

## Article

# Assessing the Overall Sustainability Performance of the Meat Processing Industry Before and After Wastewater Valorization Interventions: A Comparative Analysis

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**Abstract:** The meat processing industry is rapidly growing, aiming to enhance the accessibility and affordability of meat products. However, this vital sector also presents significant environmental and social challenges alongside substantial waste management issues. Efforts to improve sustainability in this industry include introducing advanced waste treatment technologies. This study evaluates the overall sustainability of the meat processing industry by comparing the current waste treatment system with an advanced system incorporating improved technologies for water reuse, solid waste valorization, and energy production. We conducted environmental, social, and economic Life Cycle Assessments (LCAs) using OpenLCA and the SOCA v2 database, with 1 kg of processed meat as the functional unit. The comparative analysis highlights significant improvements in the ‘50%’ scenario, where half of the wastewater undergoes advanced treatment. Environmental impacts decreased notably: Freshwater Eutrophication and Human Carcinogenic Toxicity by 25.9% and 31.5%, respectively, and Global Warming and Fossil Resource Scarcity S by 9.2% and 8.8%. Social risk indicators improved by 33.7% to 37.0%. The treatment system achieved a cost saving of EUR 0.00187 per kg of meat (EUR 63,152.70 annually), though these results are specific to this study and heavily dependent on the location and time period. Further analysis of four scenarios, including the baseline, demonstrated that increasing the proportion of wastewater treated by the new system improved environmental, social, and economic outcomes, with the 75% treatment scenario proving the most sustainable. Overall, the advanced treatment system significantly enhances sustainability in the meat industry, promoting a more environmentally, socially, and economically friendly waste management approach.

**Keywords:** environmental assessment; social assessment; economic assessment; waste treatment



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## 1. Introduction

The meat industry is one of the fastest-growing sectors in the food industry since its market value is expected to rise from 897.5 billion U.S. dollars in 2021 to over 1.3 trillion dollars by 2027 [1]. Spain is one of the largest producers of pig meat products in Europe, along with France, Italy, Germany, and Poland [2]. According to the aforementioned statistics, since the quantity of meat production is expected to rise highly [3], the annual revenues of the meat sector are going to increase accordingly.

However, meat industries are known for their contribution to the increasing rate of global climate change. Specifically, studies from 2019 have revealed that pork production generates 12.3 kg CO<sub>2</sub> per kg of product, while beef and chicken production cause 99.5 and 9.9 kg CO<sub>2</sub> per kg of product, respectively [4,5].

Due to this evidence, there are several studies in which Environmental Life Cycle Assessment (LCA) was conducted on meat industries, mainly in the United States of America [6–9]. Considering pork products, there are also some studies in which Environmental LCA was conducted in countries of the European Union [10,11]. Moreover, the cost [12], as well as the social aspect [13], have been assessed for pork production. However, there is a lack of comprehensive sustainability assessments in the field of wastewater treatment within the meat processing industry, highlighting the need for further studies [14].

Life Cycle Sustainability Assessment (LCSA) is a methodology that offers a comprehensive approach to addressing the three pillars of sustainability—environmental, economic, and social aspects [15]. The environmental aspect, evaluated through Life Cycle Assessment (LCA), serves as a powerful tool for assessing and comparing the environmental impact of various processes or products throughout their entire life cycle or specific phases. This encompasses stages from raw material extraction and transportation to manufacturing, usage, and disposal, with a focus on assessing impacts on the environment, humans, and natural resources across multiple categories. LCA helps identify critical areas, compare system efficiency, and propose solutions [16]. Addressing the social aspect, Social Life Cycle Assessment (S-LCA) serves as an evaluative tool to gauge the potential positive or negative social impacts of a product throughout its life cycle, spanning from raw material extraction to final disposal [17]. Regarding the economic dimension, Life Cycle Costing (LCC) aims to assess the total costs associated with a product throughout its life cycle. Originating in the 1930s, LCC has seen widespread application globally, particularly in the procurement of durable goods across various industrial sectors. Often, specific LCC approaches tailored to sectors or large companies feature distinct cost categories and aggregation rules [18].

Even though there are already studies that examine the environmental, the social, and the economic impact of meat industries, they mainly focus on studying typical meat production processes. In this study, Mafrica's production process, which is a meat industry specializing in pig products and located in Spain, is examined through LCSA. The examined meat industry plant consists of the production process plant and a wastewater treatment plant (WWTP) installed on-site.

Resource recovery, GWP mitigation, and the biorefinery concept are increasingly important in sustainable waste management, particularly within industries with high environmental footprints, such as the meat industry. Resource recovery focuses on extracting valuable products like biogas, nutrients, and water from waste streams, which not only reduces waste but also provides renewable resources. This approach plays a crucial role in mitigating GWP by reducing greenhouse gas emissions through processes like anaerobic digestion, which captures methane for energy use instead of allowing it to escape into the atmosphere [19]. The biorefinery concept takes this a step further by integrating various technologies to convert organic waste into a range of bio-based products, such as biofuels, chemicals, and materials, while maximizing resource efficiency. In the context of the meat industry, implementing these concepts in the wastewater treatment plant (WWTP) can lead to significant reductions in energy and water consumption while minimizing waste output, ultimately contributing to a more sustainable and environmentally friendly production process [20].

The WWTP includes certain equipment, such as a coarse-scale grid, thin-scale grid, regulator tank, dissolved air flotation, activated sludge reactor with nitrification–denitrification, sludge decanter tank, and centrifuge. These processes are partially replaced by several innovative processes, aiming to mitigate energy and water consumption while valorizing waste at the same time.

The upgraded technologies introduced are a wastewater reclamation system, including a membrane bioreactor (MBR), electrodialysis (EL), and UV disinfection processes. In

addition, animal tissues and guts, along with large solids from the WWTP, now undergo anaerobic digestion (AD) to produce biogas, generating thermal and electrical energy through a combined heat and power (CHP) system. Furthermore, sludge from the WWTP and sludge from the MBR are bio-dried to produce solid biofuel.

The influence of these upgrades was quantified through LCA, LCC, and S-LCA, respectively. Using these tools, the new processes were assessed by evaluating different scenarios regarding the proportion of wastewater directed to the new treatment system.

## 2. Materials and Methods

An overall comparative sustainability assessment was implemented in this paper in order to analyse the influence of the proposed upgraded wastewater treatment system of the meat industry in terms of environmental, social, and economic aspects.

The Environmental LCA is a well-established technique that evaluates the environmental impacts of a system or a product throughout the entire or a part of the life cycle. The results of the analysis indicate the stages of a product's life cycle with the highest environmental impacts and, therefore, could be used to identify opportunities to enhance the environmental performance of products at various points in their life cycle. Moreover, it is valuable for informing decision-makers in industry, government or non-government organizations, and marketing through the production of environmental product declarations [21].

The S-LCA examines the various social dimensions of a product or a system, considering the influence related to the stakeholders: workers, value chain actors, society, and local communities. This encompasses aspects such as labour conditions, human rights, community well-being, health and safety, and social equity. Since the fundamental goal of the S-LCA methodology is to promote improvement in social conditions throughout the life cycle of a product, human well-being is the central concept [17].

The LCC assesses all costs associated with the life cycle of a product or a system [22], providing an economic overview and assisting in hotspot identification.

LCA is divided into four phases according to ISO 14040 and 14044 [21,23]:

1. The goal and scope definition include the system boundaries, the level of detail of the study, and the determination of the functional unit used;
2. The inventory analysis (LCI) involves the collection of the data required to achieve the goals of the defined study;
3. The impact assessment (LCIA) provides additional information to help assess a product system's LCI results so as to efficiently understand their environmental significance;
4. The interpretation phase is the final phase of the LCA procedure, in which the results of an LCI, an LCIA, or both are summarized and discussed as a basis for conclusions, recommendations, and decision-making in accordance with the defined goal and scope.

The above phases of LCA are followed and analysed in this study concerning the upgraded technology integrated into the meat industry waste treatment process.

### 2.1. Goal and Scope

The purpose of this sustainability assessment is to identify key areas of concern in the meat industry's waste treatment processes by considering environmental, social, and economic factors. The analysis focuses specifically on the impacts of implementing upgraded wastewater treatment technology. A comparative analysis was conducted to evaluate the sustainability of two scenarios: the current situation (base scenario) and one where half of the wastewater is treated using the upgraded technology.

Additionally, a sensitivity analysis was performed to further explore the effects of the upgraded wastewater treatment system. This analysis examined two additional scenarios, each varying in the percentage of wastewater treated by the new system, compared to the

scenario where half of the wastewater is treated by the upgraded technology and the base scenario.

### 2.1.1. Product System

#### Base Product System X

The meat industry examined in this paper is located in Spain, as illustrated in Figure 1. The baseline of the meat industry, which is in operation for 260 days per year, consists of the production process and the WWTP. The production process includes all the required processes for the meat industry, such as scalding, skinning, and airing. Nevertheless, it has been chosen to be demonstrated as one process since there will be no changes in this part of the industry. The input flows of the meat processing phase are pigs, fresh water, and spices, while the outputs are meat products (fresh and elaborated products), meat by-products (blood, animal tissues and guts, meat trimmings, casualties and seizures, abattoir fats, fur, bones, butcher fats), which are currently being sold. Regarding the scale of the meat industry, indicative annual mass flow values include the processing of 500,000 pigs, the consumption of 120,000 m<sup>3</sup> of fresh water, and the production of 32,585 tons of fresh meat products. Moreover, the analysis also considers the solid wastes (sludge and manure) produced and the emissions into the air (CO, CO<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub>, N<sub>2</sub>O, NH<sub>3</sub>, CH<sub>4</sub>, NMVOC). Energy requirements are mostly in the form of electricity (7,958,000 kWh per year), part of it deriving from natural gas (11,380,000 kWh per year). The industry generates a substantial amount of wastewater, totaling 120,000 m<sup>3</sup> per year, which is treated in the WWTP. The WWTP includes certain equipment, such as coarse-scale grid, thin-scale grid, regulator tank, sludge decanter tank, centrifuge, dissolved air flotation, and activated sludge reactor with nitrification–denitrification. The treated water, after the aforementioned processes, is sent to the public sewer to be subsequently treated in an external urban WWTP for further cleaning. Energy (657,000 kWh per year), coagulants, and flocculants are needed for the clarification of wastewater, while solid wastes (300 tons of large and 100 tons of thin solids and 166 tons of centrifuged sludge per year) are also produced. The solid wastes produced during the production process and the WWTP are sent to an external manager for further processing.

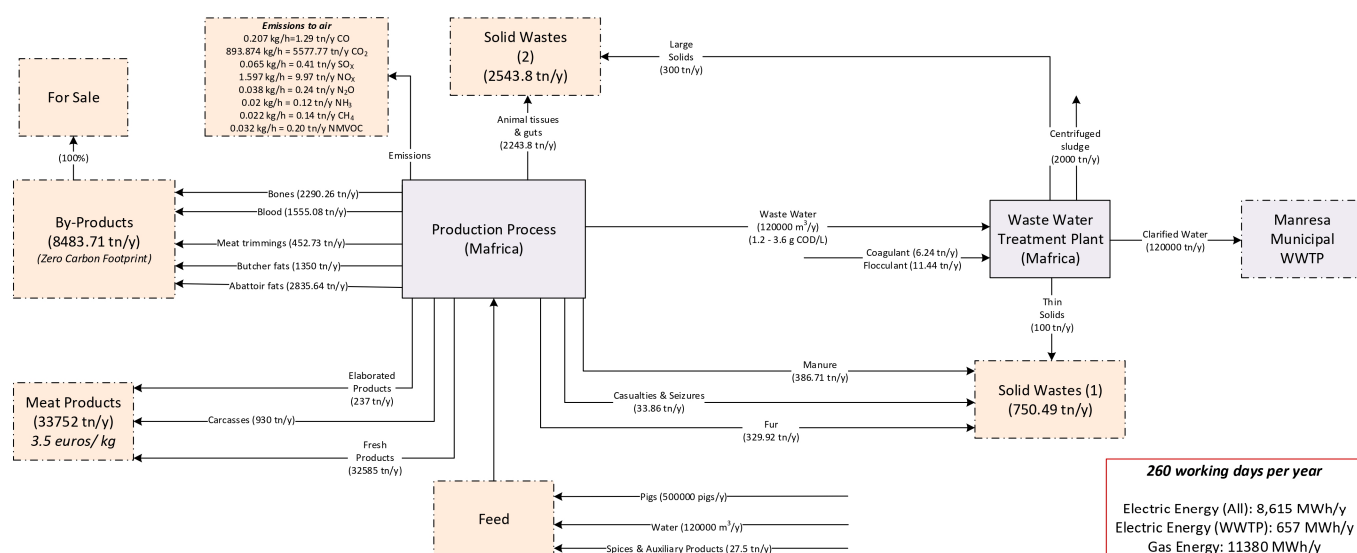


Figure 1. Flowchart of meat industry's baseline.

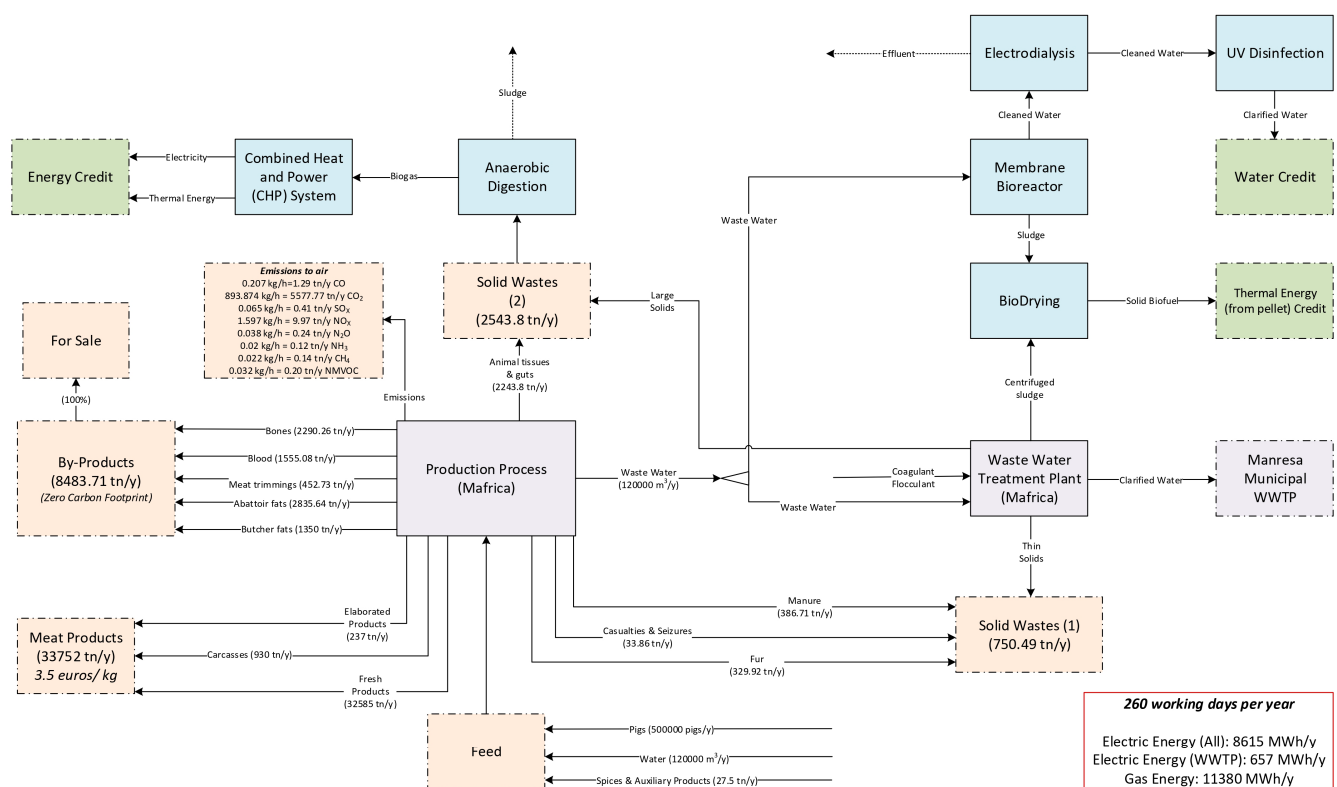
#### Upgraded Product System

The equipment installed in the wastewater treatment process aims to reduce water and energy use, as well as waste disposal. Water was purified through the implementation of

MBR, EL, and UV disinfection processes. The clarified water produced by these processes is utilized in activities such as cleaning trucks and cleaning corrals.

Waste reduction is accomplished by exploiting animal tissues and guts, centrifuged sludge, and large solids from the WWTP, as well as sludge from the MBR, generating thermal and electrical energy. Specifically, animal tissues and guts, along with large solids from the WWTP, undergo AD to produce biogas, which generates thermal and electrical energy through a CHP system. Additionally, centrifuged sludge from the WWTP and sludge from the MBR are bio-dried to produce solid biofuel.

The percentage of wastewater allocated to the new processes is a design parameter that is modified to achieve full sustainability, encompassing environmental, social, and cost impacts. The scenarios assessed in this paper vary in the level of the wastewater clarified in the upgraded treatment system. The analysis starts with the comparison of the base and the '50%' scenario where none and half of the wastewater are treated with the new equipment, respectively. To further explore the impact of the new equipment, two additional scenarios were analyzed, treating 25% and 75% of the wastewater, respectively. The upgraded treatment system applied to the WWTP is illustrated in Figure 2. The new equipment is depicted with light blue colour, while the conventional WWTP is with light purple colour. The scenarios differ in the proportion of the wastewater directed to the new equipment.



**Figure 2.** Flowchart of meat industry's future upgrades.

### Membrane Bioreactor

The MBR technology is the process that treats the wastewater previously pretreated by means of grids and dissolved air flotation (DAF) treatment. A traditional MBR system combines a conventional activated sludge process (CAS) with membrane filtration to retain the biomass. Due to the membrane's effective pore size typically being less than 0.1 mm, the MBR generates a clarified and highly disinfected effluent [24]. The MBR will replace the conventional activated sludge process, which currently comprises the WWTP. This change will result in better separation between the activated sludge and the treated water, yielding high-quality clarified water. The high quality is attributed to the long Sludge Retention

Time (SRT) and the small pores of the selected membrane. The percentage of water exiting from this process is calculated according to the Total Suspended Solids (TSSs) in the input and output of the MBR, provided by the industry of MARFICA, and are equal to 30–590 mg/L and <5 mg/L, respectively. Regarding energy consumption, it was found to be 1.06 kWh per ton of influent wastewater [25].

#### Electrodialysis

EL is a membrane-based technique that transports ions through semipermeable membranes under an applied electric field. Its applications include desalination, table salt production, wine stabilization, whey demineralization, and pickling bath recovery [26]. When treating wastewater, EL is used to remove phosphorus, potassium, nitrogen, and various organic and inorganic substances. Several studies have demonstrated EL's high efficacy against iron compounds, cationic surfactants, nitrates, and divalent cations [27]. Experiments conducted at MAFRICA's facilities on a pilot scale revealed that the EL process can clarify 95% of water using 1.06–1.18 kWh/m<sup>3</sup> of electric energy. In fact, the clean water exiting the MBR will undergo EL, while the concentrated effluent will be directed to the public sewer, and the clarified water will proceed to UV disinfection.

#### UV Disinfection

Ultraviolet (UV) radiation is a safe and efficient physical technology for wastewater disinfection, as it does not require chemical agents and avoids the production of by-products. This process aims to inactivate microorganisms using UV light [28]. Similar to the previously mentioned processes, UV disinfection requires a relatively low amount of electric energy, specifically 1.04 kWh/m<sup>3</sup> [29]. Regarding the legal feasibility of reusing the UV-treated water at Mafrica's facilities, the physicochemical and biological parameters meet the requirements for Cleaning and Process Water for the Food Industry, according to current applicable regulations (RD 1620/2007 [30]). However, specific permission is necessary for this action, which would likely restrict water reuse to processes within the industry that do not involve contact with food products, such as cleaning outdoor facilities and trucks.

#### Biodrying

BD is an aerobic process that rapidly removes moisture from biodegradable organic matter using biogenic heat while preserving most of the organic content in the final biomass fuel [31]. Therefore, in this study, the energy consumption of the BD process is considered to be zero. BD processes the sludge from the MBR and the centrifuged sludge from the WWTP, resulting in solid biofuel that can be further processed to produce thermal energy. According to preliminary experimental results from a pilot-scale BD, this process reduces the moisture content of sludge from 78% to 47%.

#### Anaerobic Digestion

AD is widely acknowledged, through LCA studies, as an effective method for reducing greenhouse gas (GHG) emissions and generating renewable energy, particularly when processing secondary feedstock and waste materials [32–34]. AD is a complex process that necessitates stringent anaerobic conditions and relies on the synergistic action of a diverse microbial community to convert organic matter primarily into biogas [35]. Biogas, consisting mainly of methane (55–65%) and carbon dioxide, originates from organic materials and serves as a potent energy resource [36]. This method stands out among biological and thermochemical conversion methods for its superior energy efficiency [37]. It is extensively employed to stabilize biomass and generate both heat and electricity through combined heat and power (CHP) systems, utilizing the biogas produced during digestion [38].

The energy consumption of this process was found to be 0.43 kWh per m<sup>3</sup> of feed [39]. Furthermore, according to preliminary experimental results, 1 kg of animal tissues and

guts, which is the feed for the AD unit, contains 0.31 kg of volatile solids, while 1 kg of volatile solids can produce 0.82 Nm<sup>3</sup> of biogas.

### 2.1.2. Functional Unit

The functional unit (FU) used for the comparative environmental, social, and cost assessments is 1 kg of meat products at the gate. This FU is widely used in scientific reports and allows for straightforward comparison across different studies [9,40,41]. It represents a standardized quantity of meat that has completed the production process and is ready for distribution. Although the plant may produce different types of products, this FU reflects the overall average output, assuming consistent quality that adheres to industry standards for safety, quality, and nutritional content. The FU specifically covers meat products ready for distribution to retailers or other end-users, with subsequent stages like transportation, retail, or consumer use being beyond the scope of this Life Cycle Assessment (LCA). The same functional unit is applied uniformly across the environmental, social, and cost assessments.

### 2.1.3. System Boundaries

The system boundaries for this analysis are defined as gate-to-gate, focusing specifically on the meat processing and associated waste treatment phases within the industrial framework. This delineation encompasses all processes from the point at which raw meat enters the processing facility through to the point where the processed meat products exit, including all related waste management activities. As a result, the scope excludes impacts related to upstream activities such as pig farming, which involves feed production, animal husbandry, and manure management, as well as downstream activities such as the distribution to retailers, consumer use, and end-of-life disposal or recycling of meat products. By confining the analysis to the gate-to-gate boundaries, the study aims to provide a detailed and focused assessment of the environmental, social, and economic impacts intrinsic to the processing and waste-treatment stages. This approach ensures a clear understanding of the impacts directly attributable to the industrial processing phase without the influence of external factors associated with the broader lifecycle of the product.

### 2.1.4. Database and Methodology

#### Database

The analysis was conducted in OpenLCA v.1.11.0, which is a Life Cycle and Sustainability Assessment software. For the full sustainability assessment, SOCA v2 database is utilized. SOCA database is the first database to allow complete, comprehensive assessment because it takes into account all three crucial dimensions of sustainability: environment, society, and economy. It combines PSILCA v3 and Ecoinvent v3.7.1 databases [42].

Based on PSILCA database, SOCA covers social risks on the four stakeholders: workers, local communities, value chain actors, and society. The social outcomes are provided as risk-assessed indicators, which are modelled for every process in the Ecoinvent database by mapping the country-specific sectors of PSILCA to the categories of Ecoinvent [42].

#### Methodology of the Environmental Analysis

As an impact assessment method for the environmental life cycle analysis, ReCiPe 2016 (Hierarchist) was used since it provides results for 17 midpoint impacts and represents the results in summary in three endpoint impacts [43]. The ReCiPe 2016 methodology integrates three distinct cultural theories: egalitarian, hierarchist, and individualist perspectives. This study adopts a hierarchist viewpoint due to its alignment with prevalent policy principles, particularly regarding time-frame, which is commonly set at 100 years, as referenced in ISO standards on LCA [43].

Damage to human health (HH), ecosystem quality (ED), and resource scarcity (RA) were quantified on the endpoint level. Damage to human health is measured in DALYs (Disability-Adjusted Life Years), representing the years lost or lived with disability due

to disease or accidents. Damage to resource availability is assessed in USD (U.S. Dollars), reflecting the additional costs of future mineral and fossil resource extraction. Damage to Ecosystems is measured by the potential loss of species over time and space in terrestrial, freshwater, and marine environments, aggregated into a unit called species/year [43].

All the input and output flows collected in the inventory were introduced to the software.

#### Methodology of the Social Analysis

The impact assessment method for the social indicators evaluation Social Impact Weighting Method was used, which contains the characterization factors of the social indicator. In SOCA v2 database, the assessment is conducted using a risk scale with six different risk levels since the indicators are measured in different, non-comparable units. The activity variable applied in this analysis is worker hours and is used to quantify the social risks. It is explained as the measure of a process activity which can be related to process output [43,44]. The risk level of each indicator is scaled to medium risk hours, as this is the unit for the results depiction, as shown in Table 1.

**Table 1.** Characterization factors for the impact assessment method in PSILCA and SOCA [42,44].

| Risk Level     | Factor |
|----------------|--------|
| Very Low Risk  | 0.01   |
| Low Risk       | 0.1    |
| Medium Risk    | 1      |
| High Risk      | 10     |
| Very High Risk | 100    |
| No Risk        | 0      |
| No Data        | 0.1    |

Based on the input data, a risk level is assigned to each social indicator. The social analysis considers the four main stakeholders of a process: the workers, the value chain actors, the local communities, and the society [42]. For each process conducted in LCA, the basic activity variable, which is the worker hours, should be calculated. Worker hours are related to 1 USD of process output and are calculated through Equation (1) as indicated in PSILCA handbook [42,44]:

$$\text{Worker hours} = \frac{\text{Unit labor costs}}{\text{Mean hourly labour cost (per employee)}} \quad (1)$$

The unit labour cost is calculated by Equation (2) as indicated in PSILCA handbook [42,44]:

$$\text{Unitlabourcosts} = \frac{\text{Compensation of employees (in USD per country – specific sector and year)}}{\text{Gross output (in USD per country – sector and year)}} \quad (2)$$

Data for calculating worker hours per process is typically sourced from national databases. As indicated in Table 1, a characterization factor of 1 is assigned to medium risk levels, so the results are expressed in medium risk hours. The software automatically multiplies the worker hours by the characterization factor for each indicator, yielding results in medium risk hours.

#### Methodology of the Cost Analysis X

The cost analysis was conducted using Microsoft Excel v.2410, employing a functional unit of 1 kg of meat products at the gate, within the established gate-to-gate boundaries. This approach excludes costs related to animal farming, cooking, and disposal, allowing for a precise evaluation of specific processing stages.

The analysis begins by systematically collecting comprehensive data on the operational expenditures (OPEX) of the wastewater treatment systems for both baseline and

upgraded treatment scenarios. Subsequently, the capital expenditures (CAPEX) for the upgraded treatment system were determined. These data, sourced from industrial partners and validated through scientific reports, are thoroughly detailed in the Supplementary Materials [27,45–52].

To perform the sensitivity analysis, with the proportion of wastewater treated by the upgraded system as a parameter, the cost data for equipment and operation were predominantly expressed in terms of cost per unit of input or output of reference flow. The reference flow, as presented in Table 2, depends on the corresponding process input or output flows such as in the case of anaerobic digester the CAPEX and OPEX are calculated using as reference flow the solid waste (input) and, in the case of CHP the electricity (output), was used as reference flow. The dependency of the reference flow from input or output flows is related to the availability of data.

**Table 2.** Reference flows of the corresponding process used for the CAPEX and OPEX calculation.

| Processes           | Reference Flow | Type   | Reference    |
|---------------------|----------------|--------|--------------|
| Anaerobic Digester  | Solid Waste    | Input  | [46]         |
| CHP                 | Electricity    | Output | [47]         |
| Membrane Bioreactor | WasteWater     | Input  | [48]         |
| Electrodialysis     | WasteWater     | Input  | [49]         |
| UV Disinfection     | WasteWater     | Input  | [45]         |
| WWTP                | WasteWater     | Input  | On site data |

The capital cost of the new processes includes both direct (main equipment purchase, delivery, installation, and auxiliary units), and indirect (engineering, supervision, etc.) costs [50]. To calculate CAPEX, a straight-line depreciation model (10 years) was applied.

The CAPEX per unit, ranged in euros per kg, m<sup>3</sup>, or kWh, based on the reference flow used, was calculated through Equation (3).

$$\text{CAPEX per unit} \left( \frac{\text{Euro}}{\text{Unit of referenced flow}} \right) = \frac{\text{CAPEX (Direct and Indirect)} \left( \frac{\text{Euro}}{\text{Year}} \right)}{\text{Annual Value of Referenced Flow} \left( \frac{\text{Unit of referenced flow}}{\text{Year}} \right)} \quad (3)$$

All equipment purchase costs are derived from the literature.

For OPEX estimation, the cost of materials, utilities, maintenance, labour, and other (rent, taxes, insurance, etc.) costs were taken into consideration. The OPEX per reference unit was calculated similarly to Equation (3), presented in Equation (4).

The equipment costs and the costs of materials, utilities, and labour were derived from the literature and adjusted to 2023 using to the present using Cost Escalation (CE) indices [50].

$$\text{OPEX per unit} \left( \frac{\text{Euro}}{\text{Unit of referenced flow}} \right) = \frac{\text{OPEX} \left( \frac{\text{Euro}}{\text{Year}} \right)}{\text{Annual Value of Referenced Flow} \left( \frac{\text{Unit of referenced flow}}{\text{Year}} \right)} \quad (4)$$

The primary objective of this analysis is to quantify the cost implications of implementing the upgraded treatment system and to determine the economic feasibility of the advanced technologies. Therefore, the analysis aims to provide valuable insights for decision-makers regarding the potential return on investment and the sustainability of adopting these innovations in meat processing industry waste treatment.

## 2.2. Inventory

The inventory includes all the data for the sustainability assessment and is provided in the Supplementary Data section. For the environmental analysis, the data were provided by the industry. For the social analysis, the data were collected through international databases for a food manufacturing located in Spain. Data for the cost dimension of the LCSA were collected from the industry and through the literature.

### 3. Results and Discussion

#### 3.1. Life Cycle Impact Assessment

In this section, the results of the LCSA for each of its elements will be presented. The study evaluates the efficiency of directing wastewater from the meat industry to new treatment technologies. For the analysis, it was assumed that half of the wastewater produced is treated in the upgraded system, while the rest is in the conventional treatment plant. Overall, the new system provided numerous benefits to the meat industry, including improvements in its environmental and social footprint and economic evaluation.

##### 3.1.1. Results of the Environmental LCA

The environmental analysis of the upgraded treatment system in the meat industry focused on four key impacts: Global Warming (GWP), Freshwater Eutrophication (FE), Fossil Resource Scarcity (FRS), and Human Carcinogenic Toxicity (HCT). The selection of the four indicators in this study was guided by two primary considerations. The GWP, FE, and FRS impact categories were chosen for their relevance to the study's aims, while the fourth indicator, HCT, was included after normalization analysis revealed it as the highest-impact category.

GWP, measured in kg CO<sub>2</sub> equivalent, serves as a crucial indicator of the greenhouse gas emissions. FE, expressed in kg P equivalent, highlights the environmental impact of nutrient discharge, particularly phosphorus, into aquatic systems. FRS, measured in kg oil equivalent, indicates the depletion of fossil resources mainly due to energy consumption. Lastly, HCT, measured in kg 1,4-DCB equivalent, reflects the potential risks to human health from carcinogenic substances released into the environment [53].

For the percentage change calculation between the baseline scenario and the alternative scenario the equation used was Equation (5).

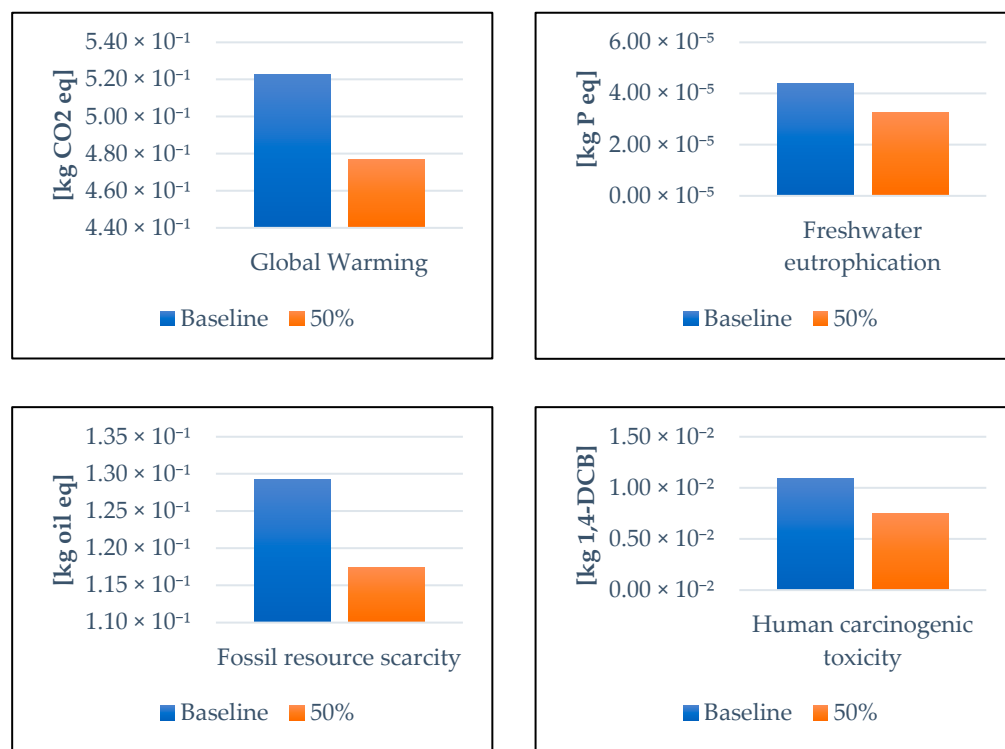
$$\text{Percentage change of impacts} = \frac{\text{Value of the impact category for the scenario assessed} - \text{Value of the baseline scenario}}{\text{Value of the baseline scenario}} * 100\% \quad (5)$$

The results reveal significant reductions in all four impacts compared to the baseline scenario, as presented in Figure 3. Notably, by introducing 50% of the wastewaters to the new treatment technologies, the emissions of CO<sub>2</sub> and equivalent gases to the atmosphere are reduced by 8.7%, contributing less to Global Warming. Simultaneously, impacts on Freshwater Pollution and on human health, regarding carcinogenicity, decreased substantially 23.8% and 26.2%, respectively, contributing to a healthier environment. FRS impact is mitigated by 9.1%, contributing to the preservation of these resources.

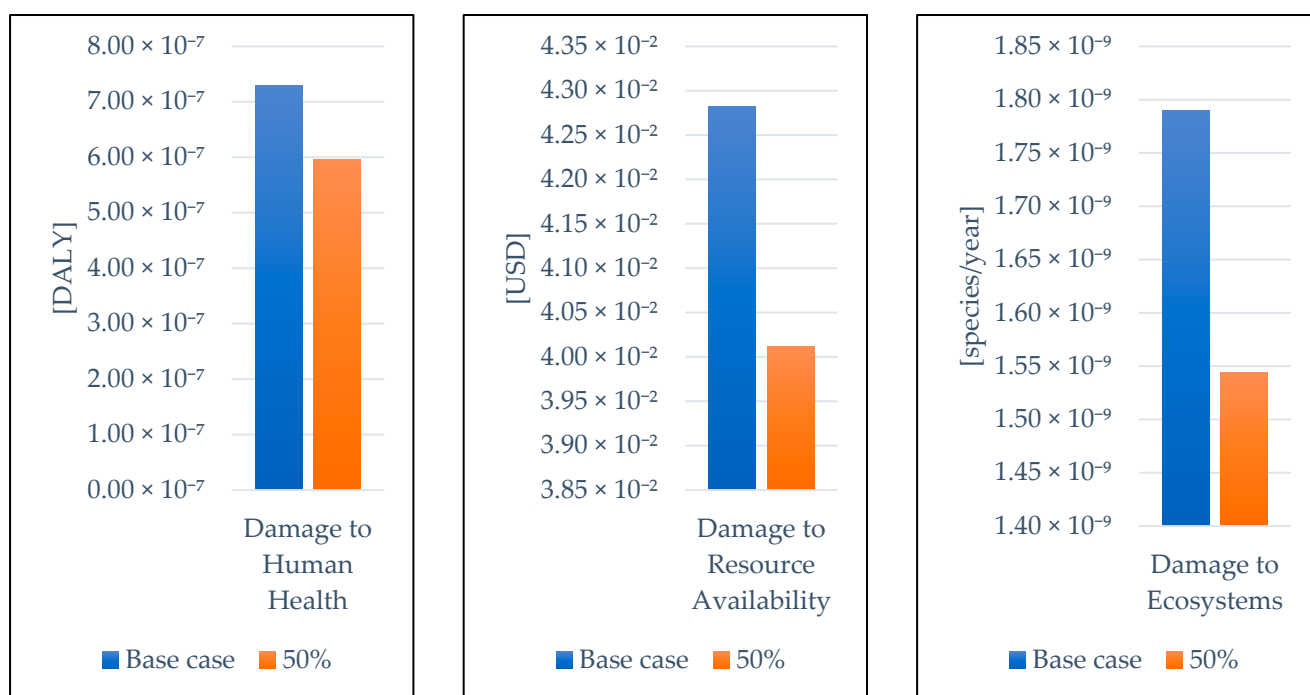
The analysis results highlight several critical findings. Notably, the AD combined with the CHP system—proved highly effective, reducing the impact on Global Warming by 4.2%, FE by 13.8%, HCT by 11.3%, and FRS by 4.6%. The significant reduction in HCT is particularly notable 10.5%, largely due to water savings. The BD process also contributes positively by reducing all environmental impacts, though to a slightly lesser extent than the AD system. Despite this, BD plays a valuable role in the overall reduction in environmental burdens. Conversely, the MBR and EL processes slightly increase environmental impacts due to their energy consumption. More specifically, the impact of these processes on Global Warming is increased by 0.14% and 0.15% though MBR and EL, respectively, but they are essential for sludge–water separation and water clarification. Further analysis of these results can be found in Section 3.2.1.

In Figure 4, the comparison of the endpoint environmental impacts is depicted between the base and the '50%' scenario.

By integrating the new treatment system, substantial reduction in damage to human health was achieved, reaching 18.2%. Moreover, decrease of 13.6% and 6.4% in the damage to ecosystems and resource availability indicators were observed, respectively.



**Figure 3.** Selected indicators of midpoint environmental impacts from the baseline of meat industry compared with the ones after the operation of the upgraded system treatment.



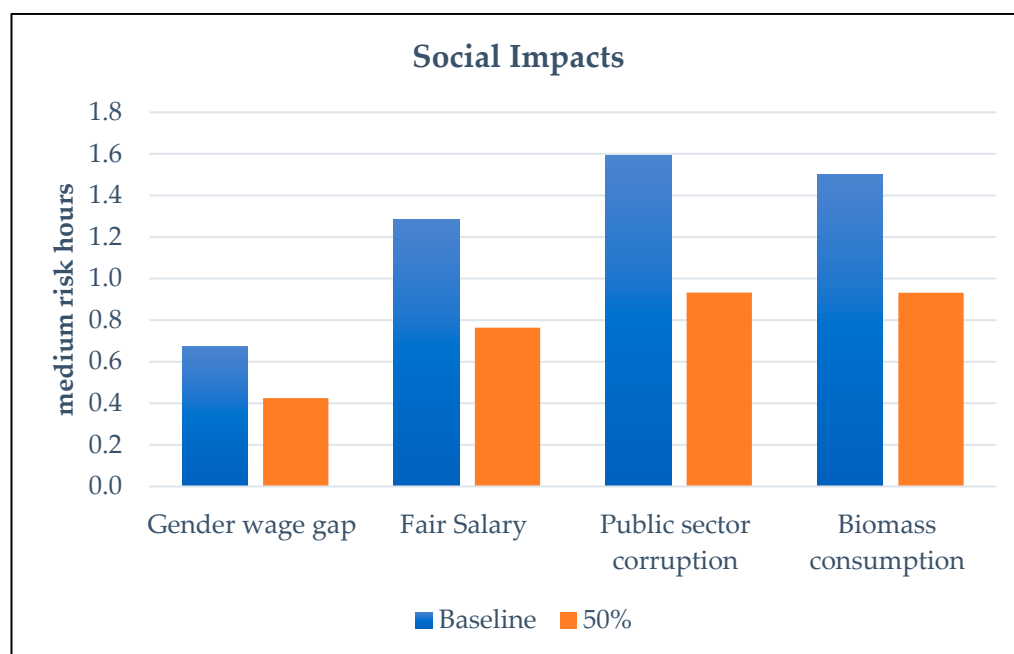
**Figure 4.** Indicators of endpoint environmental impacts from the baseline of meat industry compared with the ones after the operation of the upgraded system treatment.

### 3.1.2. Results of the Social LCA

The social analysis comparing the baseline with the '50%' scenario focused on the four most critical impacts. These impacts were chosen based on the risk levels indicated by the social indicators, as well as their relevance to the objectives of both the meat industry and this study. Therefore, the main impacts analysed are the fair salary (FS), Biomass

consumption (BC), public sector corruption (PSC), and gender wage gap (GWG). FS refers to compensation that is equitable and appropriately aligned with the value of a specific service or category of services provided. Setting a minimum fair wage should reflect the reasonable worth of the service rendered [44]. The BC indicator measures the rate of BC per process and is a critical resource affecting local communities [44]. PSC, measured by the Corruption Perceptions Index, refers to the misuse of public power for private gain, as perceived by experts and informed surveys [44,54]. The GWG indicator assesses wage disparities between men and women, following the definition of OECD (2015) [44,55].

As seen in Figure 5, the social risk of GWG, FS, PSC, and Biomass consumption are reduced by 36.0%, 37.0%, 34.9%, and 33.7%, respectively. This substantial reduction is largely attributed to the integration of AD and the combined heat and power system into wastewater management practices. Specifically, these processes lead to a 27.8 percent reduction in the risk of the GWG, a 22.2 percent reduction in unfair salary practices, a 17.6 percent reduction in PSC, and a 17.0 percent reduction in BC. These improvements underscore the significance of generating electricity and thermal energy from renewable sources and highlight the importance of waste valorization.



**Figure 5.** Selected indicators of social impacts from the baseline of meat industry compared with the ones after the operation of the upgraded system treatment.

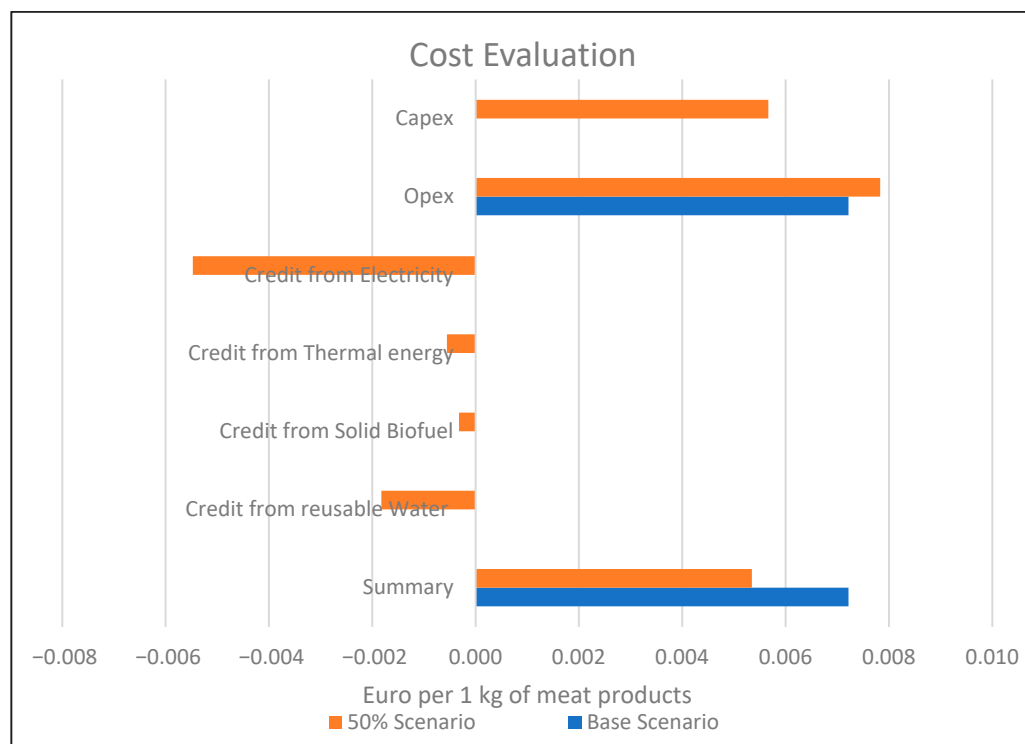
Additionally, significant reductions in social risks are achieved through water clarification and reuse. These reductions include a 5.6 percent decrease in unfair salary practices, a 3.8 percent decrease in PSC, and a 3.6 percent decrease in BC. These changes are related to the social impacts of materials used in supply network construction, indicating the social risks associated with water consumption [56,57]. However, there is a slight adverse impact on the GWG, with a 0.12 percent increase in risk.

The BD process also contributes to reducing all assessed social risks, with a 2.3 percent reduction in BC. Conversely, the MB and EL processes lead to a slight increase in social risks due to their electricity requirements, although they are necessary for sludge separation and water clarification. Further analysis of these results can be found in Section 3.2.1.

### 3.1.3. Results of the Life Cycle Costing

Regarding the cost analysis, it is important to note that this approach adheres to gate-to-gate boundaries, excluding costs related to animal farming, cooking, and disposal. The evaluation specifically focuses on the wastewater treatment system and does not consider

the costs associated with meat processing, as these remain unchanged between the two scenarios. Figure 6 illustrates the results of this analysis. In the Figure, the orange-coloured cost represents the 50% scenario, while the blue-coloured cost represents the baseline. The evaluation of wastewater treatment costs includes the equipment costs for the upgraded system, as well as the operational costs consisting of the material, utilities, maintenance, and labour costs for both the conventional and upgraded treatment systems.



**Figure 6.** Cost comparative analysis of the conventional wastewater treatment system and the upgraded system for treating 50% of wastewater in the meat processing industry.

As shown in Figure 6, the 50% scenario demonstrates a more economically advantageous outcome for the industry, with wastewater treatment costs reduced by 26%. This results in a cost saving of EUR 0.00187 per kg of meat, translating to EUR 63,152.70 in annual production savings. In this scenario, wastewater treatment is split evenly, with 50% of the wastewater treated by the conventional system and 50% by the upgraded system. The equipment cost of the conventional wastewater treatment system is excluded from this analysis, as it was established prior to this study and is, therefore, not included in the current cost evaluation. Further details are discussed in the Section “Cost Analysis—Hotspot Identification”.

It is important to note that the cost analysis is heavily influenced by the specific year and geographic location of the case study. This suggests that outcomes in different regions or time periods could yield different results. Consequently, these findings are presented as an example and are primarily intended for comparative purposes between the baseline and the 50% scenario. Further analysis of these new processes should be conducted on a case-by-case basis and for future scenarios to accurately assess the economic benefits for wastewater treatment plants in the meat processing industry.

### 3.2. Interpretation and Discussion

#### 3.2.1. Hotspot Identification

The results illustrated in Figures 3–6 clearly indicate that the ‘50%’ scenario significantly enhances various aspects of the meat industry, including environmental sustainability, social responsibility, and cost efficiency. This scenario appears to strike a balanced

approach, leading to notable improvements across these critical dimensions, thereby supporting a more sustainable and economically viable future for the industry. The outcomes are further analyzed, and the hotspots of the analysis are identified.

#### Environmental Analysis—Hotspot Identification

The '50%' scenario proved to be substantially more environmentally sustainable than the conventional treatment system. Each additional process incorporated into the wastewater treatment system is carefully assessed for its environmental implications, with a detailed analysis of its impact on the four impact categories assessed.

**Anaerobic Digestion and CHP system:** The AD and combined heat and power (CHP) system is the most effective intervention in reducing the four impact categories compared to other methods. The AD of animal tissues and guts produces biogas, which is utilized in CHP systems to generate electricity and thermal energy. This process decreases fossil fuel dependence and CO<sub>2</sub> emissions, thereby mitigating GWP [58]. The electricity generated from AD meets over one-fifth of the energy demand of the production process, enhancing the system's energy independence and further reducing its Global Warming impact [59,60].

This reduction in GWP aligns with the literature indicating that AD captures methane for energy production, offsetting emissions that would otherwise result from landfilling or direct discharge [32,61]. Additionally, the AD process reduces the organic load in wastewater, minimizing nutrients available for eutrophication [61]. The production of biogas also lowers reliance on external energy sources, contributing to a smaller environmental footprint.

The decrease in FRS is due to the reduced need for fossil fuels, as biogas from anaerobic digestion is used within the CHP system. The literature supports this, showing that integrating AD with CHP systems significantly reduces fossil fuel dependence by providing a renewable energy source, thus lowering overall fossil resource demand [62,63].

**Biodrying:** The BD process plays a crucial role in improving environmental sustainability and public health within sludge management. By significantly reducing sludge moisture content, BD produces solid fuel that can effectively replace fossil fuels. This substitution lowers CO<sub>2</sub> emissions, as confirmed by both this study and the existing literature [64]. Additionally, BD decreases sludge volume and stabilizes its contents, which can reduce the presence of harmful contaminants. Analysis shows that BD not only minimizes sludge volume but also reduces exposure to carcinogens, aligning with previous research [65,66].

While solid biofuel production is typically associated with significant emissions [67], BD presents a more environmentally friendly alternative. By using biogenic energy to reduce moisture content, BD generally results in lower greenhouse gas emissions and pollutants compared to traditional fossil-fuel-based drying methods or other conventional biofuel production processes [68]. Consequently, biofuels produced through BD are eligible for environmental credits when sold, further underscoring the benefits of this approach.

**Water Clarification System:** The integration of the MBR with EL and UV disinfection markedly improves wastewater treatment efficiency by effectively removing nutrients like nitrogen and phosphorus, which are known to contribute to FE eutrophication [69]. This advanced treatment approach has been shown to lower nutrient loads, thereby mitigating the risk of algal blooms and oxygen depletion in aquatic environments. These findings are supported by both this study and the existing literature [70].

Moreover, this combination of technologies excels in eliminating carcinogens and other hazardous contaminants from wastewater. This improvement in effluent quality helps reduce health risks for humans and wildlife [71]. The reduction in pollutants with carcinogenic potential underscores the environmental and social benefits of these advanced treatment methods, as supported by the literature [27]. The effectiveness of advanced treatment processes in mitigating carcinogenic risks is well-documented, particularly the role of EL in removing heavy metals and other carcinogens from wastewater [72].

Additionally, the clarified water produced meets all standards for reuse, which reduces the need for constructing additional water supply infrastructure. The typical construction

material for such networks, cast iron, involves processes that emit carcinogenic substances like polycyclic aromatic hydrocarbons [56,73]. Therefore, while advanced treatment processes contribute to higher energy demands, they play a crucial role in reducing carcinogenic risks and enhancing environmental sustainability, as supported by the literature.

The reduction in the impacts on the midpoint categories, along with others, contributes to the reduction in endpoint indicators like damage to human health, resource availability, and ecosystems, thereby enhancing the meat industry's environmental performance through improved energy efficiency and effective wastewater treatment.

#### Social Analysis—Hotspot Identification

The positive changes observed in social indicators align with the reductions in environmental impacts following the implementation of the new technologies. Each process incorporated into the wastewater treatment system is carefully assessed for its social impacts, with a detailed analysis of its impact on the four impact categories assessed.

**Anaerobic Digestion and CHP System:** The implementation of the upgraded AD and CHP system significantly reduces social risks associated with meat processing, primarily by decreasing reliance on the Spanish electricity grid. This reduction in dependency is crucial, as electricity production, particularly when reliant on fossil fuels like coal, is a major contributor to social risks. These risks are often heightened by poor labour practices in coal-exporting countries, as documented in multiple studies [74].

The new system mitigates these risks by generating around 20% of the industry's electricity needs internally, thereby lessening the need for imported hard coal, which is often sourced from countries with low social security standards. This reduction in imports directly addresses social inequalities and associated risks [74–77]. The conventional treatment plant, with its higher electricity demands, exacerbates these social risks, making the upgraded system a more socially responsible choice.

Moreover, by integrating renewable energy technologies like AD and CHP, the system contributes to fairer wage practices. Research from the Institute for Employment Research in Germany shows that companies producing electricity through renewable resources tend to offer better wages, thereby promoting equitable salary practices [57,75]. This mainly occurs in Spain, where electricity production has historically involved importing hard coal from developing countries with notable social security challenges.

The adoption of AD and BD technologies, which convert waste into energy or biofuels, supports sustainable biomass management. This approach not only alleviates environmental pressures but also mitigates social risks, particularly those associated with resource extraction in local communities and ecosystems [78]. By reducing reliance on external biomass inputs, these technologies contribute to more sustainable practices and lessen the negative impacts on communities linked to resource extraction [78].

Electricity production is also linked to social risks like the GWG, which is prevalent in the male-dominated energy sector. This issue is exacerbated by the importation of raw materials from developing countries, where gender wage disparities are more common. The correlation between the energy sector and the GWG is further supported by findings from the International Labour Organization [79]. The implementation of advanced technologies like AD and BD can help address these disparities by promoting a more inclusive work environment and improving wage standards.

The upgraded system also shows a significant reduction in the risk of PSC as the percentage of wastewater treated with advanced technologies increases. This improvement is attributed to the enhanced transparency and efficiency brought about by adopting renewable technologies, which reduce the industry's reliance on complex and potentially corrupt supply chains. Research by Kolstad and Wiig supports this finding, emphasizing that increased transparency in industries that embrace renewable technologies plays a crucial role in reducing corruption by fostering clearer and more accountable processes [80].

**Biodrying Process:** The BD process, which produces solid biofuels as a substitute for higher-risk solid fuels, also contributes to reducing social risks. By emphasizing industry

self-reliance within the context of Spain’s social security system, the BD process minimizes dependence on imports from countries with higher social risks. This strategy has the potential to improve wage standards, narrow the GWG, promote a more inclusive work environment, and mitigate the risks associated with substantial BC, as indicated by the analysis database and supporting literature [74,77].

**Water Clarification System:** The water clarification system, which incorporates MBR, EL, and UV disinfection technologies, has varying impacts on the four assessed social risk categories. Overall, the system has a positive effect by reducing the use of significant materials in the water supply network. The reduction in material usage mitigates social risks associated with mining, construction practices, and the emissions generated during production, as documented in several studies [56,57].

However, the system has a negative impact on the GWG category, primarily due to its high electricity consumption. As the proportion of water treated by the upgraded system increases, so does the energy demand of the clarification process, which in turn exacerbates social risks related to the GWG. This issue is particularly pronounced in developing countries’ electricity production sectors, as previously noted, where gender discrimination contributes to significant wage disparities [57,75].

#### Cost Analysis—Hotspot Identification

The economic benefits of the upgraded wastewater treatment system are evident when comparing the base scenario with the 50% scenario. As shown in Figure 6, the equipment cost of the conventional treatment system is excluded from the analysis because it was purchased prior to this study, so equipment costs are considered only in the 50% scenario.

The operational costs for the upgraded treatment system are higher due to additional processes required for energy production, waste valorization, and wastewater clarification and also due to higher maintenance costs for the conventional treatment system, likely due to increased maintenance requirements for older equipment.

Cost savings are primarily attributed to the upgraded wastewater treatment system. This system generates electricity and thermal energy through AD and a combined heat and power (CHP) system. Additionally, solid biofuel produced via the bio-drying process can be sold, generating additional revenue. The clarified water can be reused in processes that do not come into contact with meat, reducing overall water consumption.

Overall, the baseline scenario using only the conventional treatment system incurs higher costs and is less economically sustainable compared to the 50% scenario. A detailed economic analysis is provided in Table 3, which outlines the costs and revenues for each process based on an annual production of 33,752 tonnes of meat.

**Table 3.** Annual Life Cycle Cost (LCC) breakdown for baseline and 50% scenarios.

|                   | Process                                | Unit      | CAPEX      | OPEX       | Revenue     | Total Cost | Summary    |
|-------------------|----------------------------------------|-----------|------------|------------|-------------|------------|------------|
| Baseline Scenario | WWTP (including personnel cost)        | Euro/year | -          | 193,200.00 | -           | 193,200.00 | 243,600.00 |
|                   | Waste management                       | Euro/year | -          | 50,400.00  | -           | 50,400.00  |            |
|                   | AD and CHP unit                        | Euro/year | 102,666.39 | 115,968.71 | −202,884.87 | 15,750.23  |            |
| 50% Scenario      | Water clarification system             | Euro/year | 70,659.32  | 28,088.00  | −61,508.70  | 37,238.62  | 180,447.30 |
|                   | BD                                     | Euro/year | 17,950.00  | 897.50     | −10,789.05  | 8058.45    |            |
|                   | Personnel cost for the upgraded system | -         | -          | 22,800.00  | -           | 22,800.00  |            |
|                   | WWTP (including personnel cost)        | Euro/year | 0.00       | 96,600.00  | -           | 96,600.00  |            |

As shown in Table 2, in the 50% scenario, the highest equipment and operational costs are primarily associated with the AD and the CHP unit. However, these costs are offset by significant credits from electricity and thermal energy production. It is important to note that conventional treatment equipment incurs substantial operational costs, mostly for maintenance. Specifically, waste management costs amounted to EUR 50,400, which are entirely eliminated with the upgraded wastewater system due to complete waste valorization. Overall, the total cost analysis reveals a 26% reduction in costs when using the upgraded treatment system for half of the wastewater. This reduction translates to a cost saving of EUR 0.00187 per kg of meat, resulting in an annual production saving of EUR 63,152.70.

It should be emphasized that the cost analysis is significantly affected by the year and geographic context of the case study, meaning that results may vary in different locations or time periods. As such, the findings are presented as an illustrative example, mainly to compare the baseline with the 50% scenario. A more detailed evaluation of these new processes is recommended for individual cases and future conditions to fully understand their economic impact on wastewater treatment plants in the meat processing industry.

In summary, the upgraded treatment system enhances the environmental, social, and economic performance of the meat industry. By improving energy efficiency, utilizing alternative energy sources, and implementing effective wastewater treatment, the industry progresses toward achieving a sustainable balance of economic viability, social responsibility, and environmental stewardship.

### 3.2.2. Analysis of Different Scenarios

To further identify the hotspots and analyze the environmental, social, and cost impacts of introducing the new treatment system, three different scenarios were assessed. These scenarios varied based on the percentage of wastewater processed by the new system: 25%, 50%, and 75%. The assessment was implemented as previously described, using the same methodology and the functional unit of 1 kg of meat produced. The results do not include the meat processing industry part; they rather focus on the wastewater treatment systems. The blue columns in the figures represent the impacts associated with the base wastewater treatment facility, which is utilized in all scenarios but at varying percentages. The grey columns depict the impacts of AD and the CHP system, while the orange-coloured column represents the impacts of the processes associated with the water clarification, and the yellow column represents the contributions of the BD process.

#### Environmental Analysis—Different Scenarios

The analysis focuses on the four selected impact categories: Global Warming, FE, FRS, and the HCT. The environmental analysis of the wastewater treatment system in the meat processing industry reveals significant improvements across several key impact categories when varying the percentage of wastewater treated with the upgraded system (25%, 50%, and 75%). The analysis focuses on GWP, FE, FRS, and HCT. The findings indicate that increasing the proportion of wastewater treated by the upgraded system consistently reduces environmental impacts. The conventional water treatment plant remains in use for all scenarios since part of the wastewater is still routed there. The midpoint environmental impacts for each scenario defined in each process are presented in Figure 7.

The impact of all the processes regarding the wastewater treatment is added in order to analyze the percentage difference, calculated as Equation (5), on the environmental impacts between the base and the selected scenario, as seen in Figure 8.

The reduction in environmental impact across all assessed categories is primarily due to the AD process. This process effectively converts organic waste into biogas, thereby significantly reducing methane emissions and the demand for electricity, as detailed in Section 3.2.1 [32,61]. However, as illustrated in Figure 8, the environmental contributions of AD, combined heat and power (CHP), and the BD process are relatively consistent across the three scenarios evaluated. The main differentiating factor among the scenarios is

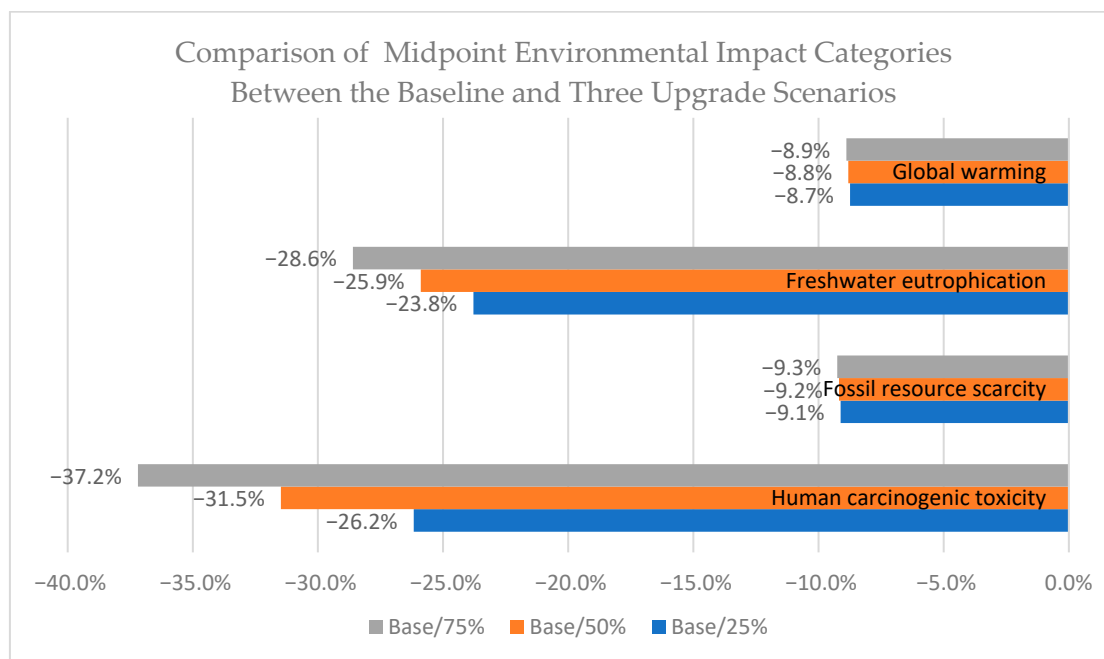
the impact of the wastewater treatment plant (WWTP) system and the water clarification system.



**Figure 7.** Sensitivity analysis results illustrating the impact of varying percentages of wastewater treated (25%, 50%, and 75%) by the upgraded treatment system on four selected midpoint environmental impact categories. The key parameter used is the percentage of wastewater treated, showing the different treatment levels affect the contributions of various processes within the upgraded system to these environmental impact categories.

**Wastewater Treatment Plant (WWTP) System:** As shown in Figure 7, the WWTP's contribution to environmental impact is notably reduced in the 75% scenario compared to the 25% and 50% scenarios. The WWTP system requires more electricity per kilogram of wastewater treated than the upgraded system, and therefore, as the proportion of wastewater treated in the upgraded system increases, energy requirements in total decrease. Additionally, the solid waste generated is not valorized but is instead sent to an

external manager. Energy production is primarily associated with increased greenhouse gas emissions, leading to impacts on GWP, as confirmed by the U.S. Environmental Protection Agency [59,60]. Furthermore, the extraction of solid fuels for electricity generation contributes to nutrient leaching into water bodies, potentially leading to eutrophication, a concern highlighted in the literature [81]. Reduced reliance on the WWTP also decreases FRS, as the upgraded system uses less energy for water treatment. Moreover, valorizing wastes instead of external management contributes to reducing HCT.



**Figure 8.** Percentage difference of the environmental impact categories between the base and the three scenarios utilizing the upgraded system.

**Water Clarification System:** This system, which includes the MBR, EL, and UV disinfection processes, shows an increasing environmental impact from the 25% to the 75% scenario, particularly in terms of GWP, FE, and FRS. This increase is due to the higher electricity demands of the clarification system, driven by the greater volume of wastewater processed as its usage increases. As previously noted, electricity consumption plays a critical role in these impact categories. However, a different trend is observed in the HCT category, where a reduction is seen. This is attributed to the effective removal of carcinogenic compounds from wastewater. The advanced treatment processes, particularly EL, are effective in removing heavy metals and other carcinogens, significantly reducing carcinogenic risks in treated effluents, as supported by Al-Amshawee et al. (2020) [27].

The results are also detailed in Table 4, presented in the units of measurement for each impact category across the three different scenarios, including the baseline scenario.

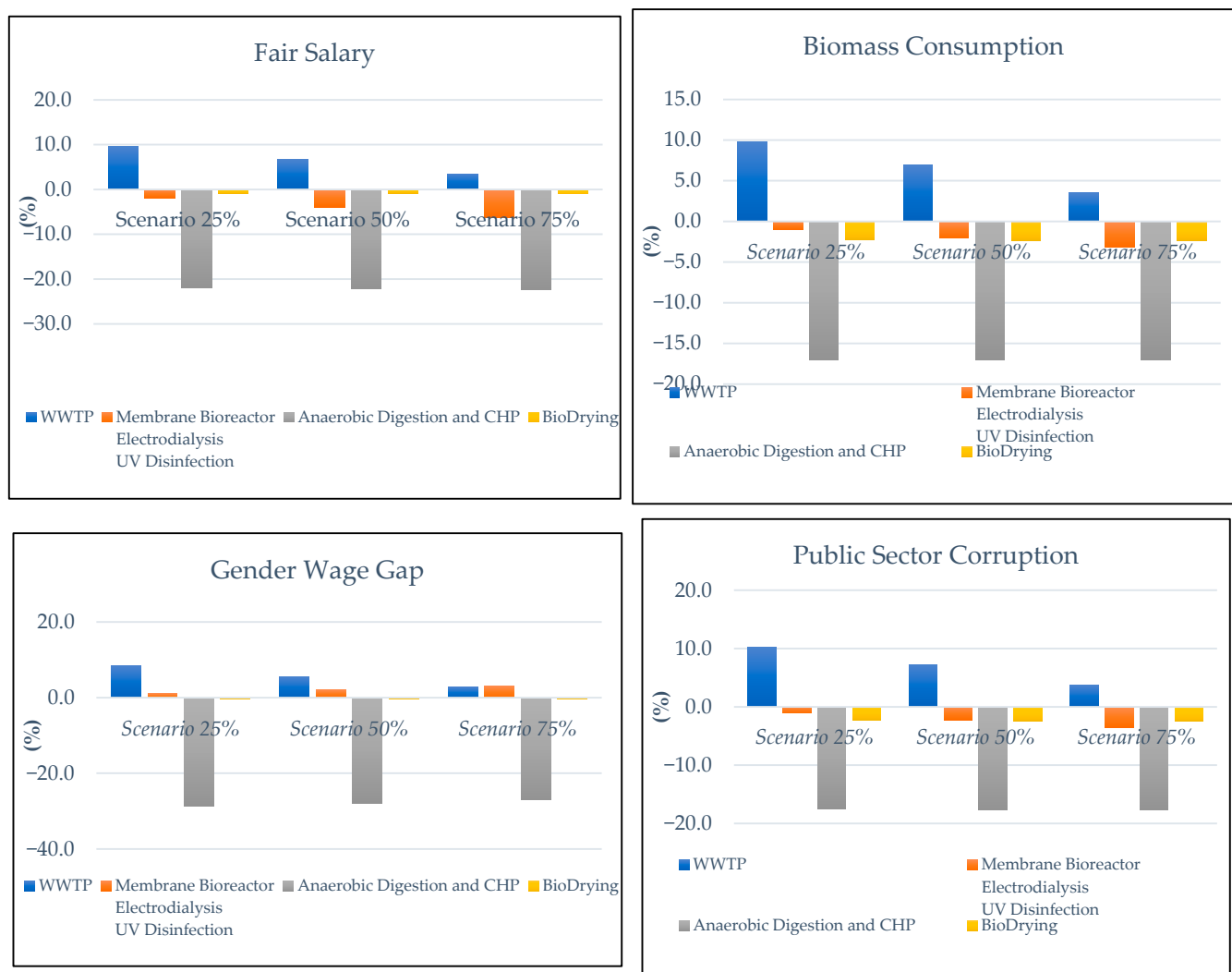
In Figure 8 and Table 4, it is evident that increasing the proportion of wastewater treated by the upgraded systems leads to a reduction across all impact categories. The extent of this reduction varies for each environmental impact, underscoring the multifaceted nature of these impacts and the importance of Life Cycle Assessment (LCA) in capturing these complexities. Among the four impact categories assessed, the 75% scenario emerges as the most environmentally beneficial, highlighting the positive impact of the upgraded equipment.

**Table 4.** Midpoint results of the environmental LCA for the four scenarios varying in the proportion of the water treated in the upgraded wastewater treatment.

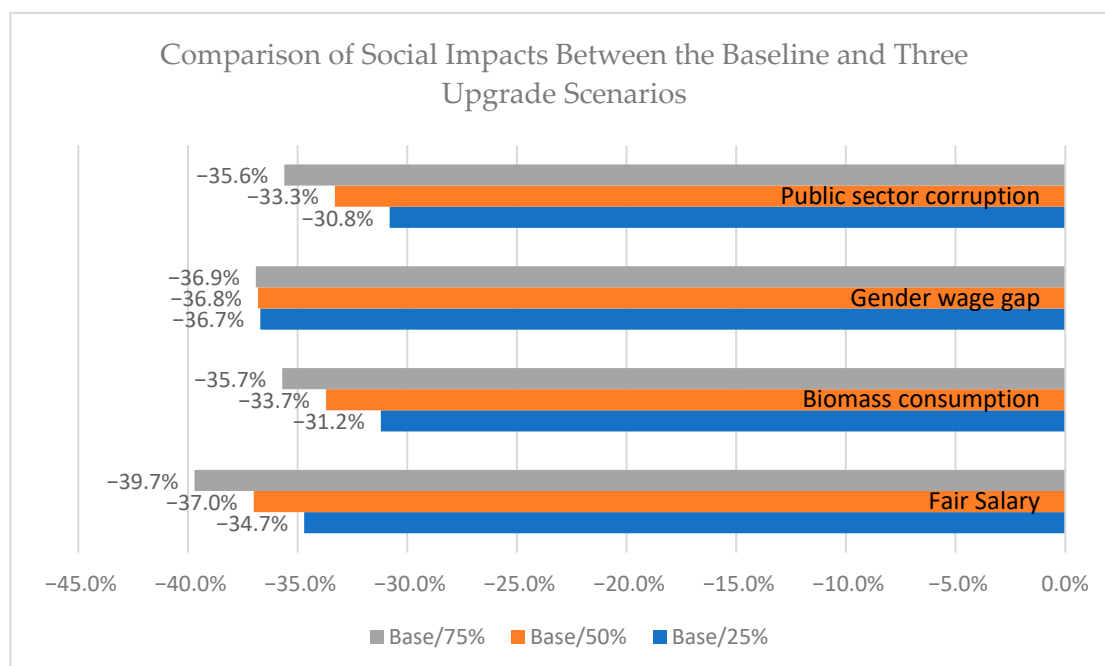
| Impact Category             | Reference Unit        | Base Case             | 25%                   | 50%                   | 75%                   |
|-----------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Global Warming              | kg CO <sub>2</sub> eq | $5.23 \times 10^{-1}$ | $4.77 \times 10^{-1}$ | $4.77 \times 10^{-1}$ | $4.76 \times 10^{-1}$ |
| Freshwater Eutrophication   | kg P eq               | $4.40 \times 10^{-5}$ | $3.35 \times 10^{-5}$ | $3.26 \times 10^{-5}$ | $3.14 \times 10^{-5}$ |
| Fossil Resource Scarcity    | kg oil eq             | $1.29 \times 10^{-1}$ | $1.18 \times 10^{-1}$ | $1.17 \times 10^{-1}$ | $1.17 \times 10^{-1}$ |
| Human Carcinogenic Toxicity | kg 1,4-DCB            | $1.09 \times 10^{-2}$ | $8.05 \times 10^{-3}$ | $7.47 \times 10^{-3}$ | $6.85 \times 10^{-3}$ |

### Social Analysis—Different Scenarios

The social analysis of the three scenarios emphasized the four highest risked impacts selected based on the aim of the analysis. Therefore, the main impacts analyzed are the ‘FS’, ‘BC’, ‘PSC’, and ‘GWG’. The social impacts for each scenario defined in each process are presented in Figure 9.

**Figure 9.** Sensitivity analysis results illustrating the impact of varying percentages of wastewater treated (25%, 50%, and 75%) by the upgraded treatment system on four selected social impact categories. The key parameter used is the percentage of wastewater treated, showing the different treatment levels’ effect regarding the contributions of various processes within the upgraded system to these social impact categories.

The impact of all the processes regarding the wastewater treatment is added in order to analyze the percentage difference, calculated as Equation (5), on the social impacts between the base and the selected scenario, as seen in Figure 10.



**Figure 10.** Percentage difference of the social impact categories between the base and the three scenarios utilizing the upgraded system.

The reduction in environmental impact across all assessed categories is primarily due to the AD process. This process effectively converts organic waste into biogas, thereby significantly reducing methane emissions and the demand for electricity, as detailed in Section 3.2.1 [32,61]. However, as illustrated in Figure 9, the social contributions of an AD, combined heat and power (CHP), and the BD process are relatively consistent across the three scenarios evaluated. The main differentiating factor among the scenarios is the impact of the wastewater treatment plant (WWTP) system and the water clarification system.

**Wastewater Treatment Plant (WWTP) System:** As shown in Figure 9, social risks associated with the WWTP system are reduced in the 75% scenario compared to the 25% and 50% scenarios. This is because the WWTP system requires more electricity per kilogram of wastewater treated than the upgraded system. As the proportion of wastewater treated by the upgraded system increases, overall energy requirements decrease.

As discussed in Section 3.2.1, the import of raw materials for electricity production from developing countries poses critical social risks, including issues related to fair wages, the GWG, and PSC. These risks are particularly prevalent in countries with underdeveloped social security systems [57,75]. Therefore, reducing electricity needs directly contributes to improving the social environment by minimizing the associated social risks linked to electricity consumption.

**Water Clarification System:** This system, which includes the MBR, EL, and UV disinfection processes, generally shows a decreasing social impact across the three scenarios for all assessed social impact categories, except for risks related to the GWG. The system influences the four social risk categories in different ways, mostly positively, as water clarification reduces the need for significant materials in the construction of a water supply network. These materials are associated with pronounced social risks noticed due to the mining, construction practices, and emissions involved in their production [56,57]. As the proportion of water reused rises, the social risks associated with fair salaries, PSC, and BC decrease, thereby reducing the overall social impact of water consumption. However, the

system shows a negative impact on the GWG category, as this category is strongly influenced by electricity consumption [77]. As the proportion of water treated in the upgraded system increases, the energy demands of the clarification processes rise, leading to higher social risks in the GWG category. This is particularly relevant in developing countries, where the electricity production sector often exhibits gender discrimination, resulting in wage disparities [57,75].

The results are also detailed in Table 5, presented in the units of measurement for each impact category across the three different scenarios, including the baseline scenario.

**Table 5.** Risk results of the social LCA for the four scenarios vary in the proportion of the water treated in the upgraded wastewater treatment.

| Impact Category          | Reference Unit    | Base Case             | 25%                   | 50%                   | 75%                   |
|--------------------------|-------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Fair Salary              | FS med risk hours | 1.21                  | $7.92 \times 10^{-1}$ | $7.64 \times 10^{-1}$ | $7.31 \times 10^{-1}$ |
| Biomass consumption      | BM med risk hours | 1.41                  | $9.67 \times 10^{-1}$ | $9.32 \times 10^{-1}$ | $9.04 \times 10^{-1}$ |
| Gender wage gap          | GW med risk hours | $6.64 \times 10^{-1}$ | $4.20 \times 10^{-1}$ | $4.25 \times 10^{-1}$ | $4.19 \times 10^{-1}$ |
| Public sector corruption | C med risk hours  | 1.43                  | $9.90 \times 10^{-1}$ | $9.32 \times 10^{-1}$ | $9.21 \times 10^{-1}$ |

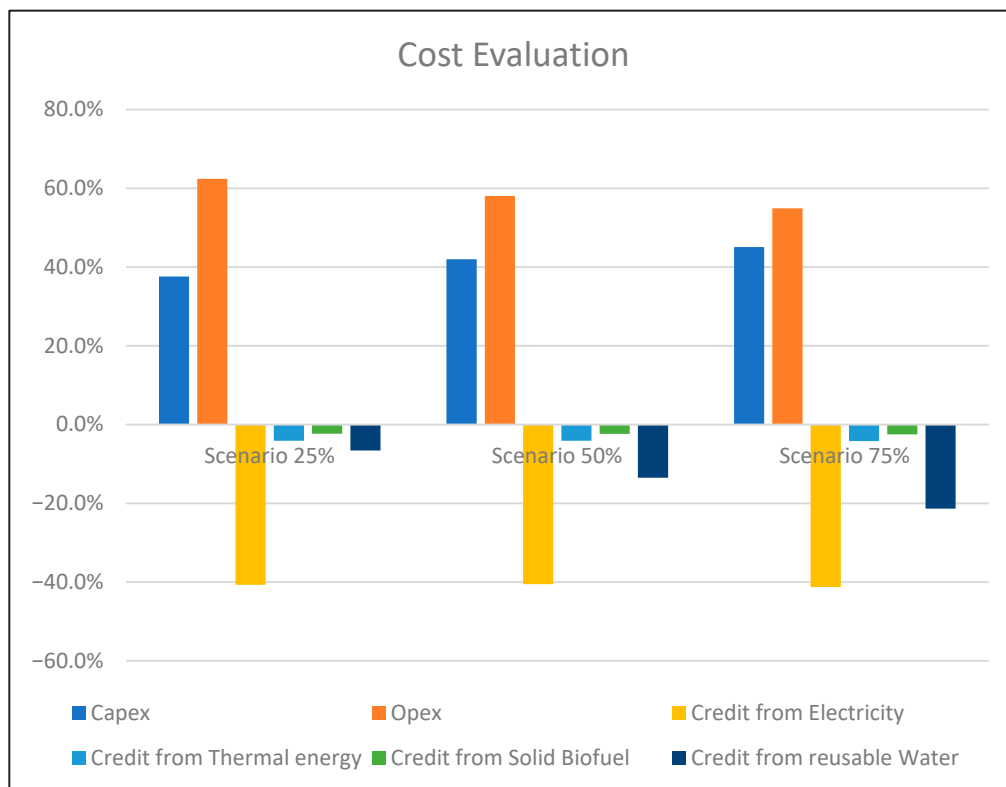
In Figure 10 and Table 5, it is evident that increasing the proportion of wastewater treated by the upgraded systems leads to a reduction across all impact categories. The extent of this reduction varies for each social impact, underscoring the multifaceted nature of these impacts and the importance of Life Cycle Assessment (LCA) in capturing these complexities. Among the four impact categories assessed, the 75% scenario emerges as the most socially beneficial, highlighting the positive impact of the upgraded equipment.

#### Cost Analysis—Different Scenarios X

To assess the economic impact of integrating new technologies into the wastewater treatment system, the proportion of wastewater treated in the upgraded system was used as a key parameter. Three scenarios were analysed based on the percentage of wastewater processed by the upgraded system: 25%, 50%, and 75%. The analysis results highlight the variations in equipment costs and operational expenses, and the potential credits from waste valorization across each scenario. These findings are illustrated in Figure 11 as percentages of the total cost for each scenario.

As illustrated in Figure 11, the equipment cost across the three scenarios increases from 25% to 75% scenario due to the increased capacity needs of the equipment since a greater proportion of the wastewater would be treated in the upgraded system in the 75% scenarios. The results are also illustrated in Table 6, including the base scenario costing.

As the proportion of wastewater treated in the upgraded system increases, a slight decrease in operational costs is observed. This is attributed to reduced reliance on the conventional treatment system, which has higher operational costs, as discussed in Section “Cost Analysis—Hotspot Identification”. However, the credits for electricity, thermal energy, and solid biofuel production decrease slightly with greater use of the upgraded system. This occurs because, as shown in Figure 2, the input of ‘large solids’ to the anaerobic digester (AD) decreases with reduced reliance on the conventional system. The ‘large solids’ flow is relatively minor compared to the main input flow in the AD unit, so this reduction has only a small impact on the credits generated by this process across the three scenarios. Additionally, in the BD process, the total sludge entering the unit remains nearly constant, regardless of the proportion of wastewater treated by the new system. However, the reduction in credits from these products is balanced by an increase in credits from clarified water, which rises significantly as more wastewater is processed through the upgraded system.



**Figure 11.** Economic impact analysis across three scenarios based on the percentage of wastewater treated in the upgraded system (25%, 50%, and 75%), showing variations in equipment costs, operational expenses, and waste valorization credits.

**Table 6.** Percentage difference of the cost flow between the base and the three scenarios utilizing the upgraded system.

| Results | Cost Category                  | Unit                     | Base                  | 25%                    | 50%                    | 75%                    |
|---------|--------------------------------|--------------------------|-----------------------|------------------------|------------------------|------------------------|
|         | Capex                          | Euro/kg of meat produced | 0                     | $5.20 \times 10^{-3}$  | $5.67 \times 10^{-3}$  | $5.78 \times 10^{-3}$  |
|         | Opex                           | Euro/kg of meat produced | $7.22 \times 10^{-3}$ | $8.63 \times 10^{-3}$  | $7.83 \times 10^{-3}$  | $7.04 \times 10^{-3}$  |
|         | Credit from Electricity        | Euro/kg of meat produced | -                     | $-5.63 \times 10^{-3}$ | $-5.47 \times 10^{-3}$ | $-5.29 \times 10^{-3}$ |
|         | Credit from Thermal energy     | Euro/kg of meat produced | -                     | $-5.70 \times 10^{-4}$ | $-5.53 \times 10^{-4}$ | $-5.36 \times 10^{-4}$ |
|         | Credit from Solid Biofuel      | Euro/kg of meat produced | -                     | $-3.21 \times 10^{-4}$ | $-3.20 \times 10^{-4}$ | $-3.18 \times 10^{-4}$ |
|         | Credit from reusable Water     | Euro/kg of meat produced | -                     | $-9.11 \times 10^{-4}$ | $-1.82 \times 10^{-3}$ | $-2.73 \times 10^{-3}$ |
|         | Summary                        | Euro/kg of meat produced | $7.22 \times 10^{-3}$ | $6.40 \times 10^{-3}$  | $5.33 \times 10^{-3}$  | $3.94 \times 10^{-3}$  |
|         | Change rate from base scenario | %                        | -                     | -11%                   | -26%                   | -45%                   |

Overall, the cost of wastewater treatment per kilogram of meat product decreases from the base scenario to the 75% scenario. Specifically, the wastewater treatment cost is reduced by 45% in the 75% scenario, translating to savings of EUR 0.00328 per kilogram of meat or EUR 110,577.72 per annual production. Thus, the upgraded treatment system

contributes to a more economically sustainable industry by enhancing the sustainability of meat processing waste treatment as its usage increases. The results align with the existing literature, which also highlights that upgrading the WWTP, despite the initial investment cost, becomes more cost-efficient when cost credits from waste valorization are factored in [82–84]. Furthermore, one study explains that there are numerous cost-effective methods available for upgrading a WWTP [85].

#### 4. Conclusions

The analysis focused on assessing the environmental, social, and cost impact of the new technologies integrated into the waste treatment process of the meat industry. The assessment emphasized the four environmental impact categories closely aligned to the goals of the improvement strategies, the four key social risk indicators for the social assessment, and the economic evaluation.

Firstly, a comparison between the base case and the ‘50%’ scenario was conducted through an LCSA, which revealed significant environmental, social, and cost alleviation. More precisely, a substantial reduction in FE and HCT indicators was observed (i.e., 25.9% and 31.5%, respectively), while a milder but still important decrease in the impacts associated with Global Warming and FRS was noticed (i.e., 9.2% and 8.8%, respectively). Similar behaviour was identified in the endpoint impact categories, achieving critical reductions in the range of 6.3% to 18.2%. As far as the social aspect is concerned, for all the social risk categories, considerable reduction was accomplished, ranging from 33.7% to 37.0%. Regarding the economic view of the upgrades in the wastewater treatment plant, an important cost saving of EUR 0.00187 per kg of meat produced, translating to EUR 63,152.70 per annual production, was reached, accounting for capital and operational expenditures. Since the cost analysis is influenced by the year and location of the case study, results may vary in different contexts. These findings provide a comparative example between the baseline and the three scenarios. Further case-specific evaluation is needed to assess the economic benefits of wastewater treatment upgrades.

To further analyze the impact of each technology, three scenarios with varying proportions of wastewater directed to the upgraded treatment system were studied. The results indicated that higher percentages of wastewater treated in the upgraded system led to improvements across environmental, social, and economic categories. In conclusion, the introduction of the new treatment system significantly enhances the sustainability of the meat production industry.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16229811/s1>. Other references in the supplementary material has been listed [86–95].

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