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Environmental Impact of Poultry Manure Gasification Technology for Energy and Ash Valorization

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Abstract: Thermochemical technologies offer potential solutions for energy recovery and mitigating the environmental impacts of biomass waste. Poultry manure (PM), a nutrient-rich biomass but also a potentially problematic biomass waste, presents an opportunity for recovery and recycling. This study compares the environmental performance of a real-scale novel gasification technology called Chimera (designed and developed through an EU LIFE program) in locally treating PM with anaerobic digestion (AD) and incineration. Using life cycle assessment (LCA), the potential environmental impacts of the technologies were assessed using the Environmental Footprint (EF) 3.0 midpoint life cycle impact assessment method. We performed an attributional LCA with substitution. The selected functional unit (FU) is the treatment of one tonne (1000 kg) PM at 40% dry matter in the Netherlands in 2021 for 20 years. The LCA results of the three technologies compared showed that no single technology outperformed the other across all the impact categories. Climate change scores for the various technologies were −383 (incineration), −206 (Chimera), and −161 (anaerobic digestion) kg CO_2 eq./FU. The results were influenced mainly by the potential utilization of the substituted heat and electricity. This study expands the existing literature on environmental sustainability assessments of PM treatment technologies. It underscores the prospects for these technologies to promote circularity while also indicating the bottlenecks for the potential environmental impacts and highlighting the most sensitive aspects that can influence the environmental performance of these technologies.

Keywords: waste valorization; thermochemical technology; anaerobic digestion; incineration; climate change

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1. Introduction

Poultry meat and eggs are projected to account for 41% of global meat production by 2030, which is estimated at 153 Mt [1]. Manure generated by poultry production poses a significant environmental hazard, emitting greenhouse gases (GHGs), odors, and nutrient leakage, especially ammonia, heavy metals, and biological pollutants if not properly handled [2,3]. Poultry manure (PM) contributes to many environmental issues, such as climate change, eutrophication, and human health [4–8]. PM disposal, not even considering transport-related emissions, amounts to an estimated 25 Mt/yr of GHGs, 0.48 Mt/yr of ammonia, and 100 kt of heavy metals in the EU with costs for disposal from 10 to 20 €/tons [9]. Several treatment technologies have been developed to manage and valorize PM to improve the overall environmental performance of chicken meat and products. However, each technology has limitations that may limit the potential environmental benefits that could be derived from it. Therefore, assessing the environmental performance of these technologies over a range of indicators and paying special attention to the aspects governing the results is vital to selecting the ideal treatment option that confers the most benefit for a given context.

PM is a nutrient-rich biomass primarily composed of water, carbon, nitrogen, phosphorus, and trace amounts of minerals and heavy metals [10]. Manure excreted by livestock can be converted into carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ammonia (NH_3) through various reactions such as decomposition, hydrolysis, ammonia volatilization, and nitrification [11]. Fresh PM is known for its high protein and amino acid concentration, which results in a significant amount of organic nitrogen [12]. This nitrogen can take various forms, including NH_3, N_2O, and nitrate (NO_3), depending on the prevailing environmental conditions [11]. Emissions of these nitrogen compounds may lead to significant environmental issues. N_2O, a potent greenhouse gas with a much higher global warming potential than CO_2, contributes to climate change. NH_3 contributes to air pollution and water contamination, adversely affecting the environment and poultry production [13]. Nitrate, being highly mobile in water, can contaminate both surface and groundwater through runoff and leaching [14,15]. Despite these concerns, nitrogen is essential for plant and animal growth. Therefore, optimizing nitrogen recovery is advantageous for any PM treatment due to the potential to mitigate environmental and economic challenges.

Among the many options for PM treatment are direct land application, composting, and reusing waste for energy, which are some of the most common [3,16]. Mechanical PM management involves land spreading PM on crop fields as an organic soil fertilizer [3,17]. However, excessive and improper application results in drawbacks such as uncontrolled emissions of GHGs, nitrate, heavy metal leaching, and the spread of microbial pathogens [3]. Alternatively, composting involves a series of biological and biochemical processes that convert PM into a valuable fertilizer [18]. However, creating an optimal condition for the biocatalysts and eliminating pathogenic microbes may be challenging if abiotic factors such as temperature and water content are not well controlled. Additionally, nitrogen, phosphorus, and carbon are partially lost during composting in open systems, resulting in the leaching of nitrate, phosphoric acid, and GHGs like CO_2 and CH_4 [3,19]. Waste-to-energy technologies (WtE) for PM treatment include thermal conversion (pyrolysis, gasification, and incineration) and biological conversion (anaerobic digestion). Anaerobic digestion (AD) transforms PM into biogas and digestate through biochemical processes under anaerobic conditions. The biogas can be further processed to obtain biomethane as fuel for heat and electricity. The digestate is useful as an organic fertilizer for soil [20,21]. Incineration converts organic waste materials into heat, flue gas, and ash through combustion, which is then released into the atmosphere without further treatment. Pyrolysis and gasification are also thermochemical processes that produce oil and syngas, respectively, which can be used as secondary energy carriers for bioenergy production. In gasification, biomass is partially oxidized using air, oxygen, carbon dioxide, steam, or a mixture of these as a reaction medium at high temperatures (500–1800 °C), while pyrolysis is carried out in the absence of oxygen at lower temperatures (250–900 °C) [22,23]. WtE processes help reduce waste volume while producing energy [22]. However, WtE technologies face challenges like the high cost of the facility, air pollutant emissions, and fly ash management, particularly the high cost required for fuel cleaning in gasification and pyrolysis technologies [22,24] and ammonia emissions during the storage and use of the digestate in the case of AD [25,26].

Life cycle assessment (LCA) is a comprehensive and widely utilized tool for systematically examining the potential environmental impacts of products and services. Furthermore, LCA aids in identifying and selecting environmentally preferred technologies by evaluating and comparing the environmental performance of different technologies [27,28]. LCA has been widely applied to assess the environmental sustainability of poultry production chains [29]. However, some studies included manure management as part of the expanded system studied [7,8,30–33]. The inclusion of PM management can significantly influence the impact assessment results. Few LCA studies have focused on different technologies, such as pyrolysis [34,35], gasification [36–38], and AD [39] for managing PM. Several studies have compared the environmental performance of different bioconversion technologies for valorizing agro-industrial residues. For instance, Bora et al. [34] found that pyrolysis methods (slow, fast, gasification, hydrothermal liquefaction, hydrothermal carbonization, and supercritical water gasification) generally exhibited lower environmental burdens than direct land application. Ayub et al. [37] and Wu et al. [40] reported similar gasification and land disposal findings. However, it is essential to consider the technology readiness level of these technologies when evaluating their environmental performance. Experimental pilot-scale models may not fully represent the environmental impacts of fully operational, commercial-scale technologies. Additionally, some studies rely on secondary data, which may not be specific to the system under study. These disparities can influence comparative assessments and potentially lead to misleading conclusions.

Therefore, this study aims to evaluate the environmental performance of a new gasification plant (Chimera) for managing PM on site. The Chimera technology optimizes nitrogen recovery and ash treatment into a biofertilizer via a double-scrubbing system coupled with energy (heat and electricity recovery) and water recycling. Additionally, the relatively small size of the equipment (pilot plant) allows it to be stationed directly on farm sites, eliminating the storage and transport of PM, which are typically associated with environmental burdens. Thus, the novel technology aims to treat and manage PM in an environmentally efficient way and focus on resource recovery. Although various technologies exist for the treatment of PM, incineration and AD are the most widely used methods in the Netherlands. Approximately one third of the PM generated is burned in an incinerator to produce electricity. Moreover, the co-digestion of PM in an AD plant is commonly practiced in the northern regions of the Netherlands and Germany, where the PM is often transported for this purpose. Given these circumstances, we compared the Chimera technology to incineration and AD to contextualize the results. The insights from this study are expected to be helpful to both researchers in the LCA and poultry production and stakeholders in the poultry sector to guide the selection of PM treatment technologies conferring environmental benefits in specific contexts.

2. Materials and Methods

We applied the LCA methodology to evaluate the environmental impacts of different PM treatment technologies as outlined in Section 2.1. Section 2.1 covers the goal and scope of the study and the environmental impacts assessed. The modeling of the various phases is detailed in Section 2.2. Finally, Section 2.3 describes the interpretation of results and sensitivity analysis.

2.1. Goal and Scope Definition

The goal of the study is to evaluate the environmental performance of a newly developed gasification technology (Chimera) for managing on-farm PM and compare the results with those of selected existing PM management technologies: anaerobic digestion and incineration. Considering the PM composition, this study aims to identify the treatment technology with the lowest environmental impacts and the highest resource recovery potential.

The functional unit is "treatment of one tonne (1000 kg) poultry manure at 40% DM in the Netherlands in 2021, for 20 years". Key physico-chemical characteristics of the functional unit are reported in Table 1.

The scope of the study covers only PM management with an expanded system to include substitutable products. Considering that the selected PM treatment technologies generate several products and services, this study examines a multifunctional system that deals with both PM treatment services and producing one or more products. Consequently, we conducted an attributional LCA with substitution. The substituted products were electricity, heat, and fertilizer. In the case of electricity, the generated electricity was a substitute for low-voltage electricity from the Dutch national grid mix in 2021, which consisted of 67.32% fossil fuels, 32.33% renewable sources, and 0.33% nuclear power. For heat substitution, the production of natural gas was avoided. Recovered nutrients in the form of ash (incineration), digestate (AD), and biofertilizer (Chimera) also substituted the production of nitrogen (N), potassium (as K_2O), and phosphorus (as P_2O_5) fertilizer. All processes were selected from the Ecoinvent 3.9.1 database. The poultry-rearing phase was outside the scope of this study.

Table 1. Physico-chemical characteristics of the poultry manure tonne^{-1} ww.

Parameter	Unit
Total solids (kg)	400
Water (kg)	600
Volatile solids (kg)	323.2
Ash (kg)	60.8
Energy content (LHV, MJ/kg TS)	15.7
Elemental composition	
C (% TS)	41.6
H (% TS)	5.5
O [a] (% TS)	33
N (% TS)	3.8
S (% TS)	0.31
K (% TS)	2.93
P (% TS)	1
Cl (% TS)	0.57
As (mg/kg)	<1
Cd (mg/kg)	0.23
Cr (mg/kg)	5.97
Cu (mg/kg)	64.6
Hg (mg/kg)	<0.05
Ni (mg/kg)	9.1
Pb (mg/kg)	<1
Zn (mg/kg)	354
Al (mg/kg)	585
Ca (mg/kg)	17,900
Fe (mg/kg)	690
Mg (mg/kg)	3930
Na (mg/kg)	4050
Si (mg/kg)	7300
Ti (mg/kg)	27.5

LHV—lower heating value, TS—total solids. [a] Calculated by difference. Volatile solids include compounds such as alcohol, ketones, alkanes/alkenes, phenols, esters, N-containing compounds, halogenated compounds, S-containing compounds, volatile fatty acids, and aromatic compounds.

We assessed the environmental performance of the technologies following the ISO 14040/14044 standards [41,42]. The LCA software EASETECH 3.4 was used for the LCA modeling and sensitivity analysis, and Microsoft Excel was used to establish the life cycle inventories (LCIs) and the result analysis. Background data for ancillary materials and energy were obtained from the Ecoinvent database version 3.9.1—allocation, cut off by classification [43] and the ELCD database [44]. We evaluated the impacts of the selected functional unit in terms of climate change (CC) estimated over a 100-year horizon, ozone depletion (OD), ionizing radiation (IR), photochemical ozone formation (POF), particulate matter (PartM), human toxicity, non-carcinogenic (HTNC), human toxicity, cancer (HTC), acidification (A), eutrophication, freshwater (EF), eutrophication, marine (EM), eutrophication, terrestrial (ET), ecotoxicity freshwater (ETF), land use (LU), water use (WU), resource use, fossils (RUF), and resource use, minerals and metals (RUM) using the Environmental Footprint (EF) 3.0 midpoint life cycle impact assessment (LCIA) method [45].

2.2. Life Cycle Inventory and Process Modeling of Selected Technologies

The following sections describe the technologies chosen for treating PM and the main characteristics included in modeling the technologies for the LCA. Table 2 highlights some key features and the energy balance of the technologies we considered.

Table 2. Features and energy–nutrient balances of the selected PM treatment technology.

Criteria	Gasification (Chimera)	Anaerobic Digestion	Incineration
Drying requirement	Required	Not needed	Required
Treatment duration per cycle	Several hours	20–90 days	Several hours
Storage	Not required	Required	Not required
Transportation	Not required	Variable	Required
Products	Syngas, energy, and biofertilizer	Biogas, energy, and digestate	Energy and bottom ash
Electricity recovery %, gross	9%	31%	25%
Heat recovery %, gross	38%	53%	62%
Energy balance			
Electricity recovery, net (kWh/tonne ww) [a]	60.16	267.34	254.24
Heat recovery, net (GJ/tonne ww) [a]	1.83	1.12	2.98
Nutrient balance			
N recovery (g/kg ww)	7.6	15.2	-
P recovery (g/kg ww)	3.72	4	3.6
K recovery (g/kg ww)	10.55	11.72	9.96

[a] Partial auto-consumption of energy.

2.2.1. Incineration Waste-to-Energy Plant (Baseline Technology)

Incineration involves the combustion of organic materials into incinerator bottom ash, flue gases, particulates, and heat. A combined heat and power (CHP) system converts the heat produced into electricity. In this case study, the system boundary for PM incineration encompassed PM transport to the plant, energy for incineration, electricity, heat production, and ash treatment (Figure 1). The average transport distance of PM from a farm to the biggest incineration plant in the Netherlands is about 124 km [46]. We assumed no storage of PM. Inventory on direct emissions was obtained from Bisinella et al. [47]. The electrical and thermal efficiency was considered to be 25% and 62%, respectively, which is typical of incineration plants [47]. Approximately 17% of the heat generated by the modeled incineration plant is used for internal processes, including pre-treating and drying manure, maintaining optimal operating temperatures, and heating the facility. Likewise, 38% of the electricity produced is consumed to power essential systems, such as incinerators, combustion chambers, material handling equipment, and control systems. This internal consumption decreases the net energy output available for external distribution. The recovered ash was considered a substitute for mineral fertilizer based on the PK content.

2.2.2. Anaerobic Digestion

We made several assumptions and choices based on a standard chain for biogas production concerning modeling the anaerobic digestion scenario for PM treatment. Figure 1 shows the system boundary of the included processes in the analyzed waste management system. The PM is transported to an agricultural biogas plant to undergo wet anaerobic digestion, which is often co-digested with maize silage to generate biogas for heat and electricity and digestate. We assumed the transport distance of the PM from the farm to the agricultural biogas plant to be 250 km, reflecting a typical distance between a poultry farm in the Netherlands and an AD plant in Germany [46]. The biomethane potential was estimated, and the anaerobic digestion process was modeled based on existing models in the EASETECH model database. The biogas produced was assumed to contain 65% methane with a gas leakage of 5%. The heat generated was considered to be partially used mainly internally, with a net heat recovery of 36%, while electricity recovery was set at 31%, which is a typical efficiency for AD plants [48]. The heat energy generated in the AD plant modeled is primarily utilized to maintain optimal conditions for microbial activity during biogas production. Approximately 61% of the generated heat is consumed for this purpose, while 45% of the generated electricity is consumed by various processes, including pumping, mixing, agitation, and system control [48]. The transport of digestate, with a moisture content of 95%, to the field was estimated to be 50 km by a 28–32 tonne Euro5 truck. However, we excluded direct emissions from the PM storage because we considered the storage tanks covered.

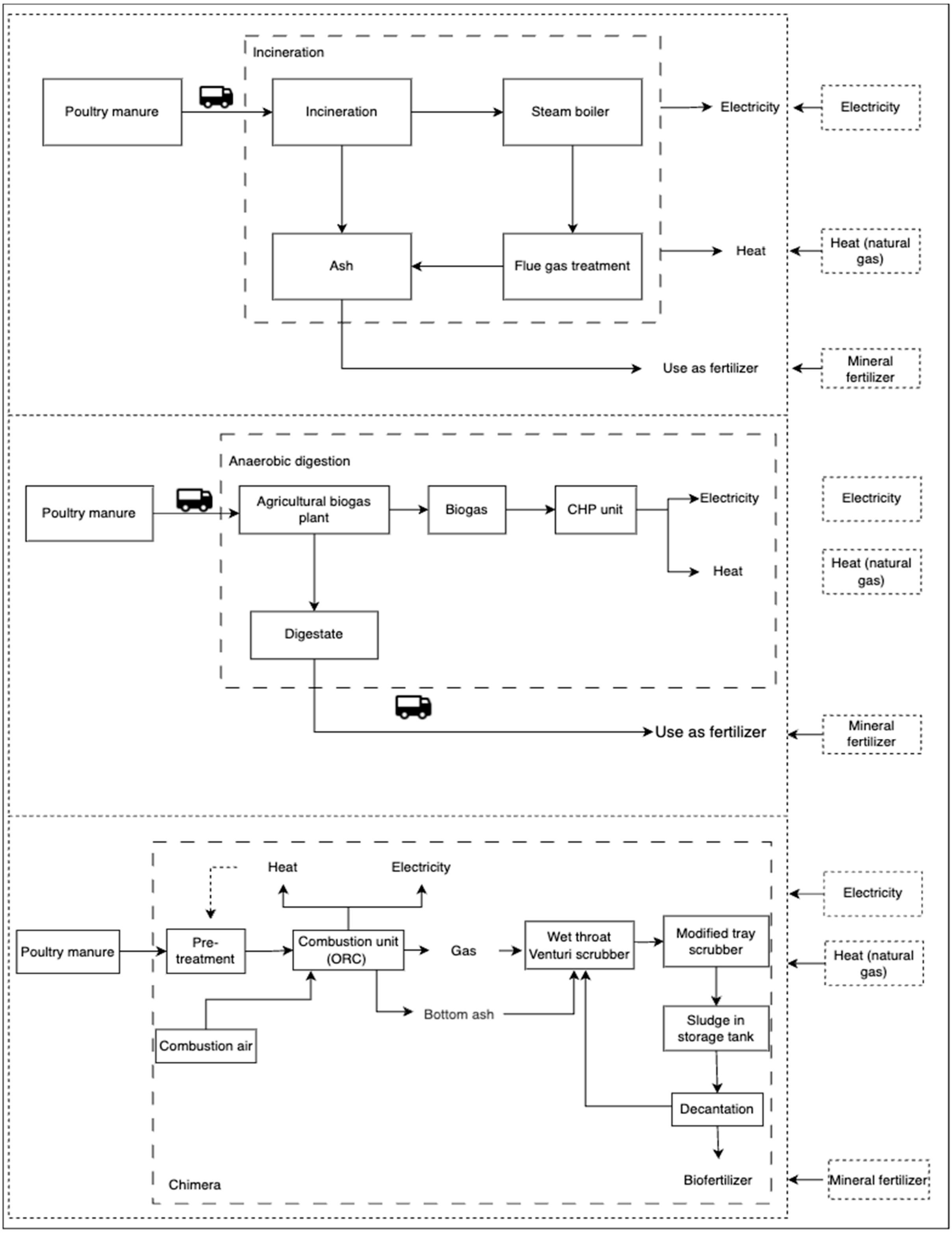

Figure 1. System boundary for the waste-to-energy (incineration) scenario, anaerobic digestion scenario, and Chimera (gasification technology). Dashed squares are for energy and material substitution (avoided production).

2.2.3. Chimera—Gasification

Chimera is a gasification technology that carries out the combustion of PM and subsequent treatment of the products of this combustion (ash and fumes), resulting in partial nitrogen recovery (Figure 2). Chimera is designed and developed through funding from an EU LIFE program. The plant's size and capacity depend on the quantity of PM generated on site, allowing farmers to immediately treat PM in a continuous cycle, decreasing storage costs and potential environmental issues like ammonia emissions. PM can be collected and treated on the same day at the farm. Data for this study were obtained from a real-scale pilot plant with dimensions of 15 × 9 × 6 m for handling a farm size of about 200,000 broilers. The PM enters the loading system (hopper and auger) at a 250 kg/h mass flow rate, which can be adjusted depending on the size of the farm. The PM is first pre-dried using recovered heat. The pre-treated PM is then combusted in the combustion unit at relatively low temperatures, around 800 °C, thus limiting the formation of nitrogen oxides and avoiding using a specific apparatus for their abatement (de-NOx). The system for recovering electrical and thermal energy is an Organic Rankine Cycle (ORC). Based on primary data obtained, approximately 50% of the generated electricity is consumed by internal systems, such as the control system, cooling system, emission control system, and conveyor belts. Additionally, 20% of the heat is used for pre-drying the manure. These energy demands contribute to a reduction in the overall net energy output of the system. The fumes treatment unit consists of devices that manage fumes and ash to produce N-P-K-rich fertilizer. The ashes generated by the combustion unit are introduced into the fume treatment circuit, which consists of two scrubbers (wet throat Venturi scrubber and tray scrubber), a centrifuge, a decanter, and a tank, and the final product obtained is a mud-rich biofertilizer. The system is controlled by software.

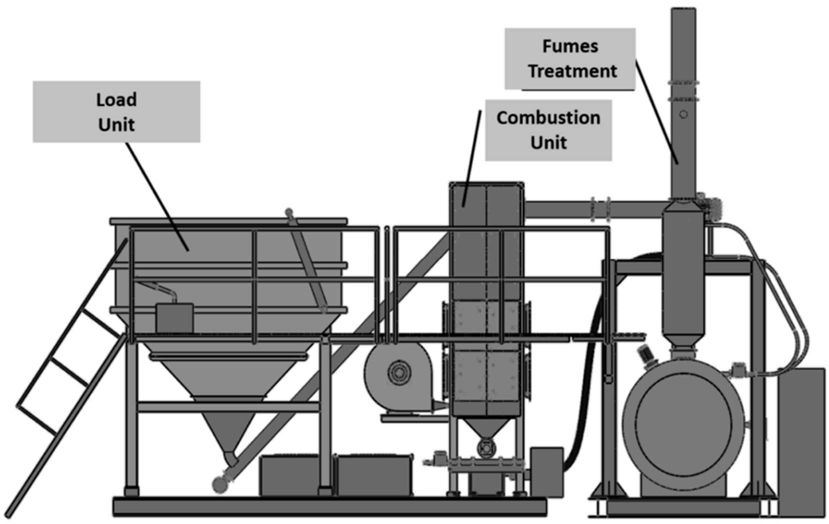

Figure 2. Chimera (gasification technology)—plant schematic.

Regarding the key assumptions made for modeling the technology, we considered no transport and storage of the PM since processing was carried out on site. Figure 1 shows the system boundary and the process flow of materials and energy for the technology, while Table 3 presents the inventory. Regarding information on direct emissions, we had primary data on CO, NOx, and C_3H_8. The remaining data were obtained from a study conducted by Sharara et al. [49]. We also assumed a full utilization of the recovered heat for warming the rearing facility. Additionally, we assumed full use of the generated electricity for lighting the farm and offices and running the technology's control center. The recovered biofertilizer is considered a substitute for NPK fertilizer based on analyses conducted on the biofertilizer.

Table 3. Inventory table for 1 tonne of treated poultry manure using the Chimera technology.

	Quantity	**Unit**
Inputs		
Poultry manure (wet weight)	1	t
Water	110	kg
Diathermic oil	7.6	kg
Compressed air	16	m^3
Acid scrubber (H_2PO_3)	1.8	l
Product outputs		
Electricity	60	kWh
Heat	1828	MJ
Biofertilizer (NPK)	8.9	kg
Emissions		
CO	6.53×10^{-3}	kg
NOx	1.81×10^{-4}	kg
C_3H_8	4.4×10^{-4}	kg
SO_2	7.6×10^{-4}	kg
HCl	4.7×10^{-4}	kg
HF	5.0×10^{-6}	kg
Particulate matter, >10 um	1.8×10^{-4}	kg
Dioxins	1.8×10^{-14}	kg
Hg	1.0×10^{-6}	kg
Ar	9.0×10^{-6}	kg
Ni	6.0×10^{-6}	kg
Cd	1.0×10^{-6}	kg

2.3. Interpretation

The midpoint characterization results per the functional unit of 1 tonne of treated PM are presented in this study. The interpretation of results includes contribution analysis of the phases and key processes (hotspot analysis) and sensitivity analysis. The LCIA results are normalized and expressed in units of Person equivalent (PE) based on the total impact of a reference region for a certain impact category in the EF 3.0 method. Each Person equivalent represents the amount of environmental impact that equals one Person's average yearly share of the total impact of a reference region for a specific impact category in 2010 [50]. Even though we had information on the heat generated from the CHP system, we could not ascertain if the poultry facility used all the heat produced. Therefore, we considered two other scenarios where the facility utilized 75% and 50% of the heat and compared the results to AD and incineration. Furthermore, we assessed the potential benefits of replacing the existing CHP system with a modernized system. This upgrade scenario indicates a projected improvement in both electricity and heat recovery. The new system was estimated to achieve a 10% increase in efficiency, leading to recovery rates of 9.9% and 41.8% for electricity and heat, respectively. We show how this upgrade affects the climate change impact scores.

3. Results

This section discusses the midpoint LCIA results of the PM treatment technologies (Section 3.1) and normalized results (Section 3.2). Details on the scenario analysis of heat utilization are provided in Section 3.3.

3.1. Midpoint Characterization Results

The LCA results for the scenarios considered are presented as a function of 1 tonne of processed PM. Four impact categories are highlighted to discuss environmental impacts: climate change, particulate matter, water use, and resource use (fossils). Full results are presented in Table 4, showing the midpoint characterization results for each of the EF 3.0 impact categories.

Table 4. Midpoint environmental impacts of processing 1 tonne of poultry manure.

Midpoint Impact	Unit	Incineration	AD	Chimera
CC	kg CO_2 eq.	−380	−161	−206
OD	kg CFC-11 eq.	-1.49×10^{-5}	-6.39×10^{-6}	-6.26×10^{-6}
HTC	CTUh	2.42×10^{-7}	-9.90×10^{-7}	1.29×10^{-7}
HTNC	CTUh	2.91×10^{-5}	3.62×10^{-5}	1.47×10^{-5}
PartM	disease inc.	2.08×10^{-5}	2.95×10^{-5}	3.13×10^{-6}
IR	kBq U-235 eq.	−21.7	−13.6	−3.54
POF	kg NMVOC eq.	0.49	0.62	0.15
A	mol H^+ eq.	3.14	4.24	0.58
ET	mol N eq.	15.7	20.8	−0.26
EF	kg P eq.	-8.15×10^{-2}	−0.23	−0.48
EM	kg N eq.	0.29	4.85	-1.99×10^{-3}
ETF	CTUe	−243	2.12×10^{3}	-3.44×10^{3}
LU	-	−594	−442	2.36
WU	m^3 depriv.	98.8	170	4.02
RUM	kg Sb eq.	1.24×10^{-7}	-1.15×10^{-5}	-5.79×10^{-5}
RUF	MJ	313	540	−168

Chimera—(gasification technology), AD—anaerobic digestion, CC—climate change estimated over a 100-year horizon, OD—ozone depletion, HTC—human toxicity, cancer, HTNC—human toxicity, non-carcinogenic, PartM—particulate matter, IR—ionizing radiation, POF—photochemical ozone formation, A—acidification, ET—eutrophication, terrestrial, EF—eutrophication, freshwater, EM—eutrophication, marine, ETF—ecotoxicity freshwater, LU—land use, WU—water use, RUM—resource use, minerals, and metals, and RUF—resource use, fossils. Negative values correspond to better environmental performance.

The selected PM treatment technologies had net environmental benefits for some impact categories. These benefits are linked mainly to energy generation and utilization, particularly heat. Performances of the different technologies varied across impact categories. For instance, Chimera performed better than AD and incineration in impact categories: A, ET, EM, EFT, WU, and RUF. Incineration also had the lowest scores for impact categories, like CC, IR, and EF. Similarly, AD also performed better in HTC. Thus, there is no clear-cut best-performing technology for managing PM, and selecting the optimal technology should depend on the impact of interest on either a site-specific or country level.

3.1.1. Climate Change (CC)

The climate change results show that all scenarios recorded a net negative score, conferring environmental benefits (Table 4). The good environmental performance of these technologies is attributed to the recovery of resources, which effectively offset the upstream energy/resource consumption or emissions associated with the processes. Although electricity generation gave environmental benefits in the case of CC, heat production was even better. The avoided emissions of electricity and natural gas were 0.51 kg CO_2 eq./kWh and 0.079 kg CO_2 eq./MJ, respectively. Due to the higher net heat recovery of incineration, it had the most total credits among the three technologies when considering complete heat utilization as a substitute for natural gas (Figure 3a). However, this heavily depends on the heat's marketability and the plants' location relative to the end-user. The potential for heat utilization from AD and incineration plants can be limited by logistical and technical challenges [51]. One major challenge is the mismatch between heat generation and demand. These plants are often located in remote areas far from urban centers with high heat demand. Consequently, transporting heat over long distances becomes inefficient and requires substantial investments in infrastructure [52]. Additionally, technical limitations, such as heat storage and integration into local heat distribution systems, can hinder effective heat utilization [51,53]. Thus, an advantage of Chimera is the certainty of partial or complete utilization of the recovered heat produced. In the context where the heat from incineration and AD is not marketed, Chimera would perform better than the others when its heat is completely utilized. AD also performs better than incineration due to the credits from recovered nutrients. Chimera only outperforms AD above 75% heat utilization. The heat generated and utilized significantly influences the overall environmental performance of the Chimera technology. The heat generated from Chimera is currently used to dry the PM further and maintain an optimal temperature within the poultry breeding facility. However, this supply may be a fraction of the heat produced and require alternative pathways to ensure complete valorization. Domestic use, connection to district heating, and greenhouse farms are avenues that could be explored for further heat valorization.

Comparing the technologies, the main advantages of Chimera are connected to the amount of heat produced and nutrients recovered rather than the absence of PM transportation or electricity produced. However, while transportation only accounted for less than 5% of the overall impacts of AD and incineration (Figure 3a), it is important to note that this contribution may vary based on factors such as the specific distance, mode of transportation, and the possibility of trucks returning empty.

The contribution analysis for the Chimera technology shows that the combustion and scrubbing phases were relatively low (Figure 3a). As stated earlier, the substituted heat source substantially influenced the results. Given the double-scrubbing phases, the nutrient recovery by Chimera was better than incineration and comparable to AD. The main primary contributing substance from the scrubbing phase was industrial-grade phosphoric acid. Thus, using more environmentally sustainable acid scrubbers, like acetic acid [54,55], could slightly improve the overall results of the gasification technology. Therefore, improving the efficiency of heat and electricity recovery using a modern ORC system could significantly improve its overall environmental performance.

In the case of incineration, the impact scores from the contributing processes were relatively similar to those of Chimera. Heat generation was the main positive contributor, accounting for −236 kg CO_2 eq./FU, which was followed by substituted electricity (−167 kg CO_2 eq./FU). PM transportation to the WtE plant was not a key contributor to the overall impact score. The amount of mineral fertilizer avoided owing to the recovered ash was negligible due to the low ash content of the PM and the inability to recover nitrogen, unlike the Chimera technology. An important factor is the valorization of the heat generated since AD and Chimera are likely to perform better in the absence of a market for heat. Thus, the location of the incineration plant is critical to its overall environmental performance.

Regarding AD, processes and emissions related to anaerobic digestion and emissions from venting were the main negative contributors. The transportation of PM and digestate were minor contributors. Most of the credits came from electricity generation due to the high electricity recovery compared to the other technologies. AD also had the highest credits from substituted mineral fertilizer from using digestate on land compared to the others regarding nutrient recovery. This study considered a 36% net heat recovery and utilization from the biogas plant. In situations where the heat is not marketed, the overall score of PM treatment through AD is reduced substantially. Additionally, the score could be further reduced if direct emissions from digestate storage, depending on the plant's technology and design, are considered. Alternatively, upgrading biogas for application as a vehicle fuel can potentially lead to significant reductions in avoided emissions, particularly when displacing petrol fuel. However, a critical factor influencing the environmental benefit of this approach is based on the fuel types being replaced. Lower environmental benefits are obtained if biogas displaces "cleaner" fuels [56,57]. The CC results are comparable to the range of −375 to −111 kg CO_2 eq./tonne treated waste (ww) reported for a generic AD facility by Møller et al. [21].

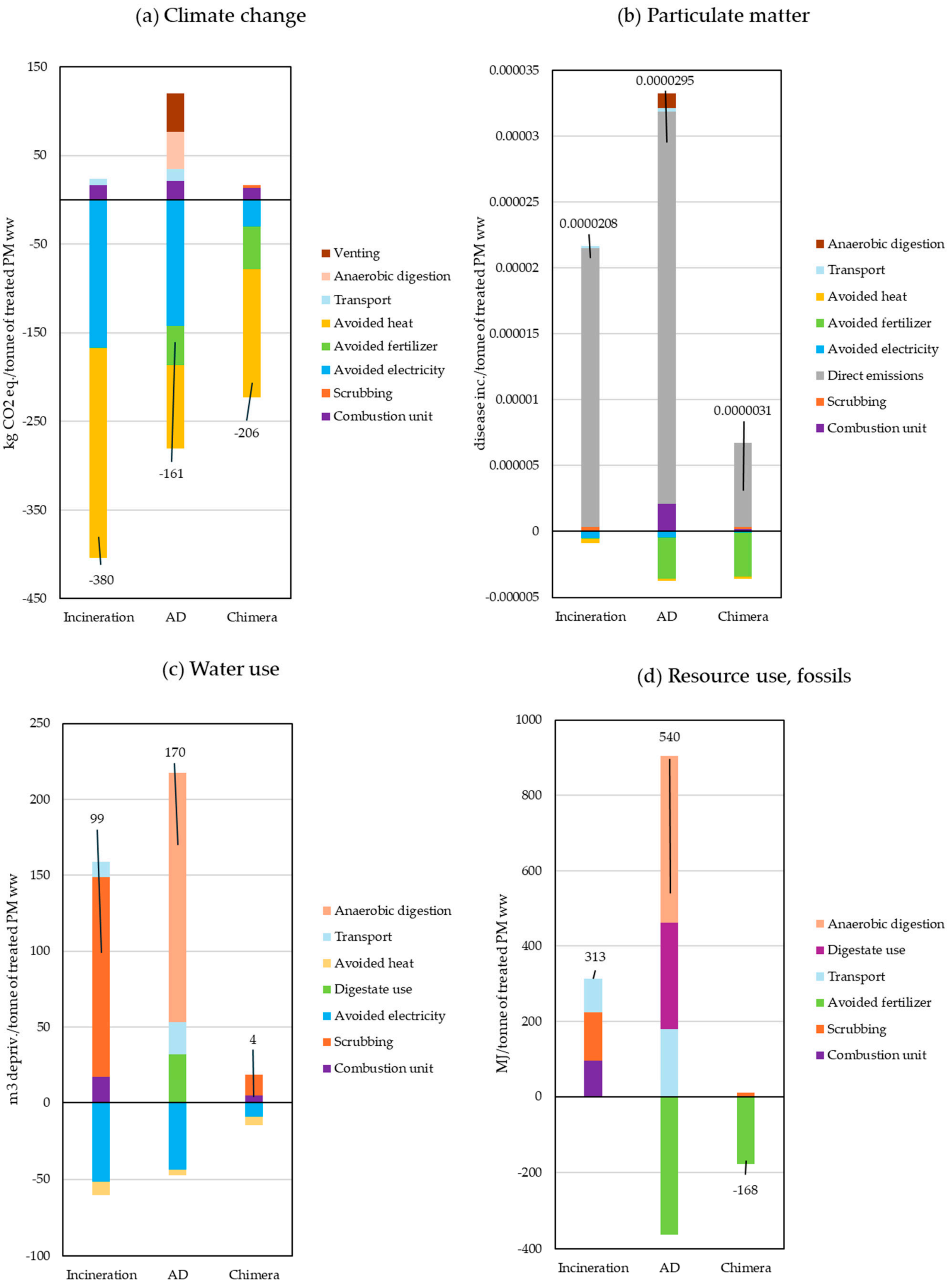

Figure 3. (**a**–**d**) Contribution analysis of LCA results of selected poultry manure treatment technologies. Net results shown. Chimera (gasification), AD—anaerobic digestion.

3.1.2. Particulate Matter (PartM)

Particulate matter consists of microscopic solids or liquid droplets that, when inhaled, can cause serious health problems. Chimera had the lowest score, followed by incineration and AD, with scores of 3.13×10^{-6}, 2.08×10^{-5}, and 2.95×10^{-5} disease inc./FU, respectively. Chimera has a double-scrubbing system for enhanced nitrogen recovery. Thus, the low score of Chimera can be primarily attributed to gas scrubbing employed in these gasification technologies to remove nitrogen-containing compounds, which is a significant source of PartM. However, direct emissions, primarily sulfur and nitrogen oxides, were the main contributing substances. Regarding incineration, the combustion unit's process-specific emissions, especially ammonia, were primarily responsible for the overall impact score. Similarly, the high impact of AD is due to direct emissions from digestate spreading, combustion, and auxiliary processes in the plant. Ammonia and nitrogen oxides were the main impacting substances emitted during digestate spreading and application on land. In the plant, the combustion of diesel (wheel loader) is responsible for the potential emissions of PartM, while process-specific emissions account for the contributions from the combustion unit. The PartM score for transportation was low for both incineration and AD. Given the relatively low impact score associated with Chimera, it may pose minimal health risks to the farmer when used domestically, especially outdoors. However, PartM remains a concern due to its ability to travel long distances via wind currents and settle on land or water bodies. Therefore, the location of an AD plant can significantly influence local air quality, potentially posing adverse health and environmental effects to the residents and workers. Environmental credits for AD and Chimera mainly came from substituted mineral fertilizer, while for incineration, the benefits came from power generation. In all scenarios, substituted heat did not translate into substantial environmental benefits (Figure 3c). Consequently, even if heat utilization is disregarded, the overall ranking of PM impact scores remains unchanged.

3.1.3. Water Use (WU)

Chimera had a water use impact score of 4 m^3 water eq. of depriv. water/FU, while incineration and AD had impact scores of 99 and 170 m^3 water eq. of depriv. water/FU, respectively (Table 4). In contrast to incineration and AD, the scrubbing process in Chimera uses recycled water obtained from decanting the biofertilizer with the residue as nutrient-rich sludge for direct field application. Therefore, although the credits from the substituted products were not much, the overall impacts were low (Figure 3c). On the other hand, the impact of water use associated with incineration is primarily due to the water needed for steam generation, cooling systems, and other minor uses related to emission control and waste handling and processing. For AD, a significant amount of water is required to hydrate feedstock for optimal biological activity and the easy transport of digestate through pipes. Water is also used in heat transfer systems to regulate the temperature within the digester. Electricity gave the most credits among the substituted products, especially for incineration and AD. However, the credits could not offset the high impact of water use. Consequently, Chimera may be a more advantageous technology for PM treatment in regions with water scarcity issues.

3.1.4. Resource Use, Fossils (RUF)

Table 4 includes the PM treatment technologies' midpoint impact scores for resource use (fossils). The assessment revealed a net environmental benefit for only Chimera (−168 MJ/FU). Incineration and AD had impact scores of 313 MJ/FU and 540 MJ/FU, respectively. The key impacting phase for Chimera was scrubbing, which was influenced by process water from groundwater (as shown in Figure 3d). However, the credits from mineral fertilizers, particularly nitrogen, resulted in a net negative impact score. Similarly, scrubbing and combustion units were the main contributing factors for incineration, comprising 72% of the total impacts. Activated carbon, ammonia, and process water were the primary contributing substances. Since no nitrogen is recovered in incineration, there was not enough credit to reduce the impact. AD had a higher RUF score, which stemmed from diesel consumption (wheel loader) and process groundwater (as shown in Figure 3d). However, credits from substituted products, mainly mineral fertilizer, were insufficient to offset the environmental burden. Transportation also significantly contributed to incineration and AD, accounting for 28% and 33% of their total impact scores. Notably, this can vary based on plant location relative to farms. Thus, Chimera's significantly superior performance in RUF could also be associated with its capability to process PM locally.

3.2. Normalized LCA Results

The normalized LCIA values obtained for the different technologies across the various impact categories in the EF 3.0 LCIA methodology are presented in Figure 4. The scores ranged between 0.2 and −0.4 PE/FU except the EF score (−0.66) for Chimera. Chimera had negative scores for all the impact categories except HTNC, A, PartM, POF, HTC, and WU. The scores for the Chimera mainly ranged between 0.03 and −0.3 PE, except for eutrophication freshwater (EF), where −0.66 PE was recorded. The credits from the substituted P mineral fertilizer accounted for the high net negative score obtained for EF (Figure 5c). The next significant savings were observed for ETF (−0.3) due to credits from the substituted P mineral fertilizer.

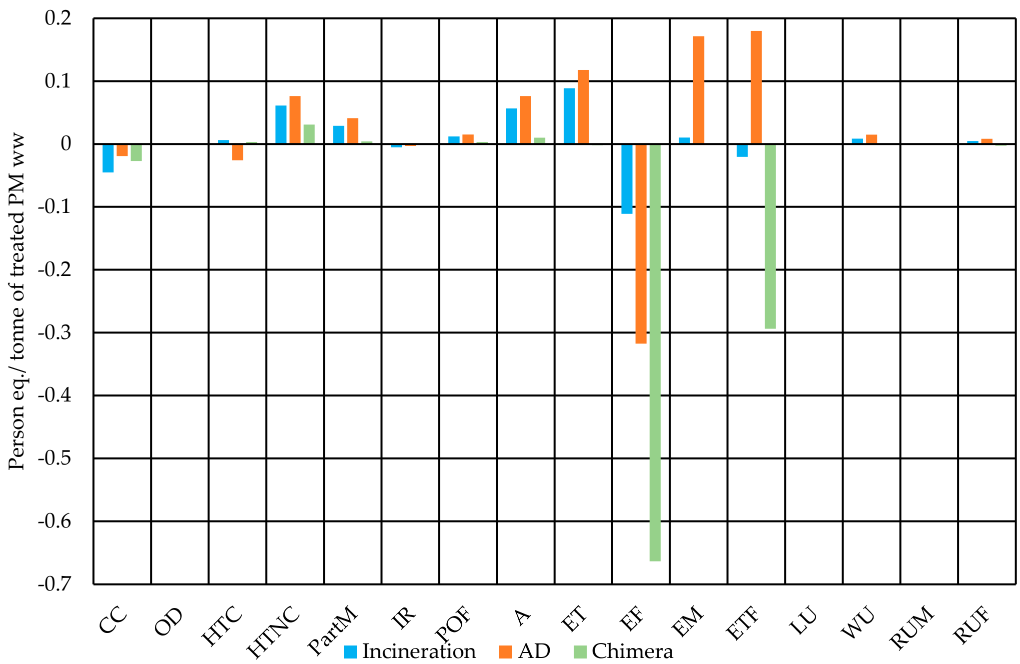

Figure 4. Normalized life cycle impact assessment results in person equivalents per 1 tonne of poultry manure treated based on the Environmental Footprint 3.0 life cycle impact assessment methodology. The bars show scores for the different technologies).

Regarding incineration, all the scores ranged between 0.09 and −0.11 PE/FU. EF recorded the highest savings of −0.11 PE, which was mainly due to substituted electricity (Figure 5a). Other impact categories to record net negative scores were CC, ETF, IR, OD, and LU. ET had the highest score of 0.09 PE/FU due to process-specific emissions, particularly ammonia and nitrogen oxides. A trend similar to the midpoint characterization results was also recorded in the CC impact category. Relative to the others, incineration had the best score, which was followed by Chimera and AD. AD showed contrasting trends across the various impact categories. The results for EF had the highest net environment credit (−0.32 PE) primarily due to avoided mineral fertilizer production and use. HTC, CC, IR, LU, OD, and RUM also recorded net environmental benefits. In contrast, ecotoxicity, freshwater (ETF), and eutrophication, marine (EM), had the highest values of 0.18 and 0.17 PE, respectively. This could be attributed primarily to input-specific emissions, specifically ammonia, for EM, and process-specific emissions, particularly copper, for EFT.

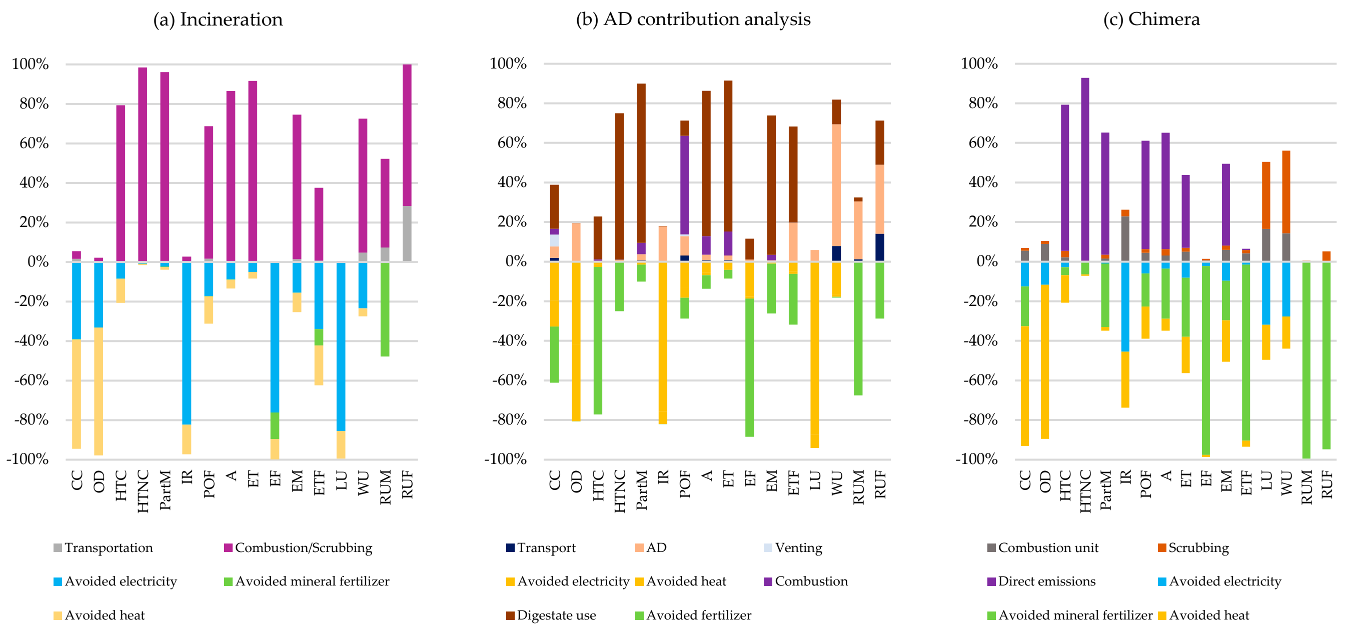

Figure 5. (**a**–**c**) The relative contribution of processes to midpoint scores for selected poultry manure treatment technologies.

When comparing the three technologies across multiple impact categories, no single option emerged as superior. Each technology had a unique environmental profile with varying performance across different impact categories (Table 4). In the case of Chimera, its positive environmental performance could be attributed to its efficient heat energy recovery, which is a characteristic commonly found in gasification technology [58]. Bora et al. [34] identified various thermochemical technologies with superior environmental performance for managing poultry litter compared to direct land application. Additionally, He et al. [5] and Nusselder et al. [46] also reported similar findings, highlighting lower greenhouse gas emissions associated with the gasification-based treatment of PM compared to direct land application, composting, and AD approaches. Chimera technology also proves advantageous when considering transportation costs and other logistical issues. In practice, determining the precise impact of Chimera technology on land use could be challenging, as its size varies based on the production scale. The installation incurs a cost for farmers, as it occupies a portion of the farmland that could otherwise be utilized for different purposes. Consequently, choosing this technology involves a trade-off between land occupation and addressing logistical issues such as storage and PM transportation. Furthermore, uncertainties remain regarding the stability and assimilation of the biofertilizer produced.

Alternatively, the advantages of incineration and AD are primarily linked to their geographical context. AD becomes more favorable when the poultry farm, AD plant, and suitable croplands for digestate application are nearby. Additionally, using PM and other residues as substitutes for conventional feedstocks like maize can be more advantageous than Chimera, though less methane would be produced. On the other hand, incineration is most suitable for poultry farms near urban areas with access to incineration plants to reduce transportation and allow for heat valorization. Harnessing the generated heat is crucial for AD and incineration to maximize their environmental benefits. District heating and agricultural applications, such as greenhouse and animal farm heating, offer promising avenues for heat utilization. However, challenges associated with heat transfer infrastructure can limit the environmental gains. Furthermore, the environmental benefits derived from substituting the heat source (e.g., residual wood chips) can vary significantly depending on the environmental footprint of the substituted product.

The LCA results may also vary across geographical regions due to climatic conditions. In hotter climates, the faster decomposition of PM could potentially lead to higher emissions during storage. However, the on-site processing capabilities of the Chimera technology can mitigate these impacts, making it a more suitable option in warmer regions. Gasification systems, a component of the Chimera technology, generally function more efficiently in warmer climates. Lower startup energy requirements, reduced heat loss, and easier management of feedstock moisture levels contribute to improved performance in warmer conditions. Colder climates may necessitate additional measures like insulation and preheating to maintain efficiency. Moreover, the composition of PM, influenced by feed factors, can also vary geographically. This variation may affect emissions and the overall environmental performance of the Chimera technology.

3.3. Scenario Analysis of Upgraded CHP System for Chimera (Climate Change)

Figure 6 presents the CC impact results for Chimera, considering an upgraded CHP system and partial heat utilization. A 10% increase in electricity and heat recovery within the system translates to an 11% improvement in Chimera's CC score. This improvement can be attributed to the increase in net electricity and heat recovered from 60 kWh/tonne PM ww and 1.83 MJ/tonne PM ww to 72 kWh/tonne PM ww and 2.01 MJ/tonne PM ww, respectively. However, incineration and AD show a greater net environmental benefit in scenarios with complete heat utilization. Nonetheless, Chimera achieves a better CC score than either of these technologies when its heat utilization exceeds 75%, while the heat generated is wasted in incineration and AD. This finding underscores the potential for even modest improvements in CHP system efficiency to yield greater environmental benefits for the Chimera technology.

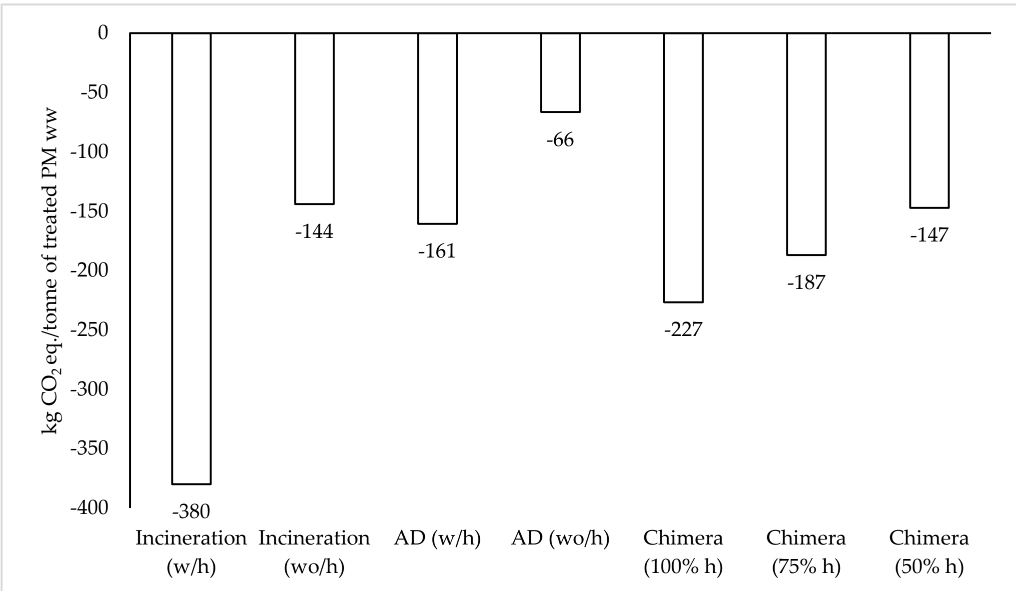

Figure 6. Comparison of Chimera (gasification technology) complete and partial heat utilization and other technologies (without heat utilization). AD—anaerobic digestion. w/h—with heat utilization, wo/h—without heat utilization. Negative values correspond to better environmental performance.

3.4. Limitations and Further Research

This study explored the environmental performance of a newly developed gasification technology for PM management. However, there are some limitations to the study that restrict the extent to which the results can be used, which could be explored further in future research. There are several various operational factors that could impact plant performance and, subsequently, its environmental outcomes. These factors pose potential risks that may offset the anticipated benefits. The present study applies the technology to a medium-sized poultry farm in the Netherlands. The system is designed and built according to the size of the farm (number of poultry birds—quantity of PM produced per day). Upscaling or downscaling poultry production in different countries may lead to substantial differences in results and, subsequently, its environmental performance due to differences in energy systems and proximity to incineration and AD plants. However, the study does not comprehensively address the influence of plant size on operational efficiency and environmental performance. Scaling the technology up or down could affect the plant's energy consumption, necessitating adjustments to optimize energy consumption and maintain environmental benefits. Future research should explore the impact of scaling by investigating how Chimera's performance (e.g., energy consumption, emissions) changes with variations in farm size and PM production rates. This would involve analyzing scenarios with larger or smaller plants to determine if adjustments like modular designs or operational changes are necessary. Additionally, if the farm size increases, the plant's capacity and the number of times it runs per day or week must be considered. A larger plant may require the temporary storage of manure before processing, which could offset the logistical and emissions advantages of the Chimera system. Addressing these knowledge gaps would provide a more comprehensive understanding of Chimera's environmental footprint under various operational scales and inform future practical implementation decisions.

As we move toward decarbonization, changes in energy mixes could also reduce the reported environmental gains (substituted electricity). Therefore, future studies could explore the impact of variability in these factors in evaluating the environmental performance of the technology. Modeling of the anaerobic digestion and incineration plants was based on data from Denmark. Data for PM treatment options within the same geographical location could be explored to reduce uncertainty. Additionally, the study showed the impact of producing and treating PM based on a cradle-to-gate approach; it does not include poultry meat production, processing, distribution, or consumption. Thus, a cradle-to-grave life cycle was outside of the scope of this study. A complete life cycle study incorporating the PM treatment as part of poultry meat production for consumption could be another area for future research.

4. Conclusions

Exploring thermochemical conversion technologies to harness energy from PM has great potential for both energy production and environmental advantages. In this study, we conducted an environmental assessment of a novel gasification technology (Chimera) applied at an industrial scale for PM treatment using an attributional LCA with substitution. In addition, we compared the performance of Chimera to two other technologies for PM treatment, incineration and anaerobic digestion. Using EASETECH software, foreground systems of selected technologies were evaluated using process and input-specific LCA models that consider the material flow within the system and the physico-chemical composition of PM.

No single technology emerged as the superior option when comparing the three technologies across multiple impact categories. Each technology demonstrated a mix of strengths and weaknesses, performing favorably in certain impact categories while underperforming in others. Consequently, the optimal choice depends on prioritizing specific impact categories relevant to the study's objectives or stakeholder preferences. The technologies had net environmental benefits for some impact categories due to the substituted products. Most of the credits for Chimera and AD came from the substituted mineral fertilizer and heat, while substituted electricity and heat accounted for most of the gains for incineration. For CC, incineration and AD outperformed Chimera. However, the results vary significantly if the heat from incineration and AD is not valorized. The location of the plants is central to the potential for residual heat valorization. The transportation of PM to incineration (124 km) and AD (250 km) plants had a negative influence on the impacts assessed. In contrast, PM transportation is absent due to the on-site treatment of PM, eliminating the need for PM storage and related emissions. However, climatic conditions may affect Chimera since gasification systems generally function more efficiently in warmer climates. Chimera is also constructed based on the scale of poultry production. However, scaling up or down the plant size, capacity, and other operations could impact plant performance and its environmental outcomes with the risk of offsetting the anticipated benefits. Moreover, an economic analysis, which has not yet been conducted, is necessary to consider the cost of the technology for small-scale poultry producers.

While all evaluated technologies exhibited net environmental benefits in most impact categories, Chimera generally outperformed incineration and AD. Credits for Chimera and AD primarily stemmed from substituted mineral fertilizer and heat, while incineration benefited most from substituted electricity and heat. Notably, incineration and AD outperformed Chimera in terms of CC, though this is dependent on the valorization of the heat generated. For incineration and AD, the potential for heat valorization depends heavily on plant location. The transportation of PM to incineration and AD facilities minimally affected most environmental scores.

In addition to its relatively better environmental performance, Chimera offers distinct advantages over the other technologies, including immediate on-site PM treatment, eliminating storage and transport needs, and scalability of the system to farm size. However, potential limitations exist. Scaling the plant size, capacity, and other operational factors can significantly impact performance and environmental outcomes, potentially negating the anticipated benefits. Additionally, a crucial aspect yet to be addressed is an economic analysis to determine the feasibility of Chimera for small-scale poultry producers.

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