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Environmental Assessment of a Waste-to-Energy Cascading System Integrating Forestry Residue Pyrolysis and Poultry Litter Anaerobic Digestion

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Abstract: Poultry and forestry waste residues, despite their environmental concerns, offer nutrient-rich content and wider availability. Utilising them in cascading approaches can create high-value products and establish new value chains in bioeconomy. This study aims to evaluate the environmental consequences of coupling forestry residue pyrolysis and poultry litter anaerobic digestion processes in a waste-to-energy cascading system. Moreover, a scenario analysis was conducted considering six scenarios with varying total solids loading with biochar (8%, 15%, and 28%) and final energy products (bioelectricity and upgraded biomethane). Life cycle assessment (LCA) results demonstrated a net reduction in selected potential impact categories across all scenarios, though with considerable variation in mitigation levels among them. Analysis revealed a major influence of selection of biogas utilisation pathway (electricity/biomethane) on overall impacts. The displaced processes such as natural gas contributed majorly towards the reduction in climate change and fossil depletion, whereas electricity grid mix contributed to terrestrial acidification and freshwater eutrophication. This study suggests that integrating pyrolysis and anaerobic digestion processes effectively valorises poultry and forestry residue waste, presenting a promising opportunity for promoting new value chains within Ireland's bioeconomy. This approach enhances bioresource utilisation, resulting in the production of value-added products with reduced environmental costs.

Keywords: forest residue; poultry litter; anaerobic digestion; pyrolysis; life cycle assessment; biogas; biochar; pyrolysis; bioenergy

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1. Introduction

The growing worldwide demand for energy, coupled with diminishing reserves of fossil fuels and the escalating issue of global warming, has prompted policy makers to prioritise the establishment of a sustainable energy supply. Moreover, these challenges have interested the development of a circular economy concept, which seeks to transition towards sustainable ways of production and consumption by preserving the value of resources within the economy for as long as possible and by mitigating greenhouse gas emissions [1]. "Cascading approach" is one of the major principles underpinning Ireland's bioeconomy strategy, where it aims to prioritise the derivation of the higher value applications (bio-based products) from bioresources, such as forestry and agriculture, prior to their usage in energy and fuel generation, allowing to maximise the value of bioresources [2].

The poultry industry is one of the fastest growing sectors in Ireland. Poultry meat exhibits the highest consumption rate at 42%, followed by pig meat at 34%, beef and veal at 21%, and sheep meat at 3% [3]. Meanwhile, it is projected that poultry meat production in Ireland will experience a modest increase of 1.2%, resulting in a total output of 166.6 thousand metric tonnes (t) by the year 2026 [4]. With this intensification of meat production comes a challenge in managing the poultry organic wastes especially poultry litter (PLT). PLT is comprised of a mixture of wood shavings, straw, poultry manure, urine, and feathers. Improper management of this waste stream has the potential to result in the contamination of groundwater and surface water, thereby presenting a hazard to the health of both animals and humans. Based on the findings of ICT Biochain [5], it has been determined that approximately 55% of poultry litter is utilised as mushroom compost, while the remaining 45% is allocated for land-spreading purposes. It is suggested that approximately 50% of the land spread volume has the potential to be redirected towards alternative applications, such as energy generation or other forms of processing [6].

Anaerobic digestion (AD) is a viable method gaining attention for stabilising and converting the organic waste into high-value products, such as biogas, biomethane, bio-electricity, and bio-fertiliser, while reducing the waste volume and mitigating the greenhouse gas emissions [7]. The advantages of biogas and biomethane as renewable fuels have been repeatedly emphasised [8]. Anaerobic digestion (AD) biogas, which contains 50–70% methane and 30–50% carbon dioxide, can be used directly in a combined heat and power (CHP) plant to generate electricity and heat [7]. Additionally, biogas can be converted into biomethane (>97% methane), which serves as a replacement for fossil-based natural gas [9]. The primary emphasis of biogas and biomethane systems lies in utilising second-generation biofuel substrates, which encompass non-edible crops, agricultural biomass, and waste residues. These systems offer numerous additional advantages, including waste treatment capabilities, sustainable utilisation of the current grid infrastructure, and an alternative means of generating income for farmers [8].

However, the low moisture content and high ammonia–nitrogen content of PLT limit the hydrolysis and methanogenesis processes in AD, resulting in reduced methane yields [10]. The performance of AD can be improved by the addition of biochar, a byproduct of biomass pyrolysis that has been conventionally used as a soil improver [11]. Earlier studies have showed that the addition of biochar to AD increases the peak daily methane yield in low-solid–ammonia-stressed digesters, owing to the hypothesised biochar's role as buffering agent (acid resistance), biofilm development (ammonia resistance), and direct interspecies electron transfer between microorganisms (improves methanogenesis) [12,13]. Other advantages for shifting to high-solid dry anaerobic digestion (TS > 20%) includes an increase in amount of treatable feedstock and decrease in water and energy input, resulting in ease of handling of the digestate residues and reduced cost of disposal [12].

Ireland's forest cover is at 11%, the highest level in 350 years, and is projected to more than double by 2035. However, sawmills and other forest operations generate a lot of waste, including treetops and branches, saw dust, offcuts, and shavings [14]. These forest residues could be diverted to energy production using appropriate technology. Currently, thermochemical processes such as gasification and pyrolysis are widely used to convert lignocellulosic feedstock to bioenergy and other byproducts [15]. Pyrolysis (PR) is regarded as a highly promising technological approach given its capacity to generate products in three distinct phases—solid, liquid, and gas—through heat decomposition of biomass in the absence of oxygen. This process produces three byproducts: a gas, a solid material resembling charcoal (known as "biochar"), and organic vapours that can be condensed to produce "pyrolysis oil", also known as bio-oil or biocrude [16].

Both AD and PR can be used to break down biomass from agriculture and forests. AD works best with easily biodegradable feedstock, while PR works best with biomass that is hard to degrade or recalcitrant in nature [10]. Both processes are well-established technologies in Europe and produce a range of products which are in demand—soil improvers and energy [17]. Biochar from pyrolysis can be fed into AD to increase biogas production [12]. The implementation of the cascading biomass use approach, which involves the integration of two or three processes, is now recognised as a novel strategy for attaining the objective of "zero waste" on an industrial level [2]. Integrating such technologies may present promising prospects for strengthening the circular economy by presenting a viable solution for addressing the challenges associated with poultry and forestry waste management within an industrial symbiosis framework [18]. This approach enhances the efficiency of resource utilisation, facilitates energy recovery, mitigates greenhouse gas emissions, and promotes soil health [19]. Other potentially synergistic combinations exist when PR and AD are combined, such as using digestate as feedstock for pyrolysis [20], energy recovery from syngas [21], or the addition of biochar to anaerobic digestion as a means of overcoming inhibition issues [22].

However, the environmental sustainability of these integrated systems remains to be explored, particularly when considering different types of feedstocks. Mayer et al. [23] conducted a comprehensive review of LCAs pertaining to waste-to-energy technologies and revealed the majority of LCA studies were related to sewage sludge treatment using AD alone. Their findings also indicated a scarcity of research specifically focused on cascaded technologies [23]. However, studies using the combination of AD and PR have gained interest recently, considering different feedstock such as livestock manure and grass silage [9], lignocellulosic biomass [16], sewage sludge [19], organic fraction of municipal solid waste (OFMSW) [20], animal manure and energy crop residues [21], and food waste [24].

To the authors' understanding, there has been limited investigation of the environmental assessment of utilising agro-forestry residues (specifically forestry wastes and PLT) through integrated PR–AD processes. Furthermore, there is a scarcity of reported consequential LCA models pertaining to the cascading utilisation of these residues. In order to address the existing gap in knowledge, this study aims to assess the environmental consequences associated with the integrated biomass-to-energy system (PR–AD) in Ireland, specifically focusing on the utilisation of forestry residue and poultry litter as feedstocks.

2. Materials and Methods

County Monaghan, as a prominent poultry producer, holds a significant share of Ireland's poultry industry, accounting for more than 50% of the market [25]. The assessment of feedstock availability in Ireland was conducted by considering the total number of birds (2,368,100) housed in the facilities that had applied for a licence as of the year 2019 [26]. The litter production rate of broilers has been estimated at 1.2 t per 1000 birds. Based on the assumption of 7 batches per year, the annual accumulation of litter would amount to 20,000 t, in addition to the existing production.

The pyrolysis process of conifer residue (spruce) results in bio-oil, syngas, and biochar. The bio-oil is assumed to be separated and refined at the end, and syngas is used within the pyrolysis process to meet the heat requirements. The pyrolysis process model and its associated equipment and operating conditions are discussed and presented in the previous work of da Costa et al. [27]. The biochar obtained as byproduct is intended to be added as an additive during the anaerobic digestion of poultry litter.

2.1. Goal and Scope

The goal of this life cycle assessment (LCA) study is to evaluate the potential environmental impacts associated with a biomass waste-to-energy technology, specifically, an integrated system combining forest waste pyrolysis and anaerobic digestion of poultry litter. The study aims to quantify the environmental trade-offs involved in this cascading value chain approach, which combines two distinct waste conversion processes. The scope of the study encompasses the following aspects: (1) assessing the environmental performance of the integrated pyrolysis and anaerobic digestion system across multiple impact categories, including climate change, fossil depletion, eutrophication, and acidification; (2) conducting a scenario analysis to investigate the influence of different biogas utilisation pathways, such as combined heat and power generation or biomethane upgrading, on the overall environmental impacts; and (3) evaluating the potential effects of improved biomethane yields and future decision-making scenarios, such as alternative uses of byproducts (e.g., anaerobic digestate as fertiliser and pyrolysed bio-oil as potential fuel), on the environmental performance of the integrated system. The system boundary includes forestry harvesting, cultivation, forestry residue processing and transportation, biomass drying, bio-oil separation and upgrading, transportation of biochar, anaerobic digestion of poultry litter in combination with biochar, CHP operation, digestate storage, processes displaced by two co-products (biogas and digestate), and the processes displaced by the initial use of the poultry litter (land spreading) (Figure 1 and Table 1). The functional unit is based on the total amount of feedstock treated in the integrated system also defined as "one year of plant operation". The reference flow considered is 43,010 t of input feedstock, i.e., 23,010 t of forestry residue (dry) subjected for pyrolysis and 20,000 t of litter for digestion.

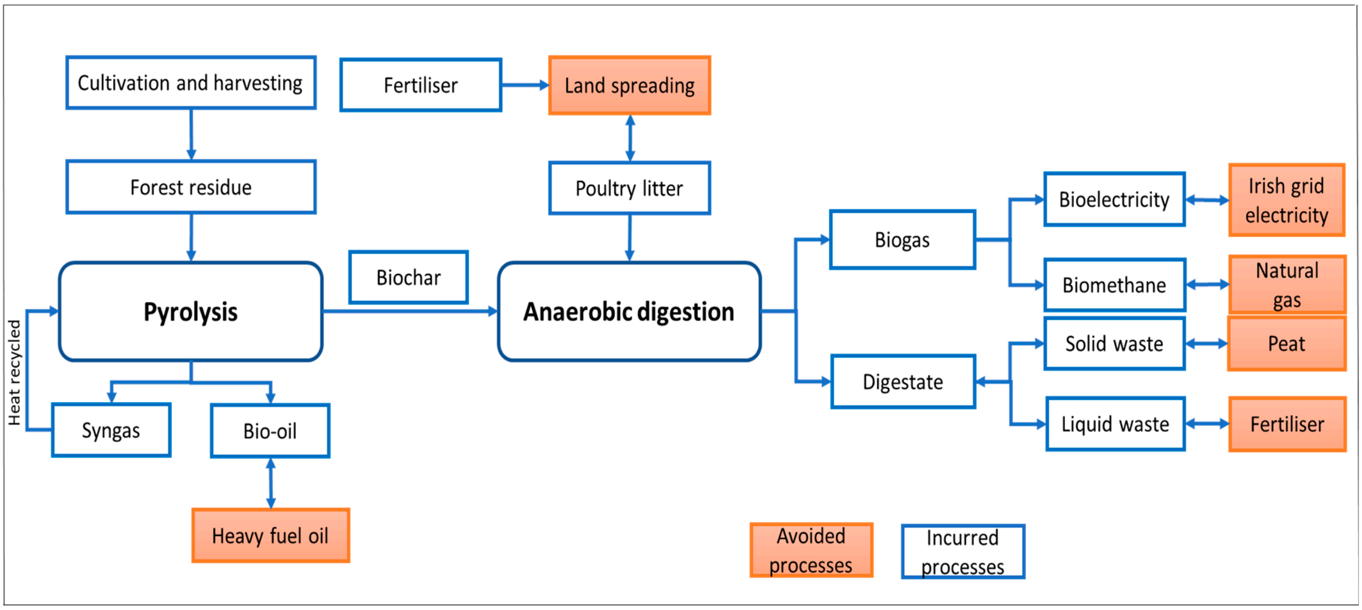

Figure 1. System boundary for the LCA involving incurred (white background) and avoided (orange background) processes.

Table 1. Scenario modelling for coupled PR+AD involving different process stages across the scenarios.

Scenario (S)	Cultivation and Harvesting of Forest Residue	PR	AD	Litter Spreading	Irish Grid Electricity	Natural Gas	Peat Moss	Fertiliser	HFO
				Displaced Processes					
BS	√	√	√	√	X	X	X	X	X
S1	√	√	√	√	√	X	√	√	√
S2	√	√	√	√	√	X	√	√	√
S3	√	√	√	√	√	X	√	√	√
S4	√	√	√	√	X	√	√	√	√
S5	√	√	√	√	X	√	√	√	√
S6	√	√	√	√	X	√	√	√	√

BS—Baseline scenario; AD—anaerobic digestion; PR—pyrolysis; HFO—heavy fuel oil; TS Loading—8% (BS, S1, and S4); 15% (S2 and S5); and 28% (S3 and S6). The √ symbolizes the inclusion of processes in respective scenarios, while the X symbolizes the exclusion of processes.

2.2. Inventory

Information regarding the cultivation and harvesting processes in forestry in Ireland, as well as the processing and transportation of forestry residues, is adopted from a study conducted by Murphy et al. [28]. This study considered the following operations: seedling production, site preparation, fuel consumption of excavators, forest road construction, and herbicide usage to avert grass growth. The CTL (Cut-to-Length) system is widely employed in Ireland for thinning and is the dominant operational method practised in the country [29].

The process of harvesting using the Cut-to-Length (CTL) system encompasses the sequential activities of felling, delimbing, and crosscutting performed by the harvester. Subsequently, the harvested material is transported to the roadside using a forwarder. The forest residue (treetops and branches) from the production of primary forest products, namely roundwood for sawmills and pulpwood for energy generation, undergoes a series of preparation steps. These include bundling, packing, chipping, and drying (to reduce its moisture content from 60% to 40%). Subsequently, the prepared forest residue biomass is subjected to the pyrolysis process in a fixed-bed pyrolysis chamber with reaction time set at 45 min. The data related to the forest reside drying, pyrolysis, bio-oil separation, and upgradation are adopted from the pyrolysis simulation model inventory developed in the work by da Costa et al. [27] and are presented in Table 2.

Table 2. Overall inventory input and output data associated with waste-to-energy system scenarios.

Inputs	Units	BS	S1	S2	S3	S4	S5	S6
Forestry residues (dry)	t	23,010.11	23,010.11	23,010.11	23,010.11	23,010.11	23,010.11	23,010.11
Energy (PR)	MWh	56.28	56.28	56.28	56.28	56.28	56.28	56.28
Heat (PR)	GJ	2.48×10^5	2.48×10^5	2.48×10^5	2.48×10^5	2.48×10^5	2.48×10^5	2.48×10^5
PL-transported	t	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Calcium ammonium nitrate	t	190,000	190,000	190,000	190,000	190,000	190,000	190,000
Electricity (AD)	kWh	1.40×10^6	1.40×10^6	1.40×10^6	1.40×10^6	1.40×10^6	1.40×10^6	1.40×10^6
AD plant	item(s)	1	1	1	1	1	1	1
Ammonia stripper	t	750	750	925.56	1087.55	750	925.56	1087.55
PL transport, litter, lorry	t	1.00×10^6	1.00×10^6	1.00×10^6	1.00×10^6	1.00×10^6	1.00×10^6	1.00×10^6
transport, solid, lorry	t × km	-	1,530,000	1,942,920	2,145,880	1,530,000	1,942,920	2,145,880
transport, biochar, lorry [a]	t × km	242,500	242,500	242,500	242,500	242,500	242,500	242,500
CHP unit	item(s)	1	1	1	1	1	1	1
Electricity (biogas upgrading)	GJ	-	-	-	-	1524.61	1524.61	1524.61
Tap water (biogas upgrading)	t	-	-	-	-	255.42	255.42	255.42
Outputs								
Bio-syngas	m^3	10,191.34	10,191.34	10,191.34	10,191.34	10,191.34	10,191.34	10,191.34
Bio-oil	t	1853.72	1853.72	1853.72	1853.72	1853.72	1853.72	1853.72
Biomethane [b]	m^3	3,080,000	3,080,000	4,276,225	5,662,504	3,080,000	4,276,225	5,662,504
Electricity (avoided)	GJ	-	33,825.61	33,825.61	33,825.61	-	-	-
Heat (avoided)	GJ	-	-	-	-	99,792.45	99,792.45	99,792.45
Ammonium sulphate (avoided)	t	-	0.35	0.44	0.50	0.35	0.44	0.50
Peat moss (avoided)	m^3	-	38,250	48,573	53,674	38,250	48,573	53,674
Heavy fuel oil (avoided)	t	-	1853.72	1853.72	1853.72	1853.72	1853.72	1853.72
Methane to air (fugitive)	t	50.74	50.74	67.45	90.28	50.74	67.45	90.28
NH_3 litter (avoided)	t	82.40	82.40	82.40	82.40	82.40	82.40	82.40
NH_3 (digestate storage)	t	2.31	2.31	3.02	4.06	2.31	3.02	4.06
N_2O (digestate storage)	t	9.43×10^{-2}	9.43×10^{-2}	1.31×10^{-1}	1.73×10^{-1}	9.43×10^{-2}	1.31×10^{-1}	1.73×10^{-1}
N_2O (CHP)	t	1.40×10^{-4}	1.40×10^{-4}	1.94×10^{-4}	2.57×10^{-4}	-	-	-
NOx (CHP)	t	1.73×10^{-2}	1.73×10^{-2}	2.40×10^{-2}	3.18×10^{-2}	-	-	-

S—Scenario; BS—baseline scenario; AD—anaerobic digestion; PR—pyrolysis; PL—poultry litter; a—biochar produced, 9700 t; and b—the average values of the increase in biomethane efficiencies were considered, i.e., 27% (S2 and S5) and 45% (S3 and S6) [11,12].

The data inventory for the poultry litter AD is based on the study by Beausang et al. [26] and is presented in Table 2. The AD system is assumed to process 20,000 tons of poultry litter per year with a hydraulic retention time of 34 days. The biogas produced undergoes cogeneration in a combined heat and power (CHP) system, where it is simultaneously converted into electrical energy and thermal energy using a CHP engine. The CHP engine exhibits an efficiency of 42% for the conversion of biogas into electrical energy and an efficiency of 42% for the conversion of biogas into thermal energy. The methane content of biogas is 54% and digestate produced is 17,500 tons per year. The AD system parameters considered in the study are based on an existing operational plant in Ireland and presented in Beausang et al. [26]. Biochar from the pyrolysis plant is assumed to be used as additive in AD system. The use of biochar in high-solid anaerobic digestors processing chicken litter substantially improves the biomethane production especially at 1:1 total solid (TS) dosage of wood biochar and feed [12]. Hence, the biochar quantity used is calculated based on total solids content of AD system, i.e., 47%. The electricity produced from biogas is assumed to be supplied to the grid, suggesting it could replace the electricity generated by other fossil-based fuels such as coal. The digestate produced from AD system consists of liquid and solid fractions. The solid fraction can be used to displace peat, which is the majorly used growing media component in the Irish horticulture industry [30]. Whereas the liquid fraction passed through ammonia stripper produces an ammonia sulphate solution, which can serve as a substitute for synthetic nitrogen fertiliser.

Calcium ammonium nitrate (CAN) is the most prominent straight nitrogen (N) fertiliser used in Irish agriculture [31].

2.3. Life Cycle Impact Assessment

The life cycle inventory modelling and environmental impact assessment is performed using OpenLCA v1.10.3 software tool, an open-source LCA tool developed by GreenDelta. OpenLCA is widely used in both academia and industry for conducting comprehensive LCA studies across various sectors, including biomass and energy systems [32]. The software's flexible data import capabilities allow seamless integration of foreground data from the studied facilities, as well as background data from established LCA databases such as Ecoinvent version 3.5 consequential model and industry-specific datasets. In OpenLCA, the life cycle inventory (LCI) modelling process includes mapping relevant unit processes, defining product systems, and establishing interconnections between processes by analysing material and energy flows. Consequently, LCI analysis quantifies emissions, such as greenhouse gases, nitrogen, phosphorus, sulphur dioxide, and nitrogen oxides, as well as resource consumption, such as fossil fuels, associated with the system being assessed. The identified emissions and resource consumption are then translated into environmental impacts using characterisation factors. These characterisation factors are derived from established impact assessment methods and allow for the conversion of inventory data into potential environmental impacts. Subsequently, the impact results are normalised to a common reference point, often expressed per unit of the defined functional unit, facilitating comparisons and interpretation across different impact categories and scenarios.

This study looks at four important impact categories in the assessment of biomass-based energy systems: climate change (CC), freshwater eutrophication (FE), terrestrial acidification (TA), and fossil depletion (FD). These impact categories are widely suggested in the analysis of biomass to bioenergy LCA studies [32]. Most recently updated, ReCeiPe 2016 v1.13 impact assessment methodology available in OpenLCA is used to estimate the environmental impacts of the studied system at a midpoint level using a hierarchist perspective. The characterisation factors employed in the study are represented in Table 3. The midpoint characterisation factors are regarded as indicators of the cause–impact pathway, and the hierarchist perspective is based on scientific consensus regarding the time frame (100 years) and integrity of impact mechanisms [33]. Moreover, the characterisation of the midpoint category exhibits a more robust correlation with environmental flows and generally entails reduced uncertainty in parameters [33].

Table 3. Characterisation factors for impact categories used in the life cycle impact assessment.

Impact Category	Flow	Factor	Units
Climate change (CC)	CO_2	1	kg CO_2-eq/kg
	CH_4	25	kg CO_2-eq/kg
	N_20	298	kg CO_2-eq/kg
Freshwater eutrophication (FE)	P	1	kg P-eq/kg
	PO_4	0.33	kg P-eq/kg
	H_3PO_4	0.32	kg P-eq/kg
Terrestrial acidification (TA)	SO_2	1	kg SO_2-eq/kg
	NOx	0.56	kg SO_2-eq/kg
	NH_3	2.45	kg SO_2-eq/kg
Fossil depletion (FD)	Crude oil	1	kg oil-eq/kg
	Natural gas	1.11	kg oil-eq/m^3
	Mine gas	1.07	kg oil-eq/m^3
	Hard coal	0.434	kg oil-eq/kg
	Brown coal	0.225	kg oil-eq/kg

2.4. Scenario Analysis

The use of biochar in high-solids anaerobic digestors processing chicken litter substantially improves the biomethane production especially at 1:1 total solid (TS) dosage of wood biochar and feed [12]. However, the biomethane yield varies at different loading TS dosages. The optimal ranges of the loading TS are based on the studies [11,12] that showed improved biomethane efficiency. The average values of the increase in biomethane efficiencies are considered, i.e., 27% and 45%. To evaluate the energy demand and environmental impacts across the entire value chain, six scenarios (S1–S6) are developed, considering different loadings of biochar at TS, i.e., 8%, 15%, and 28% and the final energy product (bioelectricity or upgraded biomethane) (Table 1). The first three scenarios (S1–S3) assume biogas conversion to bioelectricity, while scenarios S4–S6 assume 90% of the produced biogas was upgraded to biomethane for injection into the gas grid, with the remaining 10% combusted on-site in a combined heat and power (CHP) unit to provide thermal and electrical energy for the biogas plant operations. Specifically, the biochar TS loadings are 8% for the baseline and scenarios S1 and S4, 15% for scenarios S2 and S5, and 28% for scenarios S3 and S6. The displaced processes such as heavy oil production, poultry litter usage (land spreading), peat moss production, natural gas production, and electricity grid mix are included in scenario analysis. The electricity fuel mix for electricity generation for 2021 is as follows: 49% gas, 14% coal, 7.5% oil, 1.5% peat, 18% wind, 5% biomass (including renewable waste), 2% hydro, and 3% imports [34]. According to the Government of Ireland [35], there are plans in place to gradually eliminate the use of non-renewable fossil fuels, particularly coal, for electricity generation in Ireland by the year 2030. Hence, biomass-generated bioelectricity could have a great potential in future to replace the non-renewable fuel mix in Irish grid electricity. Baseline scenario (BS) assumes avoided land spreading of PL and diverting it towards digestion in AD with the use of biochar as an additive from pyrolysis process. To understand the implication of products and its management (biogas, digestate from AD, and bio-oil from PR), the avoided impacts are not included in the BS.

3. Results and Discussion

The impact categories considered in this study demonstrated a net environmental savings across all the scenarios (1–6) when compared to the baseline scenario (Table 4). Importantly, with the increase in TS loading, there was an increase in net impacts savings, where CC and FD were substantially affected by displaced natural gas production, and TA and FE were majorly influenced by displaced electricity fuel mix (Figures 2 and 3).

Table 4. Scenario analysis results towards the selected impact categories.

Impact Category	BS	S1	S2	S3	S4	S5	S6
CC	2.05×10^7	9.31×10^6 (54.55%)	6.64×10^6 (67.61%)	3.54×10^6 (82.75%)	-2.08×10^6 (110.15%)	-9.18×10^6 (144.80%)	-1.74×10^7 (184.96%)
TA	-1.68×10^5	-2.37×10^5 (29.09%)	-2.53×10^5 (33.60%)	-2.72×10^5 (38.15%)	-1.88×10^5 (10.80%)	-1.86×10^5 (9.42%)	-1.86×10^5 (9.62%)
FE	1.02×10^3	-6.74×10^2 (165.87%)	-1.31×10^3 (227.53%)	-2.04×10^3 (299.00%)	9.70×10^2 (5.27%)	9.79×10^2 (4.32%)	9.93×10^2 (2.96%)
FD	7.54×10^6	5.26×10^6 (30.24%)	4.65×10^6 (38.27%)	3.95×10^6 (47.57%)	-3.84×10^6 (105.09%)	-3.09×10^6 (141.01%)	-6.24×10^6 (182.84%)

CC—Climate change (kg CO_2-eq); TA—terrestrial acidification (kg SO_2-eq); FE—freshwater eutrophication (kg P-eq); FD—fossil depletion (kg oil-eq); and the values enclosed in brackets represent the % decrease in the respective scenario value compared to the baseline scenario (BS) for the corresponding impact category. The negative values indicate the impact savings.

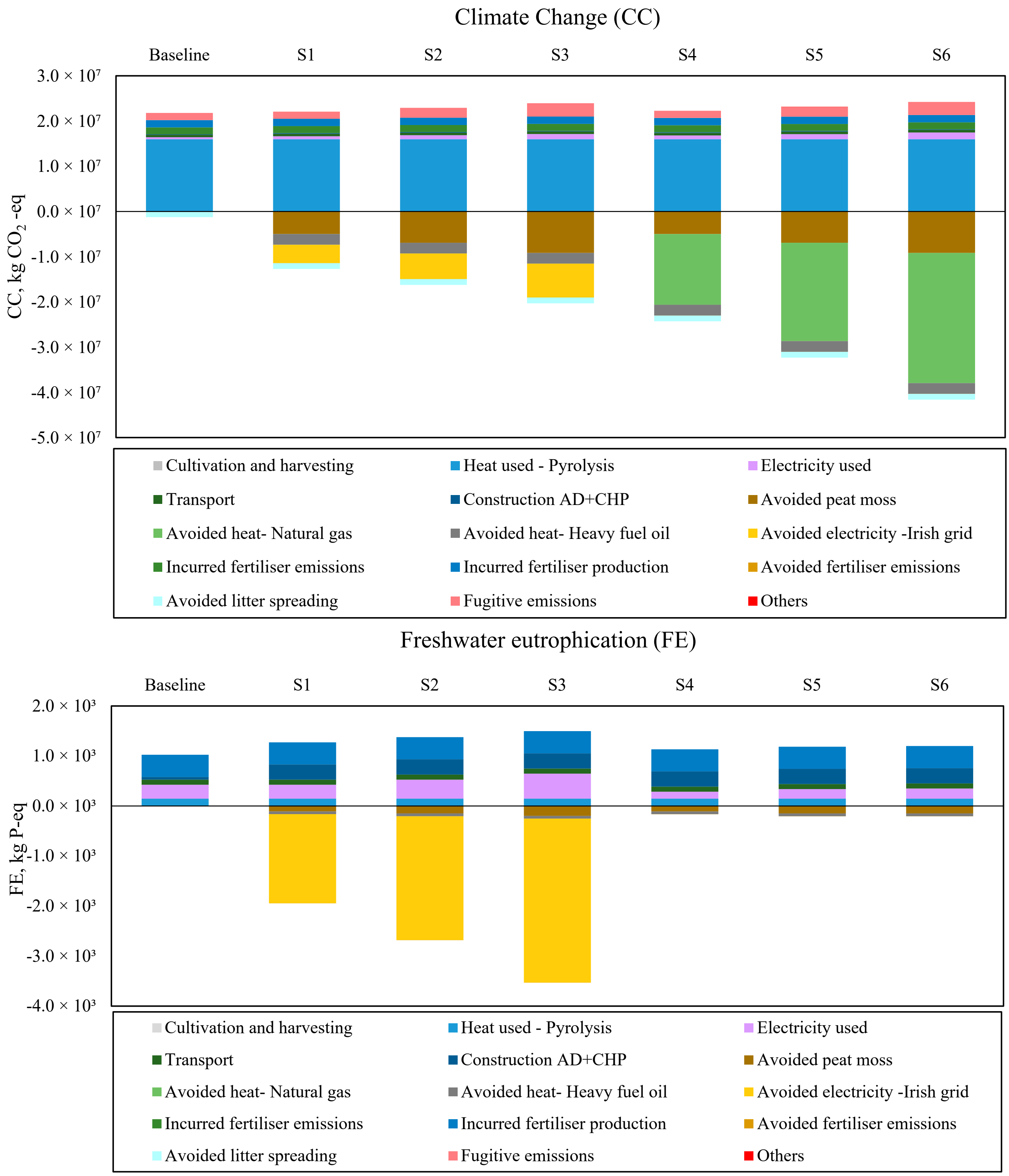

Figure 2. Process stage contributions for the climate change (CC) and freshwater eutrophication (FE) impact categories.

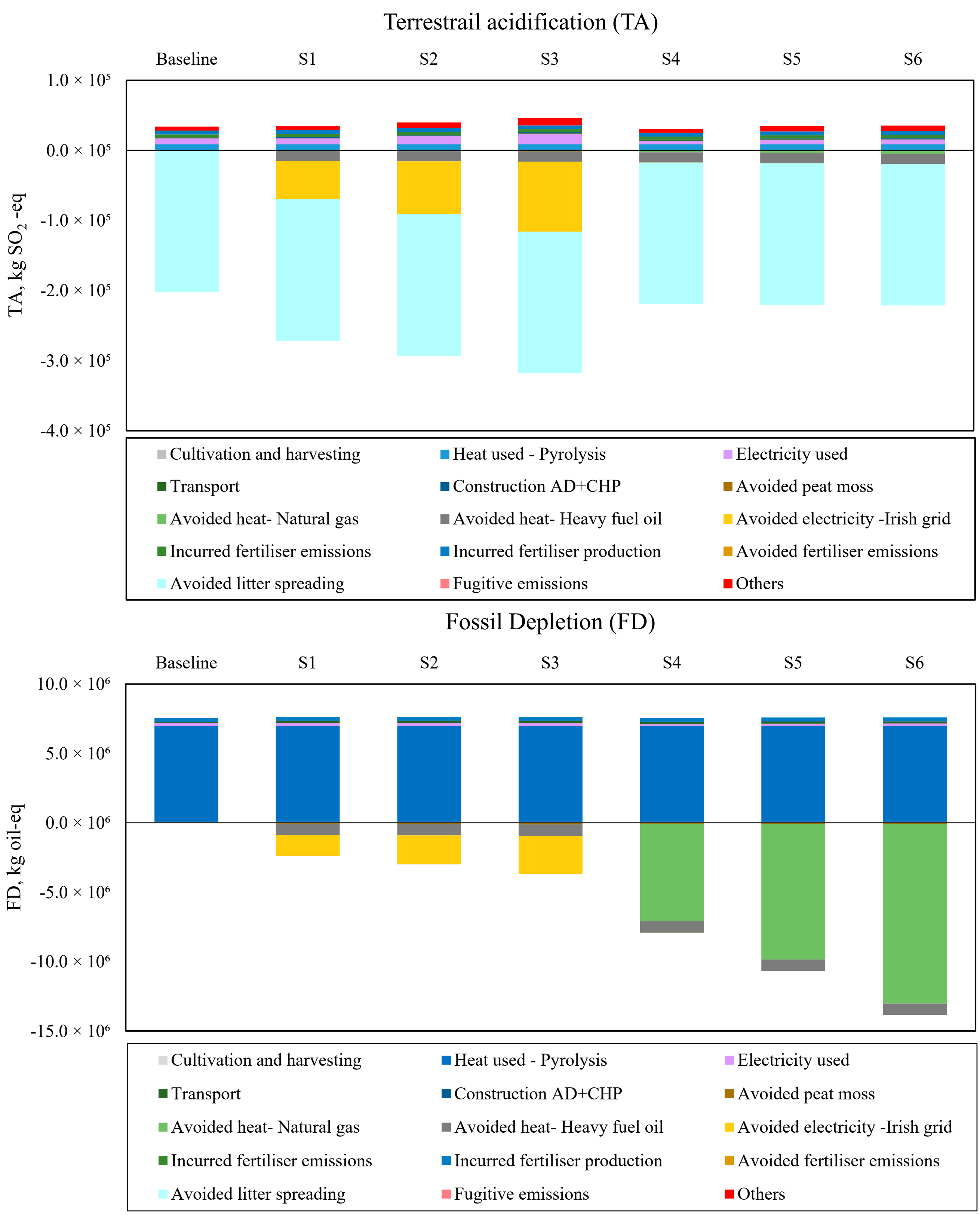

Figure 3. Process stage contributions for the terrestrial acidification (TA) and fossil depletion (FD) impact categories.

For the CC impact category, baseline scenario indicated a net positive emission for integrating PR with AD with no displaced process emissions being included. The primary reasons for the higher CC impact in the base case scenario were the use of heat in the pyrolysis process (78%) and the incurred fertiliser production and emissions (15%). The findings align with Wang et al. [20], which integrated pyrolysis and anaerobic digestion for food waste conversion to bioenergy. This study identified that energy usage in feedstock drying and pyrolysis reactor substantially contributed (80%) to CC. However, Li and Feng [19] suggested that increasing the organic fraction above 60% w/w could support thermal drying, potentially reducing associated impacts. Optimising feedstock composition and minimising drying energy requirements could mitigate the CC impacts of the pyrolysis process.

The avoided emissions of PL land spreading do not have a major impact on the overall CC category because the decrease in emissions was only 6%. Inclusion of displaced processes, on the other hand, had a substantial environmental reduction across scenarios, with results indicating CC decrease ranges of 55–83% and 110–185% for Scenarios 1–3 and 4–6, respectively, in contrast to the base case scenario (Table 4). The displaced processes such as avoided electricity production and avoided peat moss production majorly contributed to the decrease in CC impact in Scenarios 1–3. Whereas the resulted negative CC values in Scenarios 4–6 are primarily due to the avoided natural gas production and avoided peat moss production (Figure 2).

For the FE category, the base case scenario resulted in positive values, owing to the incurred emissions from fertilisation production, which impacted the highest (43%) followed by energy usage from AD (26%) and PR (14%) systems (Figure 2). However, the analysis revealed that there was a net reduction in FE across Scenarios 1–6 (Table 4). Where the decrease in FE observed in Scenarios 1–3 was mainly attributable to the avoided electricity generation, Scenarios 4–6 exhibited comparatively lower reduction in FE and was due to the avoided peat moss production process. The major contributors for the positive values of FE in Scenarios 1–6 were incurred fertiliser production and AD and CHP construction.

For the TA category, potential net reduction in emissions was observed across all the scenarios (Table 4). In base case scenario and Scenarios 4–6, this was mainly due to the avoided emissions from the land spreading of PL. Whereas in Scenarios 1–3, the net reduction was attributed to the avoided land spreading of PL and avoided electricity production (Figure 3). For the FD category, the energy usage in pyrolysis process contributes the major share of this impact category across all the scenarios including base case. Moreover, the energy usage of AD, incurred fertiliser production, and transport were the leading contributors to the overall impact with positive values for Scenarios 1–3. However, results showed overall decrease in FD for Scenarios 4–6, and this was largely due to the avoided natural gas production and avoided heavy oil production (Figure 3).

The integration of PR and AD has been widely recognised as an environmentally competitive system when compared to standalone AD and PR processes, particularly when employing feedstocks such as livestock manure, grass silage [9], and agriculture residue [21]. However, the findings from different studies have varied, highlighting the influence of specific factors on the environmental performance of these integrated systems. Opatokun et al. [24] concluded that the integrated system and standalone AD had similar environmental impacts, acknowledging the increased energy generation potential and the production of valuable byproducts as advantages of the integrated approach. Conversely, Li and Feng [19] found that standalone AD performed better than PR alone and the integrated system when employing sewage sludge as the feedstock, suggesting it required no energy and material expenditure for thermal drying and pyrolysis.

These study findings suggest that the integration of PR and AD processes for the cascading valorisation of agricultural feedstocks (specifically, forestry residue and poultry litter) resulted in a substantial net reduction in environmental burdens across multiple impact categories. The scenario analyses indicated the impact of the displaced processes outweigh the impacts of the coupled AD and PY processes itself (Figures 2 and 3). Particularly, the results reveal that the displaced processes played a crucial role in determining the overall impact of the scenarios. The current study's findings were consistent with those of Ahmadi Moghaddam et al. [36] and Caiardi et al. [37], where the authors concluded that the avoided production processes especially related to energy and fertiliser primarily contributed to the reduction in studied impacts.

As Ireland is aiming to phase out non-renewable fossil sources for electricity generation, especially coal by 2030 [35], Scenarios 1–3, which considered the penetration of renewable sources into the electricity grid mix, led to environmental savings across all the assessed impact categories with major reductions observed in the FE and TA categories. These findings align with the study by Opatokun et al. [24], which reported substantial environmental benefits, particularly in FE and TA categories, when biogas-generated electricity was used to offset electricity from the fossil fuel-dominated Australian grid mix (86% fossil fuel contribution). Hence, the emission-saving potential of biogas would play an important role in the future in terms of its penetration, which could result in further decarbonisation of electricity grid mix. Additionally, the authors highlighted the potential role of AD digestate as a bio-fertiliser, where emissions associated with synthetic fertiliser production could be avoided, contributing to further environmental benefits [24].

The environmental savings, especially for CC and FE impacts in Scenarios 4–6, were also evidenced by displacing peat with solid digestate (Figure 2), which presents an interesting alternative as a fertiliser and potential peat substitute in horticultural growing substrates [38]. In the current study, liquid digestate was assumed to displace synthetic nitrogen fertiliser, leading to notable environmental savings across all scenarios and impact categories. While numerous authors highlighted the benefits of utilising liquid digestate as bio-fertilisers [10,21], recent studies recommended exploring alternative uses for digestate, such as bioenergy extraction through pyrolysis [9] or reuse in anaerobic digestion processes [37]. These alternative applications aim to maximise the value derived from digestate and potentially unlock additional environmental and economic benefits beyond its use as a fertiliser substitute.

Corroborating the findings reported by Van Alengebawy et al. [39], the biomethane-upgrading scenario proved to be the most favourable choice in terms of the CC and FD categories when tested against the scenarios with the CHP process. Scenarios 4–6, involving biomethane upgrading, exhibited considerable environmental savings owing to the greater impact of avoided emissions from natural gas production. This clearly points out that the selection of different biogas utilisation pathways in the integrated process (PR+AD) has considerable influence on the overall results. However, other studies by Beausang et al. [26] and Tsapekos et al. [40] found that CHP performed better than biogas upgrading in certain impact categories. Beausang et al. [26] revealed that when upgrading biogas to biomethane, CC impact savings were higher when a 1:1 substitution of natural gas was employed, but the savings proportion reduced with lower substitution ratios (e.g., 1.05 and 1.02 of natural gas). On the other hand, impacts such as FE and TA savings were higher for CHP than biogas upgrading. It is worth noting that the current study and Beausang et al. [26] considered biomethane as a substitute for natural gas heating, whereas Tsapekos et al. [40] assessed biomethane as a transport fuel, which may contribute to the observed differences in environmental performance.

Moreover, it is crucial to acknowledge that the final utilisation of biogas may be contingent upon the specific policy credits allocated to a given region. For example, in Ireland, the government has implemented the Renewable Heat Incentive (RHI) scheme, which provides operational support for biomethane injection into the natural gas grid. Under this policy, biogas producers who upgrade their biogas to biomethane and inject it into the gas grid receive quarterly payments over a 15-year period. As a result, in regions where the RHI is available, the final utilisation of biogas may favour upgrading to biomethane for grid injection to take advantage of the policy incentive. Conversely, in areas without such incentives, other biogas utilisation pathways, like combined heat and power generation, may be more economically favourable [41].

This study recommends implementing cascading valorisation of forestry and poultry waste by combining the AD and PR processes, that maximises resource utilisation while producing value-added products with reduced environmental costs. Due to the considerable bioresource availability in Ireland, it is highly encouraged to implement cascading systems of technology utilisation in order to fully exploit the value of biomass wastes. However, in cases where biomass wastes are currently being utilised in a manner that is environmentally, economically, and socially sustainable, it is advisable to refrain from interfering with this system. Instead, efforts should be focused on strengthening it by exploring valorisation potential for the remaining residues. Moreover, the development of indigenous fertiliser and energy sources from accessible residue feedstocks holds significant importance for Ireland, as it serves the dual purpose of meeting market demands and contributing to the reduction in GHG emissions. This attempt aligns with the objective of achieving reduction targets and promoting the concepts of bioeconomy and circular economy.

4. Conclusions, Outlooks, and Limitations of the Study

This study evaluated the environmental implications of a novel cascading system for valorising forestry residue and poultry litter by coupling pyrolysis and anaerobic digestion processes. LCA revealed substantial impacts from the avoided processes, particularly those associated with biogas-derived products such as electricity grid mix and natural gas production. Results also indicated that the final biogas utilisation pathway has great influence on overall impacts of the system. The choice of final biogas utilisation pathway was found to greatly influence overall system impacts, with biomethane upgrading showing greater environmental savings, particularly for CC and FD categories, compared to displacing the electricity grid fuel mix. However, impacts related to FE and TA were primarily influenced by avoided emissions from the fuel mix. Overall, a potential net reduction in environmental impacts was observed across all scenarios analysed. In conclusion, effective management of poultry and forestry residues and the development of new value chains are crucial for sustaining Ireland's agricultural and forestry industries in the long term.

Integrating PR and AD for treating forestry and poultry waste is viewed as an environmentally friendly approach with promising practical applications. However, transitioning from theoretical data to actual production requires careful consideration of discrepancies, especially concerning energy inputs/outputs and mass flows. For instance, variations in TS loading can particularly affect reactor size, energy requirements, and byproduct handling. Thus, comprehensive modelling of process operations from an industrial perspective is essential to accurately capture variations in inputs and outputs, directly impacting system emissions and impacts.

Furthermore, this study's reliance on the literature data and the adoption of missing data from the Ecoinvent database underscore the need for further research and comparisons to draw definitive conclusions about the integrated pathway studied here. To gain a more comprehensive understanding of the overall sustainability of value chains integrating pyrolysis and anaerobic digestion processes, future studies should explore the impact of various biochar types, both independently and in combination with liquid digestate, on biogas production from diverse feedstock materials. Such investigations would shed light on the intricate interplay between biochar characteristics, feedstock compositions, and biogas yields, enabling the optimisation of these coupled waste valorisation systems for enhanced sustainability and efficiency.

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Abbreviations

AD	anaerobic digestion
BS	baseline scenario
CAN	calcium ammonium nitrate
CC	climate change
CHP	combined heat and power
CLT	Cut-to-Length
FD	fossil depletion
FE	freshwater eutrophication
GJ	gigajoule
HFO	heavy fuel oil
km	kilometre
kWh	kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory
m	metre
MWh	megawatt hour
OFMSW	organic fraction of municipal solid waste
PLT	poultry litter
PR	pyrolysis
RHI	renewable heat incentive
S	scenario
t	tonne
TA	terrestrial acidification
TS	total solid

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