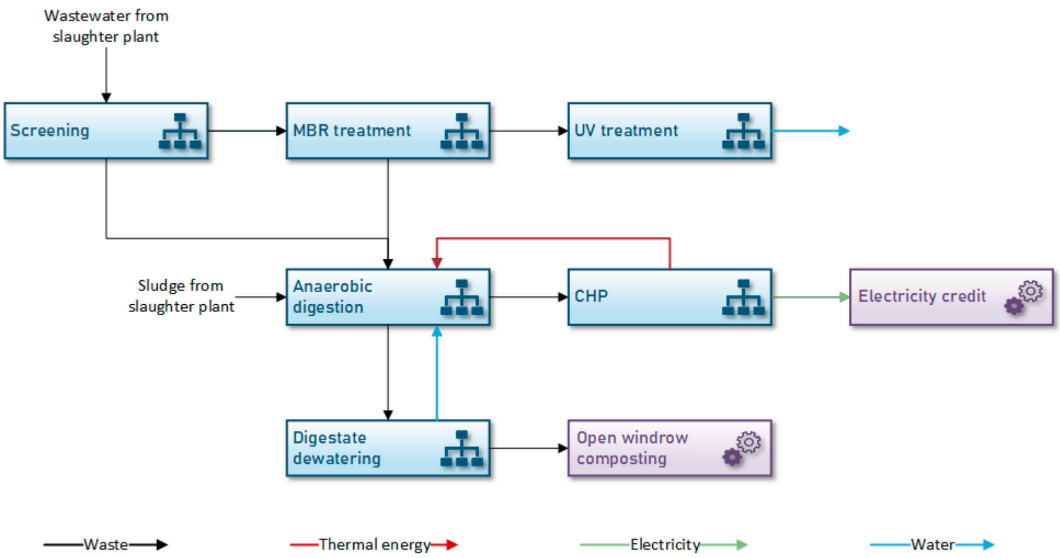

Figure 3. Wastewater and solid waste treatment, and main flows in Scenario B.

In the third studied scenario (Scenario C), wastewater and solid wastes are treated on-site within the boundaries of the industry, similar to the previously analyzed scenario (Figure 4). However, in this studied scenario, different methods were studied for the treatment and valorization of wastewater and solid wastes. More specifically, wastewater is screened as a preliminary treatment to remove large-size solids, which are then processed in landfilling and transferred to an aeration tank. During aeration treatment, air and sodium hypochlorite are transferred into the tank and are mixed with the wastewater, thus enabling the biodegradation of organic compounds. Subsequently, chlorination using sodium hypochlorite as a disinfection agent is utilized in order to eliminate any microbial and chemical hazards, with the final product being clean water that can be safely recycled in the industry or discharged into the aquatic environment [7]. Solid wastes are treated using the hydrothermal carbonization process. At first, the solid wastes are partially dried in order to increase the percentage of solids (circa 92%) and then transferred to an HTC reactor, where a slurry containing solid fuel and hydrolysates is generated, with the latter being removed via filtration and transported to a municipal wastewater treatment plant. Afterward, the obtained solid fuels are completely dried and pelletized. Finally, pellets are blown into a power generator, resulting in the generation of electricity and thermal energy [11]. The generation of thermal energy and electricity in Scenarios B and C is depicted as thermal and electricity credits, respectively. Generally, thermal and electricity credits exhibit an overall positive impact on the environmental footprint of both scenarios due to the fact that energy is produced from waste valorization and not from the conventional burning of fossil fuels. Finally, it must be stated that the wastewater generated within the meat processing industry exhibits high organic content and high concentrations of organic metabolites; thus, the applied methods should be carefully selected to obtain wastewater purification. However, according to the literature, the studied methods in this manuscript have been efficiently applied for the purification of the aforementioned wastewater effluents [18–21].

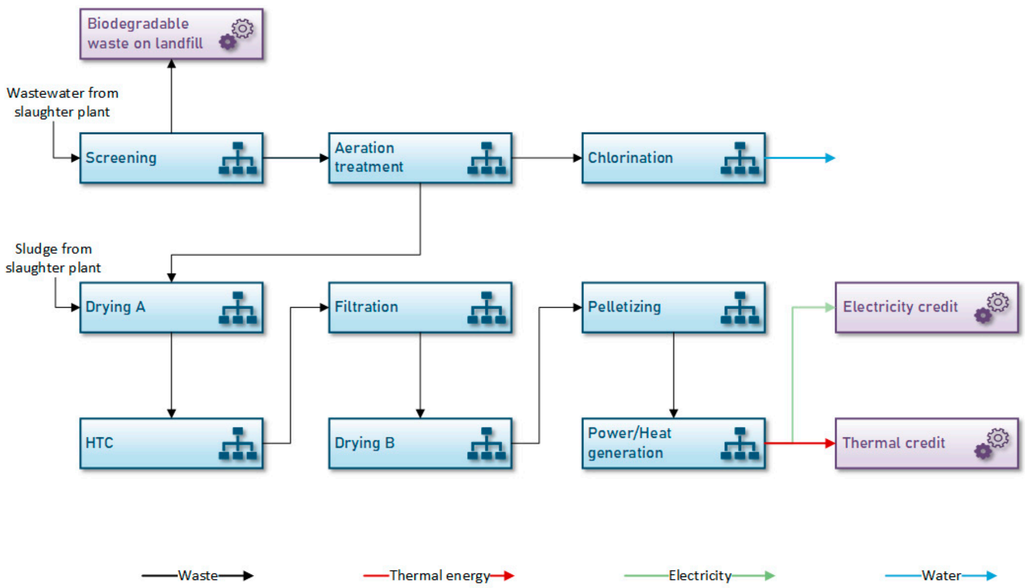

Figure 4. Wastewater and solid waste treatment, and main flows in Scenario C.

2.2.2. Functional Unit

The functional unit selected for the present work was 1 kg/d of produced meat products.

2.2.3. System Boundaries

The system boundaries for the case of the typical meat processing industry that evaluates the environmental footprint of the production of meat products are defined as gate-to-gate. Specifically, the system boundaries include all the production processes from a slaughter house to packaging. The system boundaries of the two alternative studied scenarios (Scenario B and C) are also defined as gate-to-gate and consist of the production process and the respective wastewater and solid waste treatment. The transportation of the feedstock as well as of the final meat products is not included in the system boundaries.

2.2.4. Data Requirements

The data that were used for this study were obtained from studies accessible in references; the data were also taken from GABI professional and Ecoinvent databases, referring to the geographical area of the European Union 28 (EU-28). All studies and data refer to a period of the last 5 years.

2.2.5. Assumptions and Limitations

Data used in the meat production processes and the three studied scenarios are based on the literature review; thus, they do not represent an accurate recording of an existing situation, possibly leading to a level of uncertainty in the estimation of environmental footprints [22]. However, the main purpose of this study was the confirmation of the environmental benefits of the proposed methods compared with conventional handling of wastewater and solid wastes and, thus, this uncertainty is not expected to influence the results since it affects all the studied scenarios.

2.3. Life Cycle Inventory

Life Cycle Inventory (LCI) connects the processes with quantitative data according to the selected functional unit (1 kg of meat products per day). Table 1 presents the input and output data of every process that is included in the meat processing industry, as shown in Figure 1. As a reference for the collection of the data and the establishment of the inventory, the literature data were used, as listed below; however, appropriate changes were made, and the numbers were verified via communication with the meat processing industry located in the Attica area in Greece. Environmental data were obtained from GABI professional (8007 db version 2022) and Ecoinvent (Ecoinvent 3.8) databases.

Table 1. Life Cycle Inventory (LCI) of the conventional meat processing industry (based on [23] and adjusted to current data via communication with the meat processing industry located in the Attica area).

Process	Input/Output	Flow	Unit	Value
Slaughter house	In	Feedstock	kg	1.53
	In	Electricity	kJ	7.43
	Out	Feedstock	kg	1.47
	Out	Blood (sludge)	kg	0.06
Scalding and hide removal	In	Feedstock	kg	1.47
	In	Steam	kg	0.06
	In	Electricity	kJ	3.62
	Out	Feedstock	kg	1.41
	Out	Hide (sludge)	kg	0.01
	Out	Fur (sludge)	kg	0.05
	Out	Water vapor	kg	0.06
Evisceration	In	Feedstock	kg	1.41
	In	Hot water	kg	1.02
	Out	Carcass	kg	0.94
	Out	Viscera and inedible parts (sludge)	kg	0.34
	Out	Meat prod. 1	kg	0.12
	Out	Wastewater	kg	1.02

Table 1. *Cont.*

Process	Input/Output	Flow	Unit	Value
Trimming	In	Carcass	kg	0.94
	In	Electricity	kJ	2.90
	Out	Carcass	kg	0.90
	Out	Meat prod. 2	kg	0.04
Refrigeration and chilling	In	Carcass	kg	0.90
	In	Electricity	kJ	262.62
	In	Cooling water	kg	16.35
	Out	Carcass	kg	0.62
	Out	Meat prod. 3	kg	0.28
	Out	Cooling water	kg	16.35
Cutting and deboning	In	Carcass	kg	0.62
	In	Electricity	kJ	5.43
	Out	Other meat	kg	0.47
	Out	Meat prod. 4	kg	0.07
	Out	Bones and inedible parts (sludge)	kg	0.08
Processing	In	Other meat	kg	0.47
	In	Steam	kg	0.02
	In	Electricity	kJ	53.97
	In	Fuel (diesel)	kJ	243.42
	In	Water	kg	2.90
	Out	Other meat	kg	0.47
	Out	Condensate	kg	0.02
	Out	Wastewater	kg	2.90
Packaging	In	Other meat	kg	0.47
	In	PP (tray)	kg	0.02
	In	Electricity (packaging)	kJ	102.33
	In	Electricity (tray)	kJ	42.75
	Out	Meat prod. 5	kg	0.49
Boiler	In	Condensate	kg	0.02
	In	Water (deionized)	kg	1.08
	In	Fuel (natural gas)	kJ	721.01
	Out	Steam	kg	0.08
	Out	Hot water	kg	1.02
Total meat products	In	Meat prod. 1	kg	0.12
	In	Meat prod. 2	kg	0.04
	In	Meat prod. 3	kg	0.28
	In	Meat prod. 4	kg	0.07
	In	Meat prod. 5	kg	0.49
	Out	Meat products	kg	1.00

Table 2. Life Cycle Inventory (LCI) of Scenario A.

Process	Input/Output	Flow	Unit	Value
Municipal wastewater treatment	In	Wastewater from evisceration	kg	1.02
		Wastewater from processing	kg	2.90
		Total	kg	3.92
Biodegradable waste on landfill	In	Blood	kg	0.06
		Hide	kg	0.01
		Fur	kg	0.05
		Viscera and inedible parts	kg	0.3
		Bones and inedible parts	kg	0.08
		Total	kg	0.54

Tables 2–4 present the input and output data of every process that is included in the different scenarios, as shown in Figures 2–4.

Table 3. Life Cycle Inventory (LCI) of Scenario B.

Process	Input/Output	Flow	Unit	Value
Screening [24]	In	Wastewater	kg	3.92
	In	Electricity	kJ	0.02
	Out	Solids	kg	0.01
	Out	Wastewater	kg	3.91
Membrane bioreactor [25]	In	Wastewater	kg	3.91
	In	Electricity	kJ	19.70
	Out	Wastewater	kg	3.90
	Out	Sludge	kg	0.01
UV treatment [26]	In	Wastewater	kg	3.90
	In	Electricity	kJ	0.93
	Out	Clean water	kg	3.90
Anaerobic digestion [27]	In	Sludge	kg	0.54
	In	Solid	kg	0.01
	In	Sludge	kg	0.01
	In	Wastewater (recycling)	kg	43.67
	In	Electricity	kJ	176.50
	In	Fuel (diesel)	kJ	2051.07
	In	Heat (CHP)	kJ	1467.09
	Out	Digestate	kg	44.10
	Out	Biogas	kg	0.12
CHP [27]	In	Biogas	kg	0.12
	Out	Heat (CHP)	kJ	1467.09
	Out	Electricity	kJ	1304.08
Digestate thickening [28]	In	Digestate	kg	44.10
	In	Electricity	kJ	79.37
	Out	To compost	kg	0.43
	Out	Wastewater (recycling)	kg	43.67

Table 4. Life Cycle Inventory (LCI) of Scenario C.

Process	Input/Output	Flow	Unit	Value
Screening [24]	In	Wastewater	kg	3.92
	In	Electricity	kJ	0.02
	Out	Solids	kg	0.01
	Out	Wastewater	kg	3.91
Aeration treatment [29]	In	Wastewater	kg	3.91
	In	Electricity	kJ	3.28
	In	Sodium hypochlorite	kg	4.70×10^{-5}
	Out	Wastewater	kg	3.90
	Out	Sludge	kg	0.01
Chlorination [30]	In	Wastewater	kg	3.90
	In	Electricity	kJ	0.87
	In	Sodium hypochlorite (15%)	kg	2.94×10^{-4}
	Out	Clean water	kg	3.90
Drying A [11]	In	Solid wastes	kg	0.54
	In	Sludge	kg	0.01
	In	Heat	kJ	960.00
	Out	Solid wastes	kg	0.24
	Out	Waste vapor	kg	0.31

Table 4. *Cont.*

Process	Input/Output	Flow	Unit	Value
HTC [11]	In	Solid wastes	kg	0.24
	In	Electricity	kJ	336.10
	Out	Slurry	kg	2.35×10^{-1}
	Out	Exhausted gas	kg	0.05×10^{-1}
Filtration [11]	In	Slurry	kg	2.35×10^{-1}
	In	Electricity	kJ	20.30
	Out	Solid fuel	kg	0.97×10^{-1}
	Out	Hydrolysates	kg	1.38×10^{-1}
Drying B [11]	In	Solid fuel	kg	0.97×10^{-1}
	In	Heat	kJ	20.90
	Out	Solid fuel	kg	0.09
	Out	Waste vapor	kg	0.01
Pelletizing [11]	In	Solid fuel	kg	0.09
	In	Electricity	kJ	2.30
	Out	Pelletized fuel	kg	0.09
Pellet power generation [11]	In	Pelletized fuel	kg	0.09
	In	Electricity	kJ	8.16
	Out	Electricity	kJ	389.30
	Out	Thermal energy	kJ	1133.6
	Out	Ash mix	kg	0.45×10^{-3}

3. Results and Discussion

The environmental effects of the typical meat processing industry, along with the environmental effects of each individual process, are presented in Figure 5.

According to the obtained results, the meat processing industry can be classified as an energy-intensive sector that produces large amounts of solid wastes and wastewater and exhibits severe environmental impact on various categories. Generally, the most energy-intensive, water-demanding, and environmentally harmful processes of the studied industry are the processing of meat after the removal of the inedible parts and the boiler, which is necessary for water heating and steam production and can be attributed to the amount of consumed electricity and fossil fuels. More specifically, based on the collected data and taking into account the assumptions and limitations that may lead to a certain level of uncertainty in the studied indices, approximately 0.141 kg CO_2 eq. and 0.001 kg 1,4-DB eq. are produced during the processing of meat per 1 kg of meat products, while freshwater consumption rises up to 0.005 m^3/kg of meat product. The obtained results are similar to those already existing in the literature regarding LCA in meat processing industries. According to a study conducted on pork production in Denmark, climate change was evaluated as equal to 0.1 kg CO_2 eq./kg of pork products [31], while research studying poultry production indicated that 0.16 kg CO_2 eq. are emitted per 1 kg of chicken final products [32]. Furthermore, notable environmental effects were observed for all the other studied indicators, including fossil and metal depletion (circa 0.07 kg oil eq./kg of meat product and 0.0004 kg Cu eq./kg of meat product) and marine ecotoxicity (0.001 kg 1,4-DB eq./kg of meat product). Therefore, in the context of environmental protection, sustainability, and circular economy, it is deemed necessary to incorporate appropriate methods of water purification and waste utilization for energy production within the meat processing industry to improve its environmental footprint. Based on the aforementioned, three different scenarios were selected for this work: the first hypothesizes that the meat processing industry is not directly involved in the treatment and valorization of its waste (Scenario A), while in the latter two scenarios, wastewater and solid wastes are treated on-site within the boundaries of the industry (Scenarios B and C). More specifically, in Scenario B, wastewater is treated using a membrane bioreactor and UV radiation, and solid wastes are valorized for the production of biogas, via anaerobic digestion. Whereas, in Scenario C, wastewater is subjected to aeration treatment and disinfection with sodium hypochlorite, and the valorization of solid wastes for the generation of electricity and thermal energy is achieved via HTC. Figures 6–8 depict the environmental effects of Scenarios A, B, and C, respectively. In Figures 7 and 8, the total environmental effect of the slaughter plant is not included in order to highlight the effect of each method on water purification and solid waste valorization. The total values are presented in Table 5.

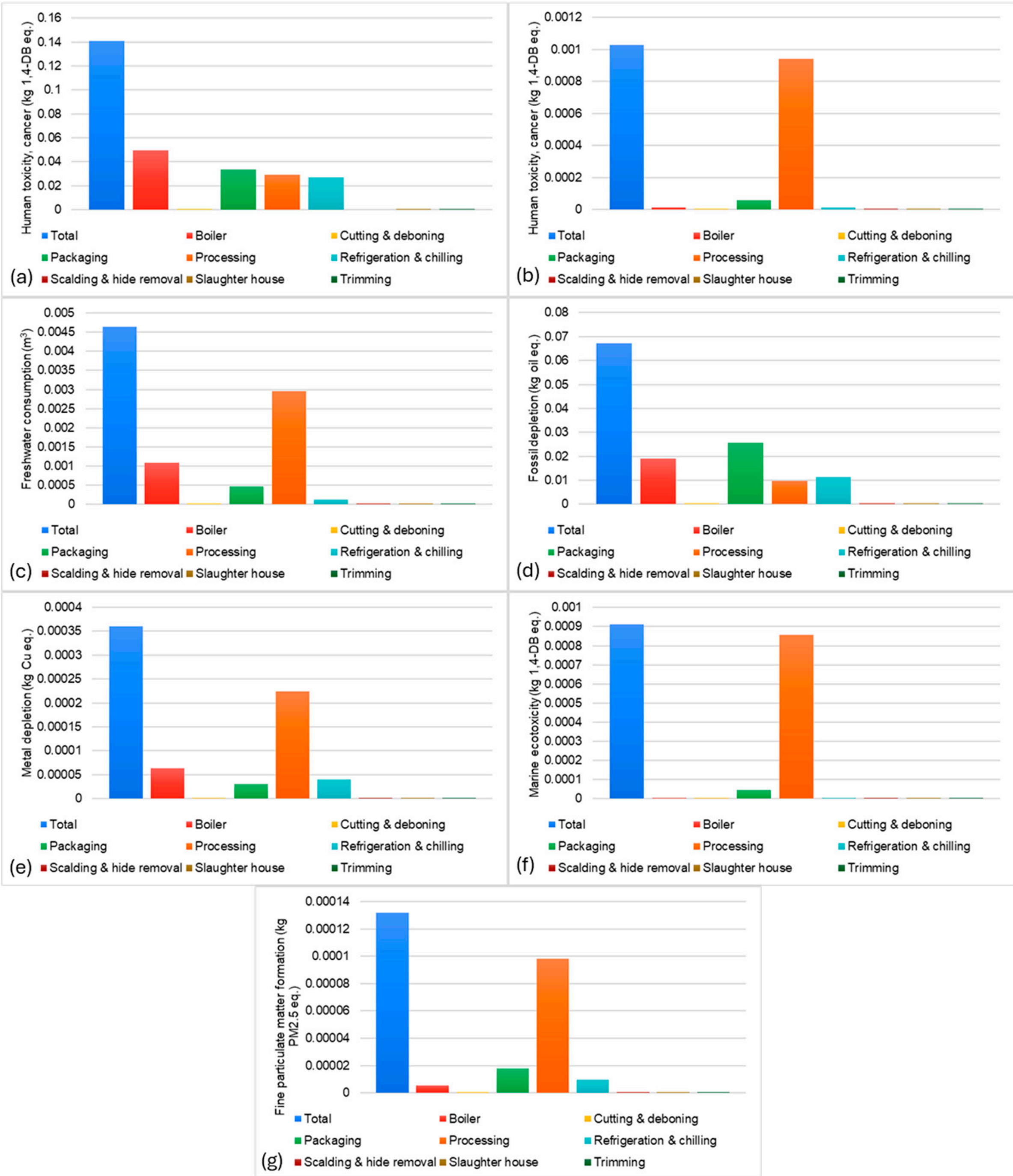

Figure 5. Environmental effects of the meat processing industry on (**a**) climate change (kg CO_2 eq.), (**b**) human toxicity, cancer (kg 1,4−DB eq.), (**c**) freshwater consumption (m^3), (**d**) fossil depletion (kg oil eq.), (**e**) metal depletion (kg Cu eq.), (**f**) marine ecotoxicity (kg 1,4−DB eq.), and (**g**) fine particulate matter formation (kg PM2.5 eq.).

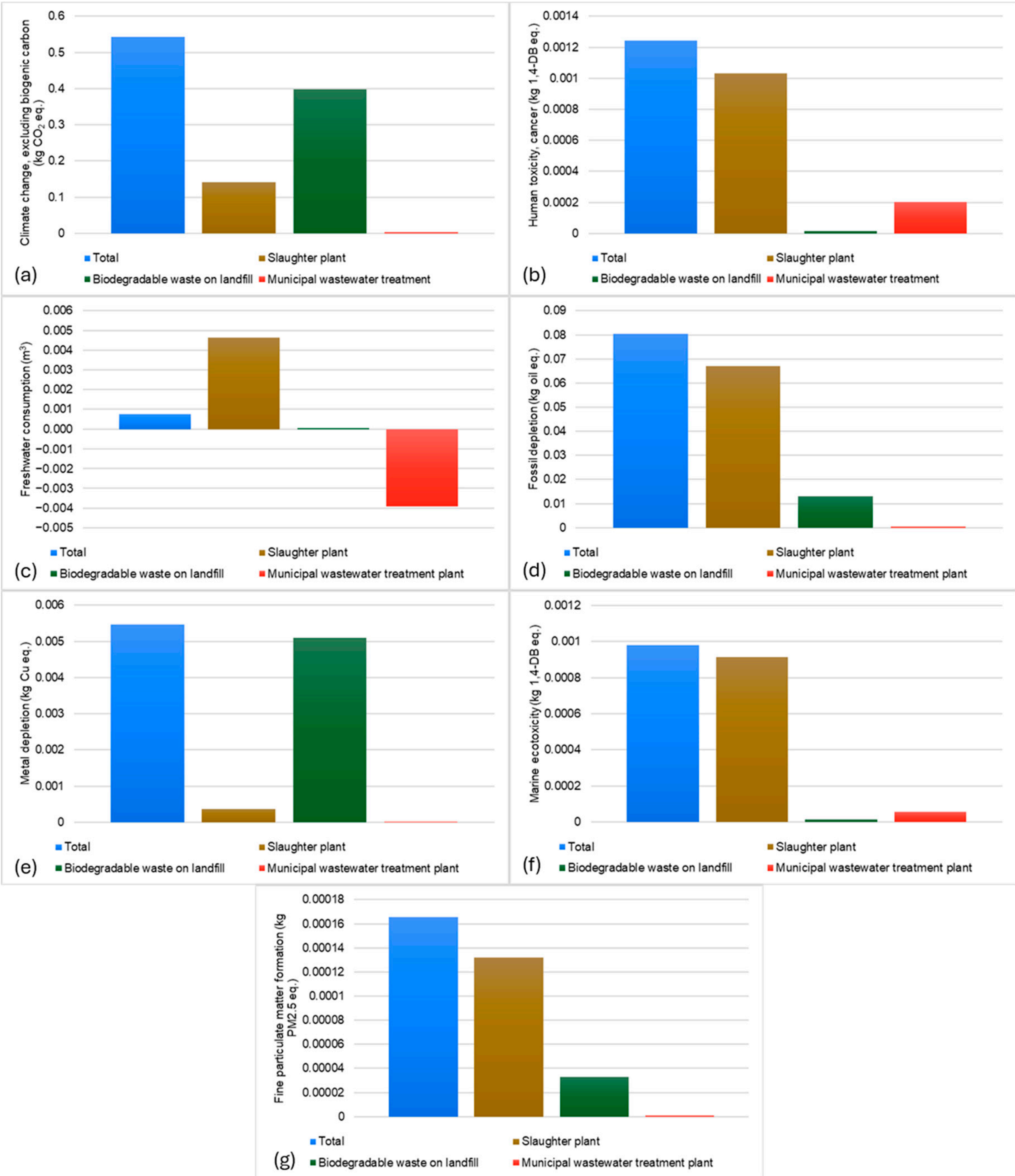

Figure 6. Environmental effects of Scenario A on (**a**) climate change (kg CO_2 eq.), (**b**) human toxicity, cancer (kg 1,4−DB eq.), (**c**) freshwater consumption (m^3), (**d**) fossil depletion (kg oil eq.), (**e**) metal depletion (kg Cu eq.), (**f**) marine ecotoxicity (kg 1,4−DB eq.), and (**g**) fine particulate matter formation (kg PM2.5 eq.).

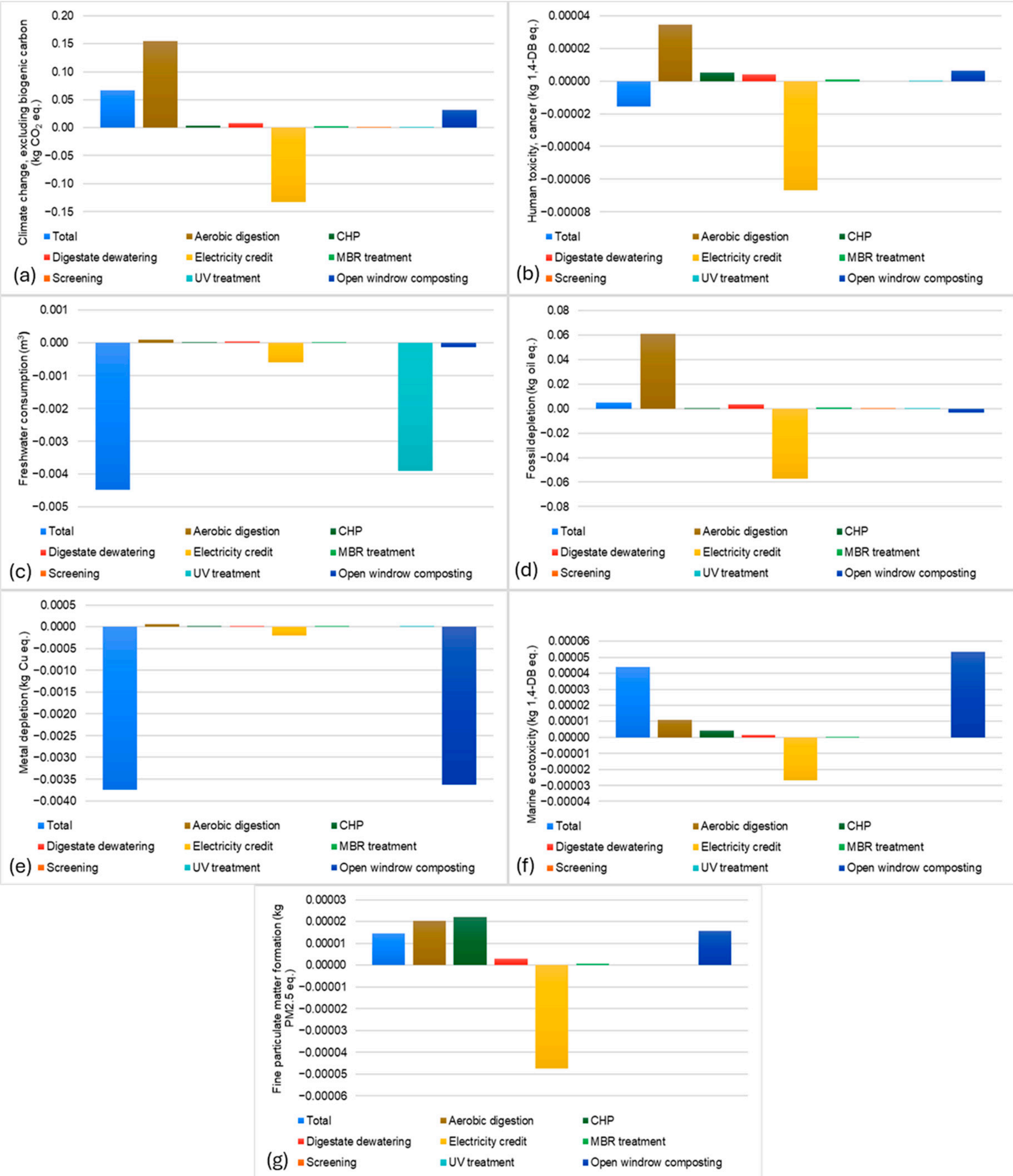

Figure 7. Environmental effects of Scenario B on (**a**) climate change (kg CO_2 eq.), (**b**) human toxicity, cancer (kg 1,4−DB eq.), (**c**) freshwater consumption (m^3), (**d**) fossil depletion (kg oil eq.), (**e**) metal depletion (kg Cu eq.), (**f**) marine ecotoxicity (kg 1,4−DB eq.), and (**g**) fine particulate matter formation (kg PM2.5 eq.).

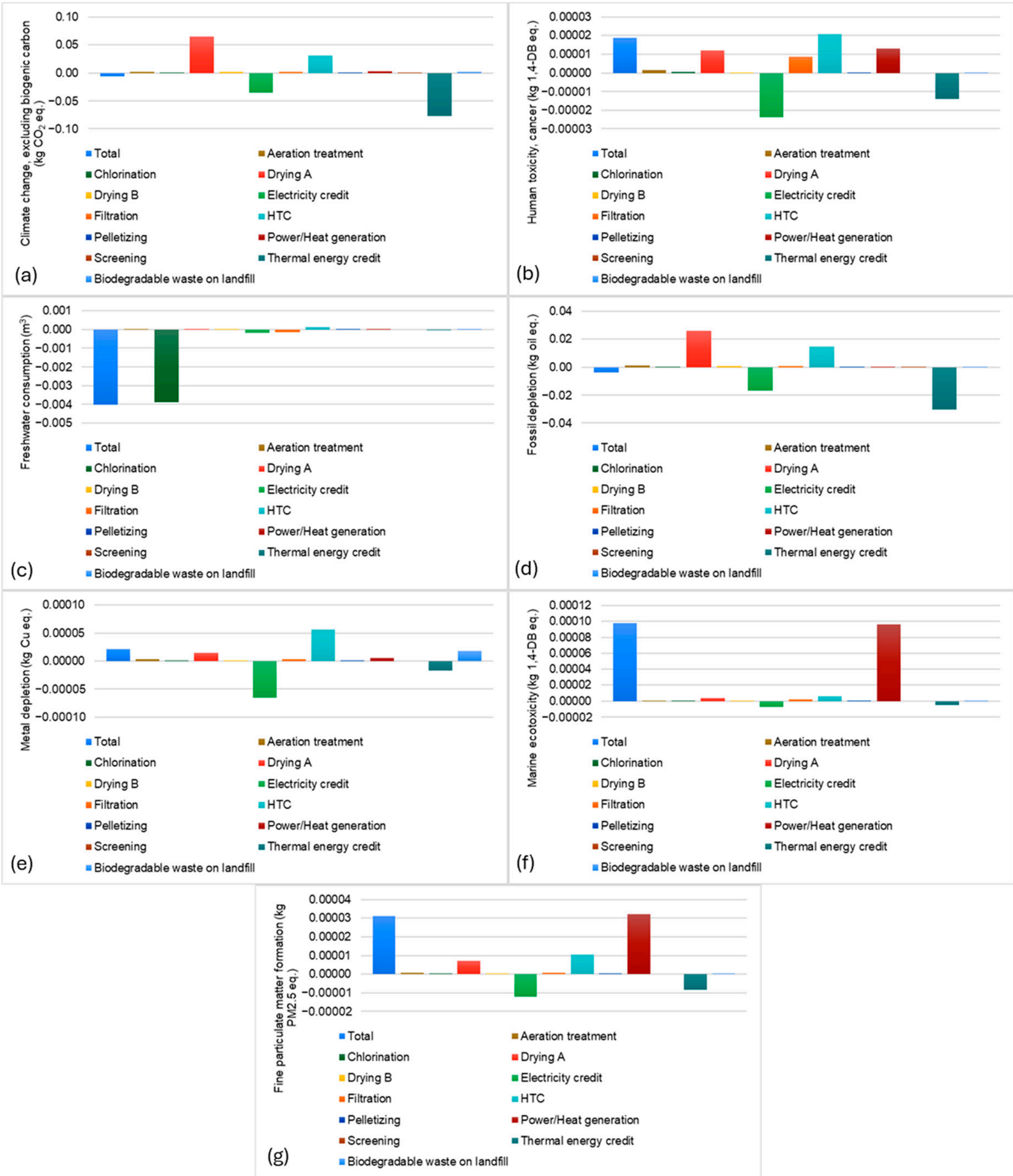

Figure 8. Environmental effects of Scenario C on (**a**) climate change (kg CO_2 eq.), (**b**) human toxicity, cancer (kg 1,4−DB eq.), (**c**) freshwater consumption (m^3), (**d**) fossil depletion (kg oil eq.), (**e**) metal depletion (kg Cu eq.), (**f**) marine ecotoxicity (kg 1,4−DB eq.), and (**g**) fine particulate matter formation (kg PM2.5 eq.).

Based on the attained results of the LCA study of the three distinct scenarios, it can be observed that Scenarios B and C exhibit substantially better environmental footprints compared with Scenario A. The disposal of solid waste on the soil as a landfill, as hypothesized in Scenario A, results in a sharp increase in the emissions of greenhouse gases, measured as climate change and expressed in kg CO_2 eq. Moreover, this specific method of solid waste handling leads to a further increase in metal and fossil depletion and in fine particulate matter formation. This can be attributed to a necessary possible pretreatment of the solids prior to their disposal and their subsequent treatment in the biodegradation site [33].

Table 5. Comparison of the environmental effects of the three studied scenarios on the studied categories.

Impact Category ($\times 10^{-3}$)	Scenario A	Scenario B	Reduction in Scenario B (%)	Scenario C	Reduction in Scenario C (%)
Climate change (kg CO_2 eq.)	541.30	207.70	61.63	85.41	84.22
Human toxicity, cancer (kg 1,4-DB eq.)	1.24	1.01	18.55	0.69	44.35
Freshwater consumption (m^3)	0.77	0.15	80.52	0.39	49.35
Fossil depletion (kg oil eq.)	80.31	71.81	10.58	41.92	47.80
Metal depletion (kg Cu eq.)	5.46	−3.38	161.90	0.26	95.24
Marine ecotoxicity (kg 1,4-DB eq.)	0.98	0.96	2.04	0.66	32.65
Fine particulate matter formation (kg PM2.5 eq.)	0.17	0.15	11.76	0.11	35.29

On the other hand, the treatment of wastewater and solid wastes in the industry via the implementation of appropriate methods leads to an enhancement in the environmental footprint of the studied case. The efficient purification of wastewater and its safe disposal in the aquatic environment leads to a notable decrease in freshwater consumption in both Scenarios B (screening, MBR, and UV treatment) and C (screening, aeration treatment, and chlorination) [34]. The burden on the environment observed due to anaerobic digestion, depicted in the quantity of GHG emissions and produced kg of 1,4-DB (Figures 7a and 7b, respectively), is successfully compensated by the production of energy and heat via cogeneration (electricity credit), resulting in a positive overall sign of waste treatment in terms of sustainability and environmental safety in Scenario B [35]. However, the generation of large amounts of thermal energy in Scenario C (approximately 1130 kJ/kg of meat products) results in a sharper decrease in the emissions of greenhouse gases compared with Scenario B, as presented in Figures 7a and 8a and Table 6. Finally, it must be noted that the implementation of Scenarios B and C results in negative values for various studied indices (i.e., freshwater consumption for both scenarios, human toxicity for Scenario B, and fossil depletion for Scenario C), thus further validating the positive environmental effect of wastewater treatment and waste valorization. The negative value of freshwater consumption is attributed to the disposal of cleaned water, following the UV treatment, back to the water environment, while the difference in the obtained value of this specific category is due to the transport of the derived hydrolysates, from Scenario C, to a municipal wastewater treatment plant for further treatment. In addition, the negative values of metal depletion for Scenario B, linked with the composting process, are due to the credits from the replacement of conventional fertilizers [36]. A direct comparison of Scenarios A, B, and C is depicted in Figure 9, and the overall reduction in the environmental footprint is presented in Table 5. Moreover, the energy balances (gains and losses of electricity and thermal energy) in the wastewater and solid waste treatment for scenarios B and C are presented in Table 6.

Table 6. Electricity and thermal energy balance in wastewater and solid waste treatment for Scenarios B and C.

Process	Energy Consumed/Generated	Scenario B	Scenario C
Wastewater treatment	Electricity consumed (kJ)	20.65	24.17
	Thermal energy consumed (kJ)	0	0
	Electricity generated (kJ)	0	0
	Thermal energy generated (kJ)	0	0
Solid waste valorization	Electricity consumed (kJ)	255.87	366.86
	Thermal energy consumed (kJ)	3518.16	980.90
	Electricity generated (kJ)	1304.08	389.30
	Thermal energy generated (kJ)	1467.09	1133.60

Table 6. *Cont.*

Process	Energy Consumed/Generated	Scenario B	Scenario C
Energy balance	Electricity (kJ) Thermal energy (kJ)	1027.56 −2051.07	−1.73 352.70

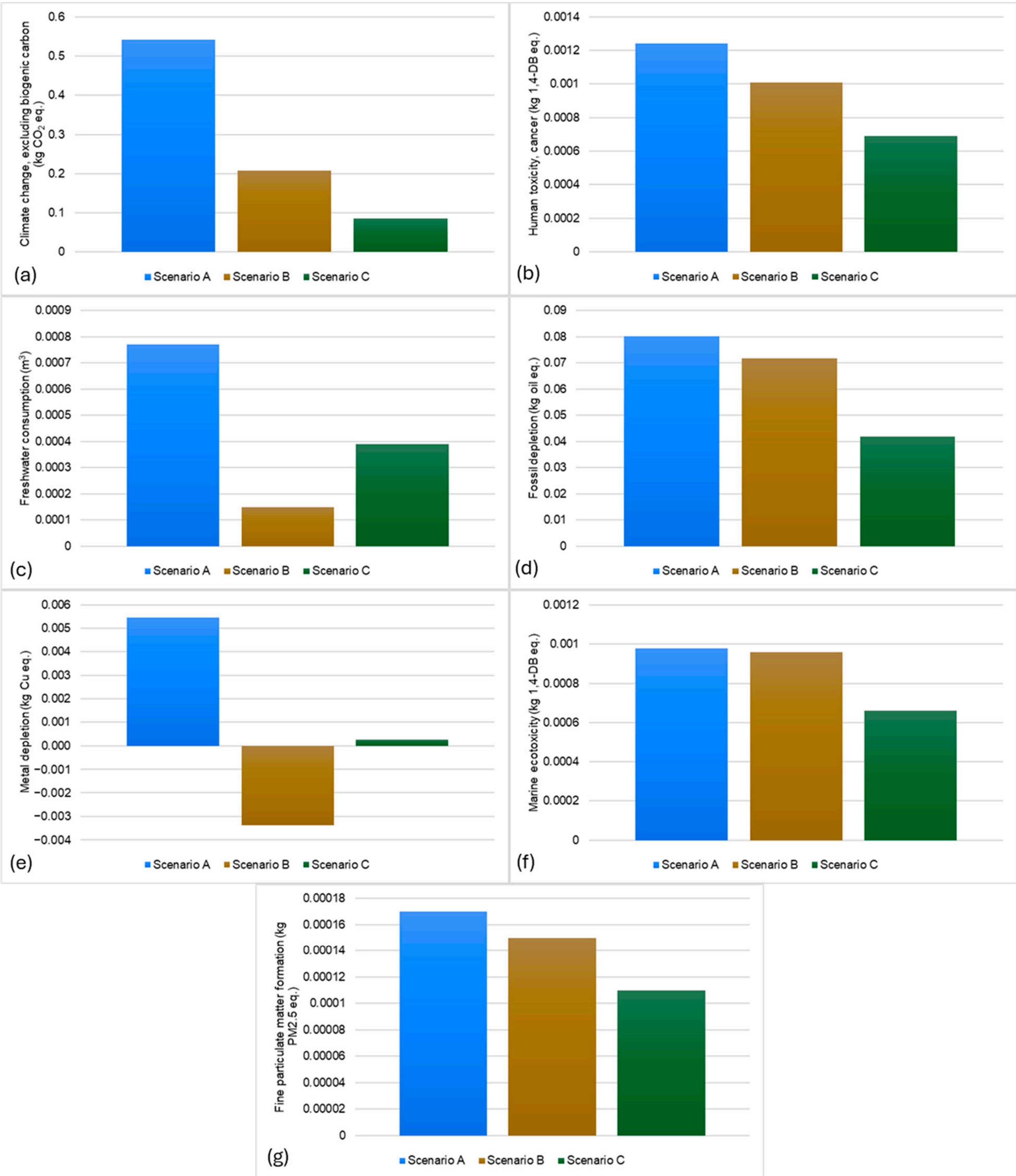

Figure 9. Comparison of the environmental effects of Scenarios A, B and C on (**a**) climate change (kg CO_2 eq.), (**b**) human toxicity, cancer (kg 1,4−DB eq.), (**c**) freshwater consumption (m^3), (**d**) fossil depletion (kg oil eq.), (**e**) metal depletion (kg Cu eq.), (**f**) marine ecotoxicity (kg 1,4−DB eq.), and (**g**) fine particulate matter formation (kg PM2.5 eq.).

The direct comparison of the three studied scenarios highlights the enhancement in the environmental footprint of the meat processing industry in all studied categories, achieved by the utilization of novel methods aiming at wastewater purification and solid waste valorization. The utilization of innovative technologies led to a significant reduction in the amount of produced greenhouse gas, in freshwater consumption, and in metal depletion in both Scenarios B and C. Specifically, the notable decrease in greenhouse gas emissions and freshwater consumption (61.63% and 80.52%, respectively, for Scenario B and 84.22% and 49.35%, respectively, for Scenario C) is a strong indication that sustainability and preservation of the environment and the ecosystems can be achieved via waste utilization and adaptation of innovative and environment-friendly treatment methods. Finally, it must be noted that the valorization of solid wastes and the treatment of wastewater in Scenario B results in a surplus in the balance of electrical energy, due to the cogeneration of biogas, and a deficit in the balance of thermal energy, which can be attributed to the large amounts of thermal energy required in anaerobic digestion. On the other hand, in Scenario C, a surplus of thermal energy is attained due to the burning of pelletized fuels, while the deficit in energy (1.73 kJ) can be considered negligible.

4. Conclusions

Three different scenarios of wastewater and solid waste treatment produced during meat processing were studied in order to evaluate their environmental effects, via LCA analysis. The first scenario consisted of conventional waste treatment techniques, with the solid wastes being disposed of on a landfill and the wastewater transferred to a municipal wastewater treatment plant, while in the latter two, waste treatment technologies aiming at energy production and wastewater purification were used within the industry. In general, the incorporation of waste treatment technologies leads to the generation of substantial quantities of energy and a significant improvement in environmental footprint. Among the studied technologies in Scenario B, anaerobic digestion exhibited the best environmental performance due to the produced electricity and heat during CHP, while the burning of the obtained pelletized fuels in Scenario C resulted in the generation of large amounts of thermal energy. Despite the fact that thermal energy is necessary for the heating of biomass during the anaerobic digestion, this energy is considerably decreased due to the utilization of the thermal energy produced in the CHP, and the observed deficit in electricity in Scenario C is negligible, thus both studied scenarios can be efficiently applied. Furthermore, the purified water from Scenarios B and C is environmentally safe and of high quality, and thus, it can be either reused reducing further the footprint of the industry, or used for other purposes, including aquatic discharge or agricultural purposes. Results derived from the present work suggest that the proposed technologies could be used for moving toward sustainable meat production. Finally, the approach proposed in this work can be broadly extended to numerous other food systems to analyze their environmental footprints, highlight the main areas that require significant improvement, and consequently propose appropriate methodologies for energy production via solid waste valorization and wastewater treatment.

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References

1. Baker, P.; Machado, P.; Santos, T.; Sievert, K.; Backholer, K.; Hadjikakou, M.; Russell, C.; Huse, O.; Bell, C.; Scrinis, G.; et al. Ultra-Processed Foods and the Nutrition Transition: Global, Regional and National Trends, Food Systems Transformations and Political Economy Drivers. *Obes. Rev.* **2020**, *21*, e13126. [CrossRef] [PubMed]
2. Djekic, I. Environmental Impact of Meat Industry—Current Status and Future Perspectives. *Procedia Food Sci.* **2015**, *5*, 61–64. [CrossRef]
3. Sayeed, R.; Tiwari, P. Wealth from Meat Industry By-Products and Waste: A Review. In *Sustainable Food Waste Management: Concepts and Innovations*; Thakur, M., Modi, V.K., Khedkar, R., Singh, K., Eds.; Springer: Singapore, 2020; pp. 191–208, ISBN 978-981-15-8967-6.
4. Al-Asheh, S.; Bagheri, M.; Aidan, A. Membrane Bioreactor for Wastewater Treatment: A Review. *Case Stud. Chem. Environ. Eng.* **2021**, *4*, 100109. [CrossRef]
5. Skouteris, G.; Rodriguez-Garcia, G.; Reinecke, S.F.; Hampel, U. The Use of Pure Oxygen for Aeration in Aerobic Wastewater Treatment: A Review of Its Potential and Limitations. *Bioresour. Technol.* **2020**, *312*, 123595. [CrossRef] [PubMed]
6. Wang, J.; Liu, H.; Gao, Y.; Yue, Q.; Gao, B.; Liu, B.; Guo, K.; Xu, X. Pilot-Scale Advanced Treatment of Actual High-Salt Textile Wastewater by a UV/O_3 Pressurization Process: Evaluation of Removal Kinetics and Reverse Osmosis Desalination Process. *Sci. Total Environ.* **2023**, *857*, 159725. [CrossRef] [PubMed]
7. Mazhar, M.A.; Khan, N.A.; Ahmed, S.; Khan, A.H.; Hussain, A.; Rahisuddin; Changani, F.; Yousefi, M.; Ahmadi, S.; Vambol, V. Chlorination Disinfection By-Products in Municipal Drinking Water—A Review. *J. Clean. Prod.* **2020**, *273*, 123159. [CrossRef]
8. Gopal, P.M.; Sivaram, N.M.; Barik, D. Chapter 7—Paper Industry Wastes and Energy Generation from Wastes. In *Energy from Toxic Organic Waste for Heat and Power Generation*; Barik, D., Ed.; Woodhead Publishing: Sawston, UK, 2019; pp. 83–97, ISBN 978-0-08-102528-4.
9. Salman, C.A.; Schwede, S.; Naqvi, M.; Thorin, E.; Yan, J. Synergistic Combination of Pyrolysis, Anaerobic Digestion, and CHP Plants. *Energy Procedia* **2019**, *158*, 1323–1329. [CrossRef]
10. Shi, L.; Simplicio, W.S.; Wu, G.; Hu, Z.; Hu, H.; Zhan, X. Nutrient Recovery from Digestate of Anaerobic Digestion of Livestock Manure: A Review. *Curr. Pollut. Rep.* **2018**, *4*, 74–83. [CrossRef]
11. Unrean, P.; Lai Fui, B.C.; Rianawati, E.; Acda, M. Comparative Techno-Economic Assessment and Environmental Impacts of Rice Husk-to-Fuel Conversion Technologies. *Energy* **2018**, *151*, 581–593. [CrossRef]
12. McCabe, B.K.; Harris, P.; Antille, D.L.; Schmidt, T.; Lee, S.; Hill, A.; Baillie, C. Toward Profitable and Sustainable Bioresource Management in the Australian Red Meat Processing Industry: A Critical Review and Illustrative Case Study. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 2415–2439. [CrossRef]
13. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: London, UK, 2006.
14. Marathe, K.V.; Chavan, K.R.; Nakhate, P. 8—Life Cycle Assessment (LCA) of PET Bottles. In *Recycling of Polyethylene Terephthalate Bottles*; Thomas, S., Rane, A., Kanny, K., Abitha, V.K., Thomas, M.G., Eds.; William Andrew Publishing: Norwich, UK, 2019; pp. 149–168, ISBN 978-0-12-811361-5.
15. Sandin, G.; Peters, G.M.; Svanstrom, M. LCA Methodology. In *Life Cycle Assessment of Forest Products: Challenges and Solutions*; Springer International Publishing: Cham, Switzerland, 2016; pp. 15–23. ISBN 978-3-319-44027-9.
16. Stramarkou, M.; Boukouvalas, C.; Koskinakis, S.E.; Serifi, O.; Bekiris, V.; Tsamis, C.; Krokida, M. Life Cycle Assessment and Preliminary Cost Evaluation of a Smart Packaging System. *Sustainability* **2022**, *14*, 7080. [CrossRef]
17. Khan, M.U.; Lee, J.T.E.; Bashir, M.A.; Dissanayake, P.D.; Ok, Y.S.; Tong, Y.W.; Shariati, M.A.; Wu, S.; Ahring, B.K. Current Status of Biogas Upgrading for Direct Biomethane Use: A Review. *Renew. Sust. Energ. Rev.* **2021**, *149*, 111343. [CrossRef]
18. Galib, M.; Elbeshbishy, E.; Reid, R.; Hussain, A.; Lee, H.-S. Energy-Positive Food Wastewater Treatment Using an Anaerobic Membrane Bioreactor (AnMBR). *J. Environ. Manag.* **2016**, *182*, 477–485. [CrossRef] [PubMed]
19. Bustillo-Lecompte, C.F.; Mehrvar, M. Slaughterhouse Wastewater Characteristics, Treatment, and Management in the Meat Processing Industry: A Review on Trends and Advances. *J. Environ. Manag.* **2015**, *161*, 287–302. [CrossRef]
20. Irshad, A.; Sureshkumar, S.; Raghunath, B.V.; Rajarajan, G.; Mahesh Kumar, G. Treatment of Waste Water from Meat Industry. In *Integrated Waste Management in India: Status and Future Prospects for Environmental Sustainability*; Prashanthi, M., Sundaram, R., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 251–263. ISBN 978-3-319-27228-3.
21. Abyar, H.; Nowrouzi, M. Highly Efficient Reclamation of Meat-Processing Wastewater by Aerobic Hybrid Membrane Bioreactor-Reverse Osmosis Simulated System: A Comprehensive Economic and Environmental Study. *ACS Sustain. Chem. Eng.* **2020**, *8*, 14207–14216. [CrossRef]
22. Brandao, M.; Heijungs, R.; Cowie, A. On Quantifying Sources of Uncertainty in the Carbon Footprint of Biofuels: Crop/Feedstock, LCA Modelling Approach, Land-Use Change, and GHG Metrics. *Biofuel Res. J.* **2022**, *9*, 1608–1616. [CrossRef]
23. Brown, H.L.; Hamel, B.B.; Hedman, B.A.; Bruce, A. *Hedman Energy Analysis of 108 Industrial Processes*; Fairmont Press: Lilburn, GA, USA, 1987.
24. Huber Technology. Energy-Efficient Mechanical Pre-Treatment. Available online: https://www.huber.de/solutions/centralized-wastewater-treatment/mechanical-pre-treatment.html (accessed on 1 November 2023).
25. Krzeminski, P.; van der Graaf, J.H.J.M.; van Lier, J.B. Specific Energy Consumption of Membrane Bioreactor (MBR) for Sewage Treatment. *Water Sci. Technol.* **2012**, *65*, 380–392. [CrossRef] [PubMed]

26. Schmalwieser, A.W.; Hirschmann, G.; Cabaj, A.; Sommer, R. Method to Determine the Power Efficiency of UV Disinfection Plants and Its Application to Low Pressure Plants for Drinking Water. *Water Supply* **2016**, *17*, 947–957. [CrossRef]
27. Wang, S.; Sahoo, K.; Jena, U.; Dong, H.; Bergman, R.; Runge, T. Life-Cycle Assessment of Treating Slaughterhouse Waste Using Anaerobic Digestion Systems. *J. Clean. Prod.* **2021**, *292*, 126038. [CrossRef]
28. Czekała, W.; Jasiński, T.; Grzelak, M.; Witaszek, K.; Dach, J. Biogas Plant Operation: Digestate as the Valuable Product. *Energies* **2022**, *15*, 8275. [CrossRef]
29. Kamble, S.; Singh, A.; Kazmi, A.; Starkl, M. Environmental and Economic Performance Evaluation of Municipal Wastewater Treatment Plants in India: A Life Cycle Approach. *Water Sci. Technol.* **2019**, *79*, 1102–1112. [CrossRef] [PubMed]
30. Siatou, A.; Manali, A.; Gikas, P. Energy Consumption and Internal Distribution in Activated Sludge Wastewater Treatment Plants of Greece. *Water* **2020**, *12*, 1204. [CrossRef]
31. Dorca-Preda, T.; Mogensen, L.; Kristensen, T.; Knudsen, M.T. Environmental Impact of Danish Pork at Slaughterhouse Gate—A Life Cycle Assessment Following Biological and Technological Changes over a 10-Year Period. *Livest. Sci.* **2021**, *251*, 104622. [CrossRef]
32. Tetteh, H.; Bala, A.; Fullana-i-Palmer, P.; Balcells, M.; Margallo, M.; Aldaco, R.; Puig, R. Carbon Footprint: The Case of Four Chicken Meat Products Sold on the Spanish Market. *Foods* **2022**, *11*, 3712. [CrossRef] [PubMed]
33. Basu, P. Chapter 2—Biomass Characteristics. In *Biomass Gasification and Pyrolysis*; Basu, P., Ed.; Academic Press: Boston, MA, USA, 2010; pp. 27–63. ISBN 978-0-12-374988-8.
34. Raghuvanshi, S.; Bhakar, V.; Sowmya, C.; Sangwan, K.S. Waste Water Treatment Plant Life Cycle Assessment: Treatment Process to Reuse of Water. *Procedia CIRP* **2017**, *61*, 761–766. [CrossRef]
35. Timonen, K.; Sinkko, T.; Luostarinen, S.; Tampio, E.; Joensuu, K. LCA of Anaerobic Digestion: Emission Allocation for Energy and Digestate. *J. Clean. Prod.* **2019**, *235*, 1567–1579. [CrossRef]
36. Mondello, G.; Salomone, R.; Ioppolo, G.; Saija, G.; Sparacia, S.; Lucchetti, M.C. Comparative LCA of Alternative Scenarios for Waste Treatment: The Case of Food Waste Production by the Mass-Retail Sector. *Sustainability* **2017**, *9*, 827. [CrossRef]