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Exploring the environmental consequences of roadside grass as a biogas feedstock in Northwest Europe

Rahul Ravi[a*], Marcella Fernandes de Souza[a], Anne Adriaens[a], Ruben Vingerhoets[a], Hongzhen Luo[a], Miet Van Dael[b,c], Erik Meers[a]

[a] RE-SOURCE LAB, Laboratory for BioResource Recovery, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure links-653, Ghent 9000, Belgium. *rahul.ravi@ugent.be

[b] Unit Separation and Conversion Processes, VITO, Boeretang 200, 2400 Mol, Belgium

[c] Environmental Economics Research Group, Centre for Environmental Sciences (CMK),
UHasselt, Agoralaan, 3590 Diepenbeek, Belgium

Abstract

The Russo-Ukrainian war has highlighted concerns regarding the European Union's (EU) energy security, given its heavy dependence on Russian natural gas for electricity and heating. The RePowerEU initiative addresses this challenge by targeting a significant increase in biomethane production (up to 35 billion m^3 by 2030) to replace natural gas, aligning with the EU methane strategy's emission reduction and air quality improvement goals. However, the use of energy crops as biogas feedstock has raised land-use concerns, necessitating a policy shift towards alternative sources such as agro-residues, livestock manure, and sewage sludge.

This study investigates the environmental impacts of using roadside grass clippings (RG) as an alternative feedstock for biogas production, focusing on selected regions in Northwest Europe (Belgium, Netherlands). The aim is to evaluate the environmental performance of RG as a mono- or co-substrate for biogas production, comparing it to the current practice of composting. Additionally, the study assesses the environmental impacts associated with biogas end-use in these regions.

The results indicate that co-digestion of RG with pig manure offers a more environmentally friendly alternative compared to mono-digestion of RG or the existing composting practice. This finding is primarily attributed to the avoided emissions resulting from conventional pig manure management. Furthermore, in terms of climate change impacts concerning biogas end-use, the study identifies that combined heat and power (CHP) systems are preferable to biomethane recovery in regions with a natural gas-based electricity mix. However, for reducing fossil resource use, biomethane recovery emerges as the preferred option.

By providing insights into the environmental performance of RG as a biogas feedstock and evaluating the impacts of different biogas end-use options, this study offers insights to policymakers for the development of sustainable energy strategies in Northwest Europe.

Keywords: Life Cycle Assessment, biogas, biomethane, grass, energy transition, climate change

1. Introduction

The biogas industry lies at the intersection of carbon neutrality and sustainable waste management. The sector increasingly relied on energy crops during the last decade, whose cultivable area accounts for about 2% of the total land area in the EU-27 and the United Kingdom (Strapasson et al., 2020). The land use impact of energy crops has prompted the biogas industry to shift towards alternate side streams such as manure, food processing waste, and sewage sludge among others. Using these side streams as biogas feedstock not only mitigates greenhouse gas (GHG) emissions from their conventional treatment pathways (landfilling, incineration, composting) but also generates ‘green’ energy in the form of biogas/biomethane.

Combined biogas and biomethane production in 2020 in the EU totalled 18 billion cubic meters (bcm) (close to the entire natural gas consumption of Belgium) and represented 4.6% of the natural gas consumption in the EU-27 (EBA, 2021). In comparison, prior to the war, Russian natural gas imports to the EU amounted to approximately 200 bcm per year, accounting for about 36% of the market share (McWilliams et al., 2021). The biogas sector is thought to offer a medium to long-term upheaval in terms of helping the EU wean itself off Russian natural gas and improve its energy security and independence (IEA, 2022). The European Commission, in its REPowerEU plan, has set targets to increase the EU’s biomethane production to up to 35 bcm by 2030 (EU, 2022) and the International Energy Agency (IEA) has envisioned an increase in production of up to 125 bcm in 2040.

One strategy to achieve the EU’s biogas/biomethane goals and simultaneously limit the land use impact is to valorise alternate streams such as roadside grass clippings (RG). RG are residual biomass resulting from mowing roadsides under the “cut-and-collect” regime of EU member states to improve the biodiversity of the roadside verges (Noordijk et al., 2009). RG, under the EU Waste Framework Directive (2008/98/EC), is currently viewed as waste, with only a small fraction being valorised into compost (Souza et al., 2020). Therefore, it cannot be used for the highest valorisation purpose, i.e. usage of feed. However, there is potential to further valorise RG for bioenergy since it has a comparable yield and fibre concentration to semi-natural grass (Piepenschneider et al., 2016). The inventoried RG potential in EU-27 and Switzerland is 6.3 million tonnes per year (Hamelin et al., 2019), of which approximately 0.60 bcm could be tapped in the form of biogas.

This study illustrates select regions in Northwest Europe (Belgium, France, the Netherlands and the UK) where RG could potentially be valorised to biogas. The region comprises 1712 biogas plants and a combined total annual production of 30.55 TWh-equivalent of biogas and 11.37 TWh-equivalent of biomethane (Meeus, 2019). A breakdown of types of feedstock used at these biogas plants is elaborated in (EBA, 2021). Biogas in these regions is mostly utilized for combined electricity and heat generation, whereas biomethane is primarily used as a natural gas substitute with only a small proportion used as a transportation fuel (EBA, 2021). According to Meeus (2019), the area under investigation has 176,000 hectares of RG that could produce up to 2 million tonnes of grass per year (on a fresh matter basis). The harvested RG, if digested, could potentially produce 188 million m³ of biogas or 1.5 TWh-equivalent of energy, and it is crucial to understand the environmental externalities from RG digestion.

To study the environmental sustainability of using RG as feedstock for biogas production, we compare mono-digestion of RG or co-digestion of RG with other feedstocks to the status quo, i.e. composting. This is done through a life cycle assessment (LCA) to inform policymakers on the role of RG in mitigating emissions from the waste sector as well as reducing the reliance on primary energy sources. Previous studies (Bedoić et al., 2019; Boscaro et al., 2018; Nilsson et al., 2020) have evaluated the technical feasibility of digesting RG, but the life cycle implications of specifically managing RG have only been studied once as a sub-scenario (De Vries et al., 2012). Furthermore, Voinov et al. (2015), who calculated the projected return on energy invested for RG, recommended a comprehensive life cycle assessment to assess different management scenarios of RG.

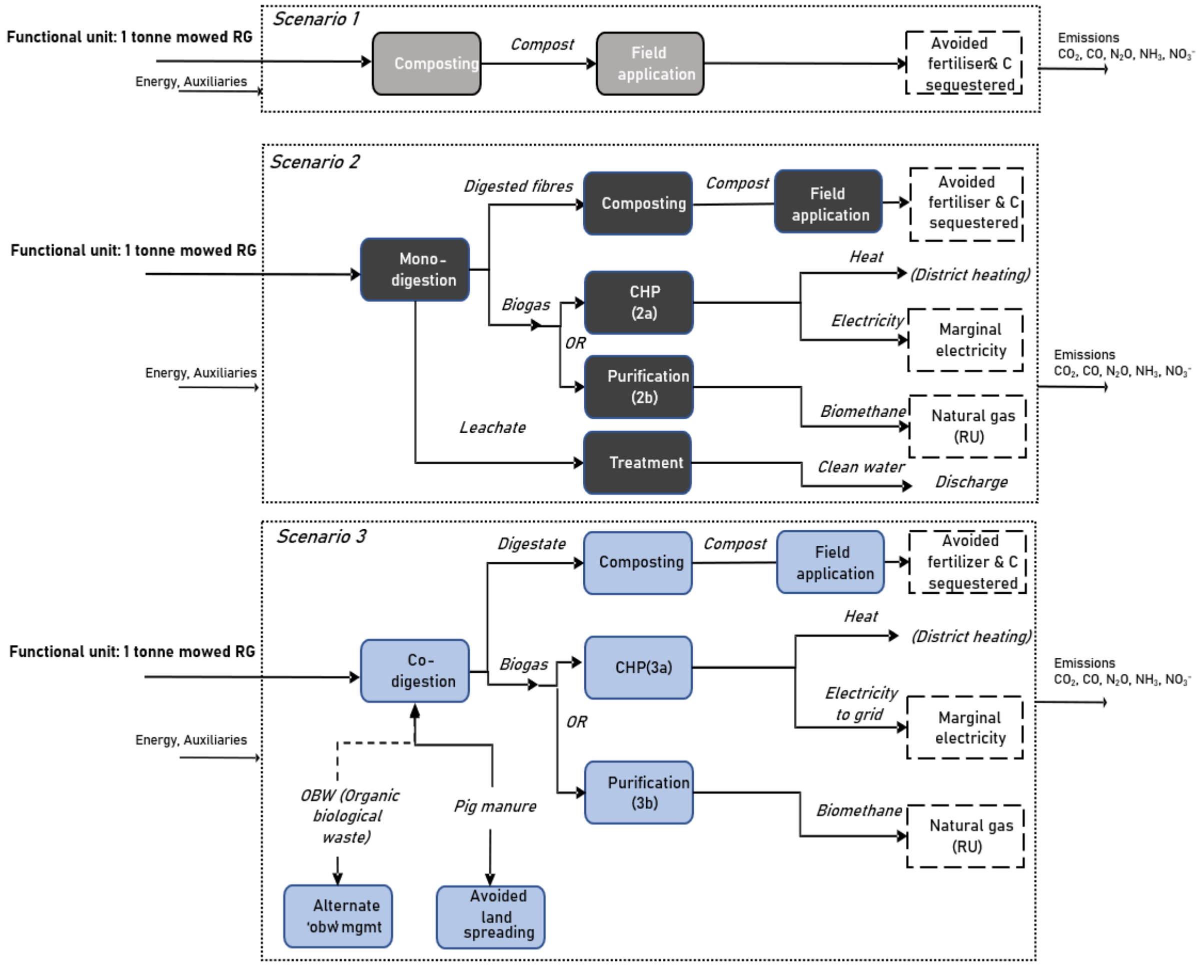
Therefore, the objectives of this study are: (i) to determine whether experiences from regional RG digestion could be extrapolated to the rest of the EU; (ii) to measure the effects of the marginal feedstock as a consequence of adding RG to co-digestion, and (iii) to compare the end-use of biogas produced from RG, i.e. valorisation in a co-generation or combined heat and power unit (CHP) versus purification to biomethane.

2. Methodology

A consequential perspective was applied in this study since it can best describe and estimate the consequences of a decision (in the present case, these relate to the management of RG) (Ekvall 2019). The system boundaries aim to include the alternative or 'marginal' products on the market displaced by the co-products from the RG value chain. The geographical scope of this study is set to Flanders, Belgium owing to primary data availability from the pilot facilities.

2.1. System boundaries

The functional unit (FU) of the system is **1 tonne of mowed roadside grass (RG)** and 3 scenarios are considered, i.e. composting, mono-digestion and co-digestion (Figure 1). For composting, data from literature were considered, whereas for mono-digestion and co-digestion, primary data from pilot facilities were used to build the life cycle inventory (LCI). This study focused exclusively on evaluating the environmental impacts of RG management strategies. However, an accompanying analysis of the economic and technological aspects of these scenarios can be found in in (Van Dael et al., 2021)



- Detailed list of inputs and outputs available in the supplementary information
- Dashed boxes refer to avoided processes
- Alternate 'obw' (food waste from industry, retail etc) management if biogas sector shows:
  - Increasing tend: Anaerobic digestion
  - Decreasing trend: Incineration

Figure 1. System boundaries to manage 1 tonne of roadside grass clippings (RG). Dashed boxes indicate avoided processes 'a' and 'b' represent sub-scenarios concerning biogas valorisation. Scenario 3 uses system expansion to isolate the environmental impacts of RG from co-digestion. Subjecting RG to co-digestion with pig manure displaces food waste, whose alternate management is included. Pig manure, if not subject to co-digestion, would be field applied.

2.1.1. Scenario 1: Composting

As per legislation (Flemish verge decree-1984), RG must be composted, and hence, windrow composting is considered the status quo. In Belgium and the Netherlands, there are sporadic cases of RG being cut and left by the roadside, but this scenario has not been modelled due to the evident negative externality of GHG emissions from biomass decomposition.

Many LCAs studying bioenergy value chains ignore the effects of biogenic CO_2 emissions on climate change by assuming it to be Carbon (C)-neutral. However, as Wiloso et al. (2016) pointed out, the neutrality assumption induces a bias to the 'true' values in the LCI. We consider their recommendation and use the agro-mechanistic model DAISY (Abrahamsen & Hansen, 2000) to simulate the long-term dynamics of C from compost application.

The model was calibrated using long-term field trial results from Tits et al. (2014), who studied the C and nitrogen (N) dynamics of VFG (vegetable, fruit and garden waste) compost. Furthermore, the initialisation of the C-pools for the compost was based on Nett et al. (2012), who focussed on organic amendments such as manure and crop residues. The latter was assumed to be the closest representative to RG-derived compost and was used to calibrate the soil organic matter module in DAISY. The ecoinvent process 'treatment of biowaste, industrial composting' was modified to suit the study and the rest of the LCI (i.e. mass and energy flows, auxiliaries usage) for the baseline scenario is built from (De Vries et al., 2012; Hamelin et al., 2014).

2.1.2. Scenario 2: Mono-digestion

Digesters are usually fed with a continuous throughput of feedstock to ensure stable biogas production throughout the year. RG, however, is not perennial and is available in only two peak moments in Flanders, i.e. mid-June and mid-September, following the "Verge Decreet" (Bermbesluit, 1984). To avoid the need for storage, RG was digested in a batch mode (Scenario 2) at a landfill cell in Rumbeke, Belgium (volume: 1750 m^3). The cell was lined with HDPE, and equipped with a drainage, leachate recirculation system and piping for biogas extraction. Input to the cell was 320 tonnes RG (in terms of fresh matter) and the biogas yield was monitored over a period of 8 months. The time series for biogas output and methane percentages are available in the supplementary information S2.

Two sub-scenarios are considered in the context of biogas end-use from mono-digestion (Figure 1). The first sub-scenario (Scenario 2a) considers the valorisation of biogas in a CHP and the ecoinvent process 'heat and power co-generation, biogas, gas engine-BE-electricity, high voltage' is considered (capacity: 160 KWe; $\eta_{electricity}$= 38% and η_{heat}= 53%). Electricity generated from the CHP is fed to the grid and equivalent credits are included within the system boundaries.

Around 97% of the heating market in Flanders is decentralized, with district heating providing only 3% of the region's total heat demand (current supply: 5710 GWh out of 145438 GWh). This is sub-par relative to regions such as Denmark, where the market share of district heating caters to 63% of the total heat demand (Aumaitre et al., 2018). Flanders' district heating networks are anticipated to expand due to their inherent energy efficiency, which is increased by making the most use of the exergy or "quality" of various energy carriers (Juwet, 2020). Furthermore, district heating can recover residual heat from high-exergy processes (industry or horticulture) for use in low-exergy processes (building heating) in a 'heat cascade' (Vandevyvere & Stremke, 2012) thereby playing a crucial role in decarbonising the heating and cooling sector (European Commission. Directorate General for Energy et al., 2022). Given these benefits, this study considers the residual heat from the CHP to be distributed to the network. According to expert estimations on-site, the heat from the CHP supplied to the district heating network varies between 50% and 75% over the summer and winter, with the remaining portion being recirculated to the digester. We consider natural gas as the marginal provider of heat since it is the primary fuel for the Belgian heat market.

The second sub-scenario linked to mono-digestion (Scenario 2b) is biogas purification to biomethane. Biogas is purified to remove the trace elements as well as to adjust its calorific value (Ryckebosch et al., 2011). We consider membrane separation to purify biogas since it dominates the market share for upgrading biogas (ecoinvent process *"biogas purification to biomethane by membrane technique"*).

Besides the production of biogas, the by-products, i.e. digested fibres and leachate, are generated during mono-digestion. The digested fibres are composted and their application is simulated on DAISY. The leachate is partially recirculated to homogenise the feedstock whilst the remaining fraction is treated before being discharged. For leachate treatment, the ecoinvent process "*treatment of wastewater from grass biorefinery*" was modified to local conditions.

2.1.3. Scenario 3: Co-digestion of Roadside grass with manure

Scenario 3 explores the consequences of using RG as a co-substrate with pig manure (PM). PM is an N-rich substrate and can induce NH_3 inhibition during digestion (Chen et al., 2008). Therefore, the recommended practice is to co-digest PM with a C-rich feedstock (in this case, RG) to balance the C/N ratio and counteract the chances of foaming in the digester (Vergote et al., 2020). Co-digestion was carried out over a period of 5 weeks with daily feeding at a pilot anaerobic digester operated by Inagro Inc in continuous mode (Continuous Stirred Tank Reactor configuration: 150 m^3 filled in capacity), with an electrical power of 31 kW, operated at mesophilic temperatures. RG was ensiled before being fed to the digester to ensure a stable quality during the feeding period and the co-substrate mixture represented 17% of RG, 53% PM and 30% of solid fraction of PM. The concentration of RG was chosen based on pilot experiments conducted by (De Moor et al., 2013) and the PM concentrations were chosen to optimise the moisture content.

Valorising RG in the digester would mean that the feedstock that was originally used as a co-substrate with pig manure would have to find an alternative management pathway. Based on market statistics, RG would ideally substitute organic biological waste or OBW (i.e. food waste from industry, retail etc) since the latter dominates the Flemish market share for anaerobic digestion (AD) substrates (OBW 63%, manure: 27%, and energy crop: 10%) (Vingerhoets et al., 2023). Thus, the effects of alternate food waste management are captured in the consequential model, for which the ecoinvent process *'treatment of biowaste by anaerobic digestion'* was adapted to suit Flemish conditions. Furthermore, the effects of avoided conventional manure management were considered if pig manure was not co-digested with grass. The conventional pathway for pig manure and solid fraction of pig manure is assumed to be land application.

According to the waste management cascade in Flanders, valorisation or recycling of material and energy (via anaerobic digestion) precedes removal/destruction (incineration/ landfilling) in the order of preference for OBW waste management (Braekevelt (2017). This results in two possibilities - AD or incineration. Whether this OBW is subject to AD or incineration depends on the current AD market. According to Weidema (2003), when a market shows an increasing or stable trend, then the marginal supplier is the most competitive technology (AD), whereas if there is a negative trend, then the least competitive technology is considered to be the marginal supplier. We used the data provided by (Vingerhoets et al., 2023) to run a Mann-Kendall trend test and ascertain whether there is a statistically significant trend (increasing or decreasing) in the time series data for OBW waste processing via AD.

Similar to Scenario 2, two end-use options for biogas obtained from co-digestion are compared, i.e. valorisation through a CHP (Scenario 3a) and purification to biomethane (Scenario 3b). The digestate is composted and subsequently field applied. The nutrient dynamics from compost application were modelled in DAISY.

2.2. Key Life Cycle Inventory

Table 1 lists the inputs and outputs of the LCI in this study. A comprehensive list of unit processes, their exchanges and values (including uncertainty) is presented in the supplementary file A (*Life Cycle Inventory_Grassification manuscript.xlsx*). Since there was no supporting evidence from earlier AD-related LCAs of grass regarding the relevance of including infrastructure, this study did not address the effects of capital goods and their end-of-life. Furthermore, code for the LCA model is enclosed (Supplementary file B). It must be noted that transportation of RG from the verges to the treatment facilities has been cut off from the system since it is common for all scenarios. However, based on the MooV optimisation model (de Meyer, 2023), transport distance from the verges to the treatment facility is estimated to range between 1.6-2.1 km per tonne of mowed roadside grass (de Meyer et al., 2021).

Table 1. Salient features of the life cycle inventory. For additional information, refer to the supplementary material

Unit process	**Input/output**	**Scenario**			**Unit**
		S1	**S2**	**S3**	
		Value			
Composting					
Inputs	***Mowed grass (Functional unit)***	**1000**	742.00	4235.28	**kg**
	machine operation, diesel, >= 74.57 kW, low load factor	0.35	0.35	0.35	hour
	Water	123.33	91.51	522.34	litres
	Electricity	50.00	37.10	211.50	kWh
Outputs					
	Compost	495	367.29	211.76	kg
Emissions	*CO_2*	64.12	43.48	2498.82	kg
	NH_3	0.35	0.22	270.46	kg
	N_2O	0.08	0.05	1.16	kg
	CH_4	2.09	1.41	0.48	kg
	CO	0.24	0.16	2.53	kg
Field Application					
Inputs	Compost	495.00	367.29	2498.82	kg
	Compost loading and spreading, by hydraulic loader and spreader	495.00	367.29	2498.82	kg
	inorganic Phosphorus fertilizer, as P_2O_5	-5.65	-5.65	-29.00	kg
	inorganic Potassium fertilizer, as K_2O	-10.00	-10.00	-29.00	kg
	inorganic nitrogen fertilizer, as N	-1.96	-1.39	-17.09	kg
	transport, freight, lorry >32 metric ton, EURO6	49.50	36.73	499.76	t-km
Outputs					
Emissions	*CO_2, biogenic*	223.22	105.08	409.80	kg
	N_2O	0.03	0.03	0.26	kg
	NO_3^-	0.52	0.52	5.28	kg
	CO_2, seq	-21.96	-31.39	-21.57	kg
Mono-digestion					
Inputs	***Mowed grass (Functional unit)***		**1000**		***kg***
Outputs					
	Biogas		96.40		m^3
	Digestate		752.00		kg
	Leachate		0.05		m^3

Emissions	*Fugitive* CH_4		0.58		m^3
Co-digestion					
Inputs	***Mowed grass (Functional unit)***			**1000**	**kg**
	Raw pig manure			3117.64	kg
	Solid fraction pig manure			1176.46	kg
Outputs	Biogas			97.38	m^3
	Digestate			4235.28	kg
Emissions	Fugitive CH_4			0.58	m^3
Alternate 'obw' management					
	Modified ecoinvent process “treatment of biowaste”			549.47	kg
Avoided landspreading					
	Pig manure			-3117.64	kg
	Solid fraction of pig manure			-1176.46	kg
Combined heat and power production (For scenarios S2a and S3a)					
Inputs	Biogas		94.47	94.85	m^3
Outputs	electricity, high voltage		224.93	225.83	kWh
	heat		1159.94	1164.55	MJ
	internal use		869.95	873.42	MJ
	supply to district heating		289.98	291.14	MJ
Purification to biomethane (For scenarios S2b and S3b)					
Inputs	Biogas		94.47	94.85	m^3
Outputs	biomethane, high pressure		61.41	61.65	m^3
	natural gas, high pressure, import from RU		-61.40	-61.65	m^3

2.3. Life cycle impact assessment

The impacts were quantified using the Environmental Footprint methodology (EF) and the LCA was modelled using Brightway2 and Activity Browser. Results from midpoint indicators were normalised and weighted to represent the best- and worst-case scenarios through a single score. Impact categories that together contributed to at least 80% of the overall scores were identified as the most relevant (Zampori & Pant, 2019). Finally, the contribution analysis and uncertainty for the relevant impact categories for all the scenarios are presented. The uncertainty analysis was performed using a dependent sampling approach, wherein all scenarios under comparison were sampled using the same technology and biosphere matrices for a given FU (Cucurachi et al., 2022).

3. Results

The time series for OBW processing at anaerobic digesters in Flanders showed an increasing trend (further information in the supplementary material). This implies that the digesters in the future can cater to the marginal increase in feedstock availability. Therefore, the marginal technology for OBW that replaces an equivalent amount of RG during the co-digestion scenarios is AD.

3.1. Overall impacts

Figure 2 illustrates the overall impacts of the various scenarios after normalization and weighting in accordance with the PEF. Scenario 1 represents composting of RG, Scenario 2 represents the mono-digestion of RG whereas Scenario 3 represents the co-digestion of RG with pig manure. The sub-scenarios ‘a’ and ‘b’ (for Scenarios 2 and 3) represent biogas valorisation in a combined heat and power unit (CHP) and biogas purification to biomethane respectively. Composting, i.e. Scenario 1, appears to have the highest net impact (-3.16E-03) when compared to mono-digestion, i.e. Scenario 2 (2a: -1.17E-02; 2b: -1.05E-02) and co-digestion, Scenario 3 (3a: -4.13E-02; 3b: -3.83E-02).

The majority of the burdens in Scenario 1 (composting) are a consequence of climate change potential and terrestrial eutrophication potential (contributing to 34% and 3% of the total impacts respectively). These burdens are mostly offset by benefits due to freshwater ecotoxicity potential and resource use as fossils (contributing to 40% and 13% of the overall impacts).

The pattern is identical for Scenario 2a (mono-digestion with CHP valorisation of biogas) and Scenario 2b (mono-digestion with biomethane recovery from biogas). Here the burdens resulting from climate change potential (16% of the total impacts for 2a and 20% for 2b) and terrestrial eutrophication potential (2% of the total impacts for 2a and 2b) are outweighed by the benefits resulting from freshwater ecotoxicity potential (50% of the total impacts for 2a and 2b), resource use as fossils (6% and 10% of the total impacts for 2a and 2b) and resource use as minerals (18% and 11% of the total impacts for 2a and 2b).

For Scenarios 3a (co-digestion with CHP valorisation of biogas) and 3b (co-digestion with biomethane recovery from biogas), the burdens from marine eutrophication potential (2% of the total impacts for 3a and 3b), ionising radiation potential (0.16% of the total impacts for 3a and 0.19% of the total impacts for 3b) and land use (1% of the total impacts for 3a and 3b) were offset by the benefits due to the rest of the impact categories (climate change potential, freshwater ecotoxicity potential, freshwater eutrophication potential).

The following section analysed the outcomes for the most relevant impact categories based on this criterion.

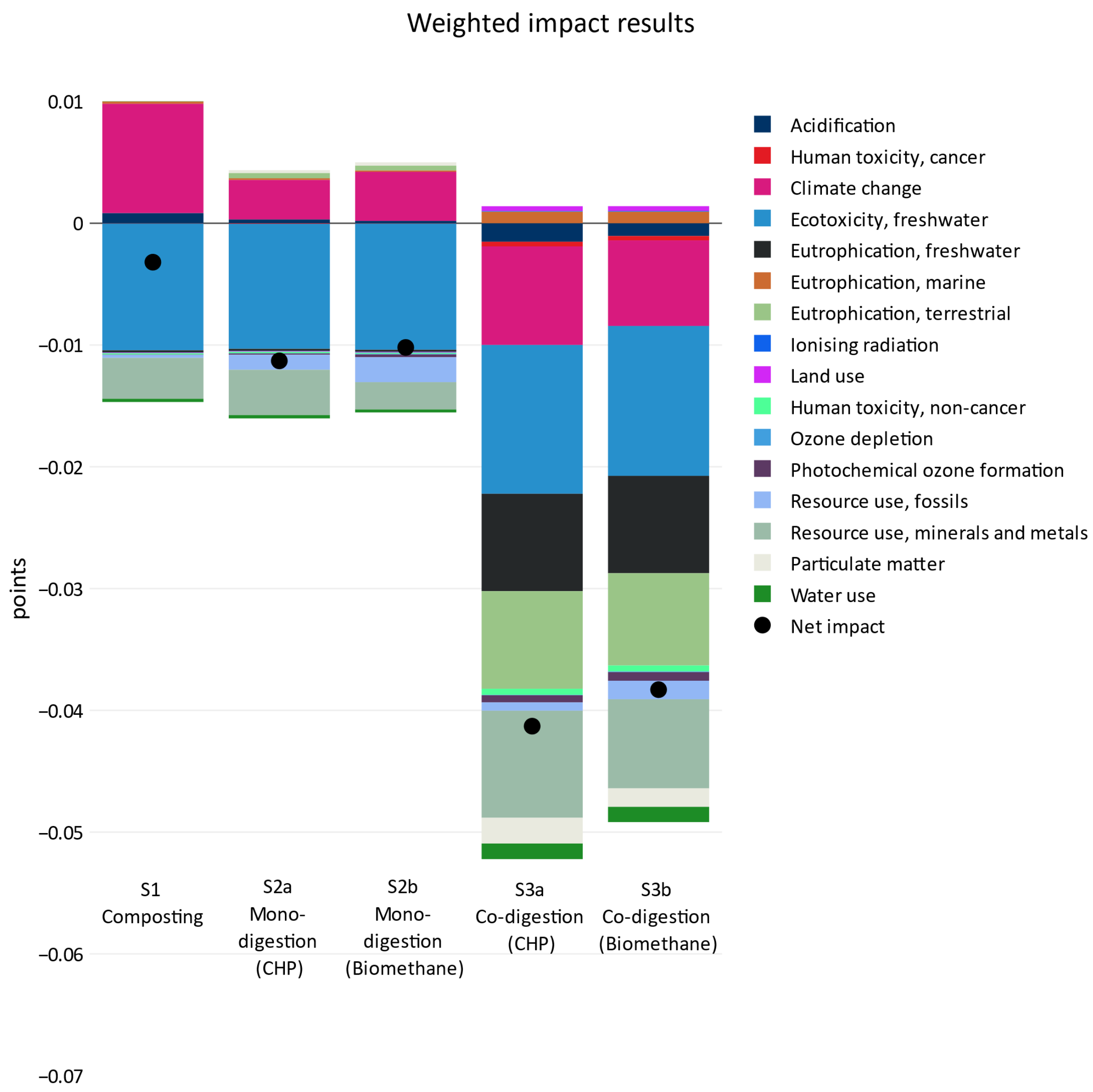


Figure 2. Overall impact score after normalization and weighting per functional unit, i.e. processing of mowed roadside grass

3.2. Most relevant impact categories

This section presents the overall impacts (Figure 3) and contribution analysis (Table 2) for the most relevant impact categories. The bar charts in Figure 3 depict the mean value, while the error bars represent the uncertainty. Specifically, Scenario 1 pertains to composting of RG, Scenario 2 refers to mono-digestion of RG, and Scenario 3 involves co-digestion of RG with pig manure. The sub-scenarios 'a' and 'b' in Scenarios 2 and 3, respectively, depict the valorization of biogas in a combined heat and power unit (CHP) and the purification of biogas into biomethane.

In Table 2, the values that are enclosed in brackets denote environmental burdens, while those without brackets indicate environmental benefits. The processes categorized as 'technosphere' refer to the electricity and auxiliary usage, while the 'biosphere' processes pertain to the emissions released into the environment.

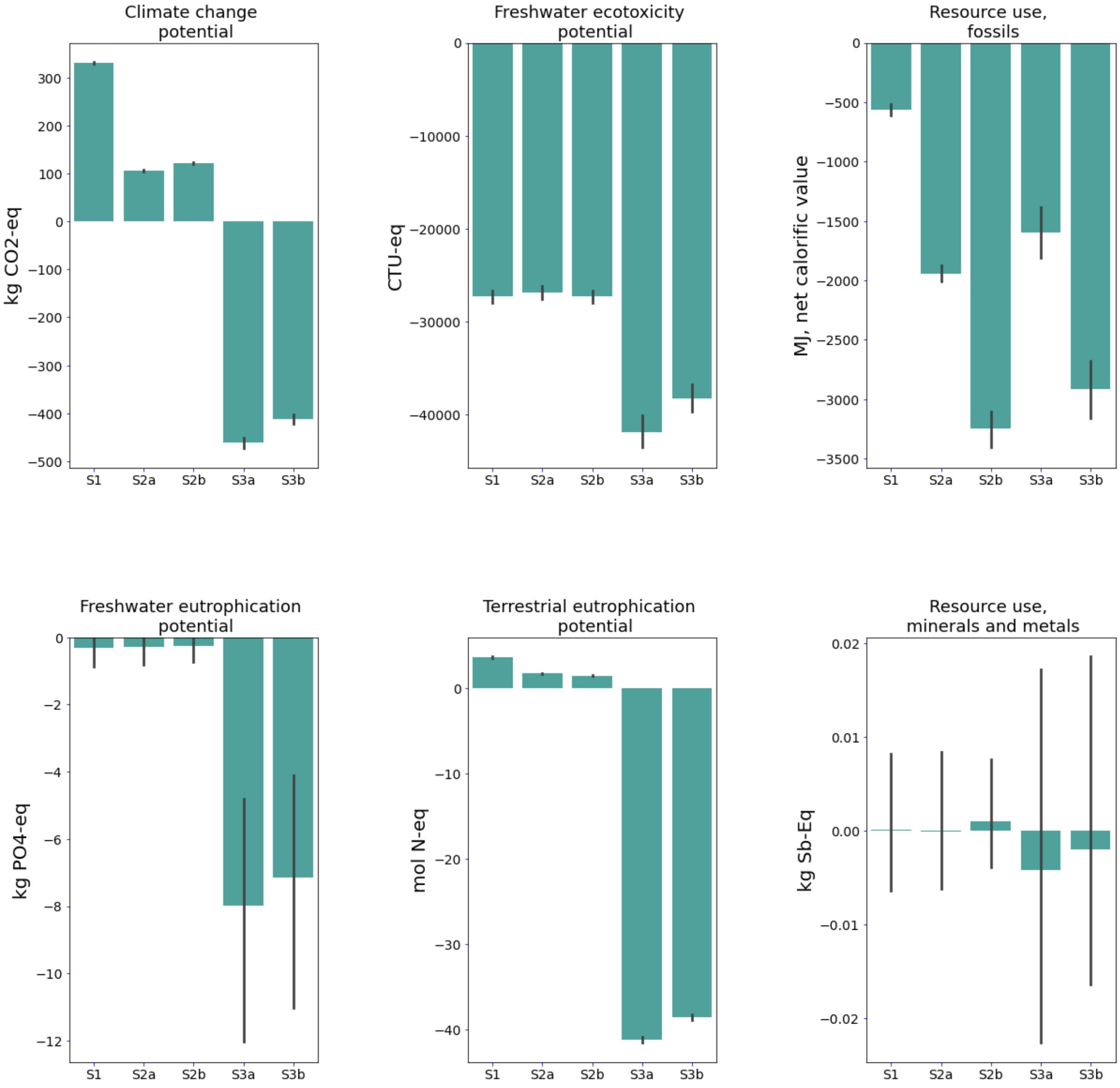


Figure 3. Overall impacts for the most relevant impact categories per functional unit, i.e. processing of mowed roadside grass after 1000 Monte Carlo runs.

3.2.1. Climate change potential

For climate change, the mono-digestion (Scenario 2a: 107.57 and 2b: 127.69 kg CO_2-eq) and co-digestion scenarios (Scenario 3a: -427.29 and 3b: -380 kg CO_2-eq) appeared to have a lower impact compared to composting (Scenario 1: 333.63 kg CO_2-eq). The high burdens in Scenario 1 were a consequence of biogenic emissions during composting (CO_2 and CH_4) as well as field application (CO_2 and N_2O), which contributed to 40% and 47% of the overall impacts respectively (Table 2). On the flip side, the environmental benefits from

Scenario 1 included C sequestration (-21.96 kg CO_2) due to compost application as well as avoided NPK fertilizer.

The impacts due to climate change potential were roughly three times lower in the case of mono-digestion compared to Scenario 1 (i.e. RG composting). This can be attributed to the biogas recovery and the ensuing benefits from valorising the biogas. The burdens during mono-digestion include fugitive emissions from the digester, accounting for around 21 kg CO_2-eq. Furthermore, the treatment of leachate, a by-product from mono-digestion, contributed to 4.8 CO_2-eq. The digested fibres from mono-digestion caused environmental burdens due to biogenic emissions from the composting stage. Impacts from field application of the composted fibres included biogenic emissions, which contributed to 23% of the overall impacts for Scenario 2. These burdens are partially offset by avoided NPK fertilizer (14%) as a consequence of field application. The amount of CO_2 sequestered, however, was higher in Scenario 2 (-31.39 kg CO_2-eq) in relation to Scenario 1 (-21.96 kg CO_2-eq) and this could be attributed to the higher C by N ratio in the composted fibres after mono-digestion.

As far as the comparison of sub-scenarios for mono-digestion is concerned, valorising biogas through CHP (Scenario 2a) appeared to have lower climate change potential (-63.40 kg CO_2-eq) when compared to biogas purification (Scenario 2b) through membrane technique (-35.85 kg CO_2-eq). Emissions during CHP contributed to 5.59 kg CO_2-eq but these burdens were offset by avoided use of electricity (-60.50 kg CO_2-eq) and natural gas (-8.49 kg CO_2-eq) due to electricity and heat production respectively. Although the production of biomethane offsets the impacts of avoided natural gas import from Russia (-51.18 kg CO_2-eq), these environmental benefits were reduced due to the electricity needed to purify the biogas (9.82 kg CO_2-eq) and emissions during purification (9.23 kg CO_2-eq). A deeper analysis of the climate change potential for electricity revealed that 55% of the impacts were due to electricity production in a combined cycle power plant that used natural gas (Table 2).

Compared to mono-digestion and composting, the environmental savings due to climate change potential in the co-digestion scenarios (Scenario 3a and 3b) can mainly be attributed to avoided conventional management of raw pig manure (-486.13 kg CO_2-eq) and solid fraction of pig manure (-616.47 kg CO_2-eq), which, without being subject to digestion, would be field applied. Therefore, RG plays an intrinsic role in improving the anaerobic digestion of manure by balancing its C/N ratio. Mono-digestion of manure would otherwise require energy-intensive pre-processing to reduce inhibition during biogas production (Vergote et al., 2020), causing a negative environmental externality. The primary environmental benefits from manure digestion instead of conventional management are the avoided CH_4 emissions during storage (-566.11 kg CO_2-eq for raw PM and 656.27 kg CO_2-eq for the solid fraction of PM). Also, the avoided transport of solid fraction of PM (-21.08 kg CO_2-eq) showed greater environmental benefits owing to a larger transport distance when compared to raw PM (-13.93 kg CO_2-eq). Other savings include the avoided use of manure-spreading equipment (-11 kg CO_2-eq). These savings are offset by the need to use synthetic NK (41 kg CO_2-eq and 41.81 kg CO_2-eq) and synthetic PK (23.32 kg CO_2-eq and 41.81 kg CO_2-eq) in lieu of raw pig manure and solid fraction of PM, which are redirected for co-digestion.

Alternate management of OBW waste, as a consequence of being displaced by RG during co-digestion, also showed environmental benefits, owing to it being digested (-26.27 kg CO_2-eq). Furthermore, the sub-scenarios concerning biogas valorization in Scenario 3 showed a similar trend to Scenario 2 for climate change potential, i.e. valorizing biogas in a CHP engine has a lower climate change potential (-65.77 kg CO_2-eq) when compared to biomethane recovery (-36.08 kg CO_2-eq). This can be attributed to emissions (9.26 kg CO_2-eq) as well as electricity use (9.86 kg CO_2-eq) during biomethane recovery.

The composting stage in Scenario 3 had the highest potential climate change impact (583.4 kg CO_2-eq) when compared to Scenario 1 (180.3 kg CO_2-eq) and Scenario 2 (125 kg CO_2-eq). This can be attributed to the volume of digestate (4.2 tonnes) per FU that has to be processed in Scenario 3 as opposed to 0.49 tonnes in Scenario 1 and 0.74 tonnes in Scenario 2, where RG is solely processed. Owing to the higher volume of digestate in

Scenario 3, there is a proportional increase in C and N content, leading to an increase in biogenic CO_2 and N_2O emissions (499.52 kg CO_2-eq). However, because of the higher nutrient contents in the ‘composted’ digestate as supplemented by raw PM and solid fraction of PM, approximately half of the burdens from composting are offset by the benefits due to avoided NPK fertilizer (-241.74 kg CO_2-eq) during Scenario 3.

3.2.2. Freshwater ecotoxicity potential

Freshwater ecotoxicity potential is represented by Comparative Toxic Unit for ecosystems (CTUe) and the characterisation factors quantify the potential toxicological impact of chemicals on the freshwater ecosystem. The toxicity calculations were recently updated in the EF method and more information is available in Sala et al. (2022).

For freshwater ecotoxicity, the co-digestion scenarios (Scenario 3a: -37,654 CTUe and 3b: -34,423 CTUe) performed better relative to Scenario 1, i.e. composting (-26,063 CTUe) and Scenario 2 mono-digestion (Scenario 2a: -25,338 CTUe and 2b: -25,956 CTUe). The environmental benefit regarding freshwater ecotoxicity in all scenarios is mainly a consequence of avoided K fertilizer production due to the field application of compost (Table 2). A deeper analysis of the impact contribution of K fertilizer revealed that around 79% of the CTUe was caused by potassium chloride production. Besides the benefits due to avoided K fertilizer, the treatment of the marginal feedstock, i.e. AD of OBW, contributed to a lower overall CTUe in the co-digestion scenarios (Scenario 3a and 3b) (Table 2).

3.2.3. Resource use, fossils

For fossil resource use, the scenarios with biomethane recovery, i.e. Scenario 2b (-3104 MJ) followed by Scenario 3b (-2835 MJ), outperformed Scenarios 2a (-1902 MJ), Scenario 3a (-1575 MJ) and Scenario 1 (-514 MJ) (Figure 3).

The high fossil resource use savings in Scenarios 2b (73% of the total score) and 3b (24% of the total score) are a direct consequence of biomethane recovery from biogas and its subsequent injection into the grid (Table 2). This, in turn, reduces the import of natural gas from Russia. In Scenario 2a, in which the biogas from mono-digestion is valorised through a CHP, the fossil fuel savings are lowered by 46% when compared to 2b since natural gas is only partially substituted for the heat generated from the CHP (-403 MJ). Also, electricity production from the CHP helped offset 927 MJ, mostly due to avoided electricity production from combined cycle power plants processing natural gas. The co-digestion scenarios (Scenario 3) followed the same trend as Scenario 2, with Scenario 3b (i.e. biomethane recovery) outperforming Scenario 3a (valorisation through a CHP).

The contribution analysis identified that the composting process in all three scenarios was a hotspot in terms of fossil resource depletion, which was primarily due to diesel consumption and electricity use (Table 2).

3.2.4. Freshwater eutrophication potential

Freshwater eutrophication potential is represented in the form of PO_4 emissions since P is considered to be the limiting factor in freshwater environments. Scenario 3 had the lowest overall score (3a: -7.97 kg PO_4-eq and 3b: -7.14 kg PO_4-eq) compared to Scenario 1 (-0.30 kg PO_4-eq) and Scenario 2 (2a: -0.28 kg PO_4-eq and 2b: -0.26 kg PO_4-eq), albeit with high uncertainty. This can mostly be attributed to the treatment of the marginal feedstock, i.e. OBW displaced by RG.

3.2.5. Terrestrial eutrophication potential

Terrestrial eutrophication potential is characterised by NH_3 and N_2O emissions to the air since N is the limiting factor. While Scenario 1 (3.64 mol N-eq) and Scenario 2 (2a: 1.75 mol N-eq; 2b: 1.45 mol N-eq) had an overall positive score and caused an environmental burden, Scenario 3 resulted in a net environmental benefit (3a: -41.22 mol N-eq; 3b: -38.65 mol N-eq) (Figure 3).

The hotspot analysis revealed that the composting stage contributed majorly to potential terrestrial eutrophication impacts for all scenarios (79% for Scenario 1; 65% for Scenarios 2a and 2b; 21% for Scenarios 3a and 3b) (Table 2). In absolute terms, the composting stage in Scenario 3 had the highest potential terrestrial eutrophication impacts (16.11 mol N-eq) among all scenarios (Scenario1: 4.71 mol N-eq; Scenario 2a and 2b: 3.11 mol N-eq). This could be attributed to the NH_3 emissions (1.16 kg NH_3 per FU) during composting for the co-digestion scenarios as opposed to 0.22 kg NH_3 for the mono-digestion scenarios and 0.35 kg for the baseline, i.e. composting. The higher NH_3 emissions in Scenario 3 are due to the increased N content in digestate due to co-digestion with manure. However, these burdens were offset by avoided storage emissions during conventional management of PM and solid fraction of PM, contributing to 37% and 29% respectively (Table 2).

3.2.6. Resource use, minerals and metals

The mineral and metal resource use are an indicator of abiotic depletion potential. It is the ratio of the annual production and the square of the ultimate (crustal content-based) reserve for the resource divided by the same ratio for a reference resource (antimony; kg Sb-eq). Although it appears that the co-digestion scenarios (3a and 3b) outperform mono-digestion and composting, the results are characterised by high uncertainty (Figure 3).

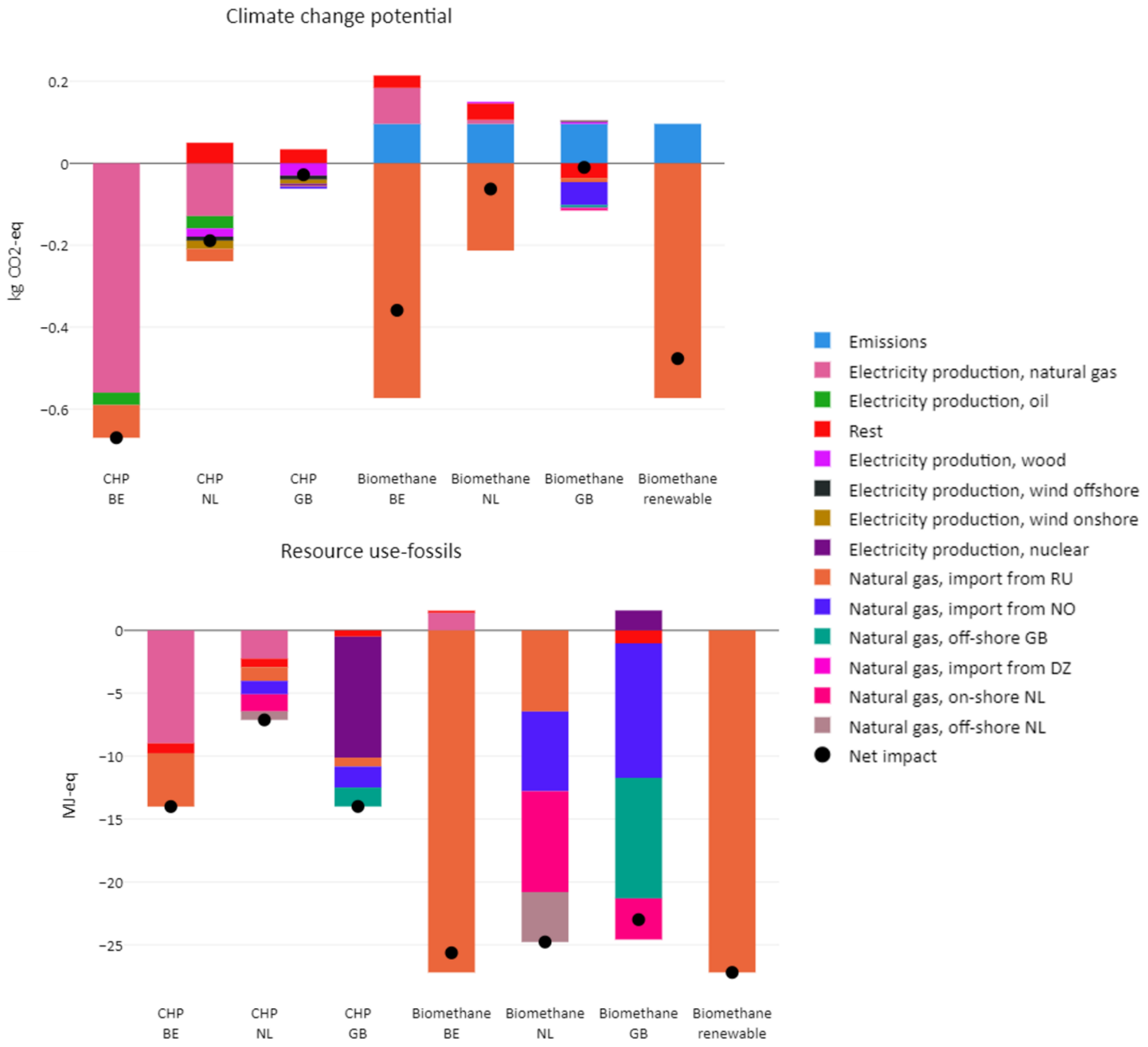
Table 2. Contribution analysis of different scenarios for selected impact categories. Values with brackets represents environmental burdens and values without brackets represents environmental benefits

Unit process	Activity	Climate change potential			Freshwater ecotoxicity potential			Resource use, fossils			Terrestrial eutrophication potential		
		S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Composting	*Technosphere*	(5%)	(5%)	(3%)	(1%)			(28%)	(11%)	(13%)	(3%)	(3%)	(1%)
	Biosphere	(35%)	(30%)	(17%)	(0.2%)						(79%)	(65%)	(21%)
Mono-digestion	*CHP*		21%			(3%)	(1%)		57%	13%		8%	
	Biogas purification		21%			(3%)	(1%)		73%	24%		8%	
Avoided PM management	*Technosphere*			(4%)			(21%)			(19%)			
	Biosphere			20%									37%
Avoided SF PM management	*Technosphere*			(3%)			(20%)			(13%)			
	Biosphere			23%									29%
Marginal feedstock management	*Anaerobic digestion of food waste*			(1%)			(15%)						(4%)
Co-digestion	*CHP*			(2%)									

	Biogas purification			(2%)									
Field application	*Biosphere*	47%	23%	16%									
	P fertilizer	(3%)	(4%)	(2%)	(10%)	(10%)	(8%)	(16%)	(5 - 8%)	(8-9%)	(4%)	(5%)	(2%)
	K fertilizer	(7%)	(8%)	(3%)	(85%)	(86%)	(33%)	(38%)	(11-18%)	(12-14%)	(11%)	(14%)	(3%)
	N fertilizer	(2%)	(2%)	(3%)	(3%)	(1%)	(2%)	(12%)	(3-4%)	(10-11%)	(3%)	(3%)	(2%)
	Rest	1%	1%	2%				6%	1-2%	7-8%	1%	1%	1%

3.3. Performance of Combined heat and power units versus biogas upgrading techniques in the selected parts of Northwest Europe

The performance of CHP in the context of both mono- and co-digestion outscored biomethane recovery for climate change potential whereas, for fossil resource use, the trend was reversed (Figure 4). To understand the regional impacts of valorising 1 m^3 of biogas, the environmental performance of a CHP versus biomethane recovery was compared for different regions within the scope of this study, i.e. Belgium (BE), Netherlands (NL) and Great Britain (GB) (Figure 4).



Climate change potential

Resource use-fossils

Figure 4. Climate change potential and fossil resource use for valorising 1 m³ of biogas via CHP versus biomethane. "Biomethane renewable" considers electricity from wind energy to facilitate biomethane recovery. The country acronyms include-'BE'-Belgium; 'NL'-the Netherlands; 'GB'-Great Britain; 'NO'-Norway; 'RU'-Russia; 'DZ'-Algeria

For climate change potential, it appears that valorising biogas in BE performs the best either through a CHP (-0.67 kg CO_2-eq) or biomethane recovery (-0.35 kg CO_2-eq), followed by NL (CHP: -0.18 kg CO_2-eq; Biomethane recovery: -0.06 kg CO_2-eq) and GB (CHP: -0.028 kg CO_2-eq; Biomethane recovery: -0.01 kg CO_2-eq) respectively. The lower net score in BE with regard to climate change potential can be attributed to the avoided use of natural gas and its import from long-distance pipelines from Russia. This is in contrast to NL and GB, where the potential climate change savings are much lower owing to (i) reduced reliance on natural gas-powered combined cycle power plants (natural gas constitutes 14% of the total electricity mix for NL as opposed to 45% for BE) or a nuclear power based electricity mix (25% of the total electricity for GB) and (ii) reduced reliance on natural gas imported from Russia due to local production (for instance NL and GB sources 46% and 34% of its total natural gas needs locally). Furthermore, it was demonstrated that transitioning to a 100% renewable electricity mix from the conventional Belgian electricity mix to power biomethane recovery improves the potential climate change score by 35%.

For fossil resource use, it was evident that biomethane recovery (BE: -25.64 MJ-eq; NL: -24.78 MJ-eq; GB: -23 MJ-eq) is beneficial to the environment as opposed to CHP valorisation (BE: -14.01 MJ-eq; NL: -7.11 MJ-eq; GB: -14 MJ-eq) in all the three regions (Figure 4).

4. Discussion

A scopus indexed search with the keywords 'LCA', 'mono-digestion' and 'co-digestion' yielded 18 hits. Among these, six (Boscaro et al., 2018; De Vries et al., 2012; Hamelin et al., 2014; Jiang et al., 2021; Tsapekos et al., 2019; Zhang et al., 2021) could be partially compared with ours since they focused on mono-digestion and co-digestion of manure, albeit with different substrates such as silage grass, food waste or roadside grass.

Jiang et al. (2021) compared conventional management of food waste (a combination of composting and anaerobic digestion) and pig manure (direct land application) versus co-digestion of food waste and pig manure. Their LCA concluded that co-digestion of pig manure with food waste showed environmental benefits for all categories except acidification and eutrophication, which was a consequence of high ammonia emissions during co-digestion owing to mineralization of organic N during co-digestion. Zhang et al. (2021)identified that co-digestion of pig manure with additional organic waste materials improves the environmental sustainability of anaerobic digestion processes compared to mono-digestion of pig manure alone and the environmental impact of digestate application depends on various factors, including the nutrient content of the digestate, application rates, timing, and weather conditions. Proper management practices, such as optimizing application rates and timing based on crop nutrient requirements and soil conditions, are crucial to minimize potential environmental risks.

From an environmental standpoint, previous research (Boscaro et al., 2018; De Vries et al., 2012; Hamelin et al., 2014) identified that co-digestion of RG with manure is beneficial relative to mono-digestion and composting. De Vries et al. (2012) compared co-digestion of manure and maize versus manure and other waste/by-product residues (beet tails, wheat yeast concentrate, RG) and included the counterfactual scenarios for the by-product residues within the system boundaries. They identified manure co-digestion with RG (with avoided composting as the counterfactual treatment pathway for RG) to be the most sustainable alternative in terms of climate change, acidification, eutrophication and particulate matter potentials. Similar to our study, the major contributions to their net score were from substituted NPK as well as avoided emissions during conventional manure storage and application. Hamelin et al. (2014), in a similar study, compared the environmental consequences of manure co-digestion with maize versus manure co-digestion with different

C-rich side streams (straw, household and commercial food wastes, garden waste) and solid fraction of pig manure. Amongst the co-digestion scenarios in their study, garden waste (which partly contained RG) had the best environmental performance. Boscaro et al. (2018), who evaluated different logistical approaches to grass harvested on riverbanks, also reported improved environmental performance regarding fossil depletion and GHG emissions. For biogas end-use, all these studies considered valorization in a CHP, except Tsapekos et al. (2019), who concluded that CHP production is an environmentally friendly alternative when compared to biomethane recovery The aforementioned studies primarily focused on manure management or silage grass management and the results from this study, whose FU was to manage RG, corroborated that co-digestion of RG is an environmentally friendly alternative relative to the status-quo, i.e. composting as well as mono-digestion of RG. However, the reason for the enhanced performance of the co-digestion scenario for RG is due to benefits from avoided conventional management of pig manure (mostly due to storage) and OBW displaced by RG.

As far as biogas yields are concerned, the experiences from the pilots showed that the difference in biogas yield between mono-digestion (96.4 ± 72.3 m^3/ tonne fresh matter of RG) and co-digestion (97.38 ± 33.98 m^3/ tonne fresh matter of RG) was marginal. Nevertheless, high uncertainties of biogas yields were obtained during both mono-digestion and co-digestion, which can be attributed to operational challenges. During mono-digestion, due to the relatively large dimensions of the cell (volume: 1750 m^3), the monitoring of pH, temperature, gas flow and composition was sub-optimal and not necessarily representative of the whole system (Adriaens et al., 2021). Also, the possible settlement of biomass during digestion entails a risk of fugitive CH_4 emissions since the tensions can cause the seals to detach. The operational challenges during co-digestion were due to motor malfunction, thereby affecting the monitoring period and subsequently the data quality (Miserez et al., 2021).

Taking into consideration the operational challenges or limitations encountered during mono-digestion and co-digestion in this work, future LCA studies could possibly factor in a mechanical or thermal pre-treatment step of RG and its effects on the biogas yield. Furthermore, other LCIA indicators such as biodiversity and the crustal scarcity indicator to identify critical raw materials can be possibly incorporated.

The study also identified that the net environmental impacts of biogas valorization for the digestion scenarios, be it CHP recovery or biogas purification to biomethane, was dependent on the substituted electricity and energy/heat and their marginal supplier in certain parts of Northwest Europe. In Belgium and the Netherlands, which have natural gas-dependent electricity mixes, CHP seemed to score better over biomethane recovery in terms of climate change potential, whereas in Great Britain, whose electricity mix is not reliant on natural gas-powered power plants, the difference was marginal. For fossil resource use, however, it appeared that all three regions were conducive to biomethane recovery, owing to avoided imports or local extraction of natural gas. Florio et al. (2019), who compared different biogas upgrading techniques, also concluded that CHP has a better environmental performance over biomethane recovery in all impact categories except fossil resource use. In contrast, Alengebawy et al. (2022) concluded that biomethane recovery was more environmentally sustainable over CHP and biogas valorization in boilers, but their system boundaries only encompassed the process-based emissions (i.e. a gate-to-gate analysis) and not the effects due to substituted electricity and heat.

While waste feedstocks such as roadside grass and agro-residues are a constrained resource, this study validated the views of Lodato et al. (2022) that emissions from conventional management pathways are still higher when compared to anaerobic digestion as an intermediate step. Furthermore, we identified that, despite the trade-offs in environmental impacts between climate change potential and fossil resource use for CHP and biomethane recovery, it is evident that any form of biogas recuperation and valorization is imperative given the current political climate and its impact on EU energy security.

According to McWilliams et al. (2021), natural gas consumption in the EU ranges between 346-470 billion m^3 per annum, with weekly demand ranging between 6-8 billion m^3. Current natural gas imports to the EU (as of week 38 in 2022) stand at 309 billion m^3, with Russian imports (i.e. via Nord Stream, Yamal, Ukraine and Turkstream corridors) contributing to 19% of the total share of imports. This contrasts with 2021, when the imports from Russia stood at 36% of the total share. This gap in supply (~59 billion m^3) is currently being met by an increase in liquid natural gas (LNG) imports as well as natural gas imports. Despite this solution, the EU may be unable to meet 25% of the peak winter demand for gas if imports from Russia are completely suspended (Acatech, 2022). This can be attributed to a lack of transmission infrastructure (pipeline and LNG terminal capacity). Until the infrastructure is expanded to completely offset Russian imports, the EU can utilize residual waste streams to produce bioenergy and for member states, such as Belgium or Germany, whose electricity mix is highly reliant on natural gas-fired power plants, using nuclear energy and/or coal as a stop-gap may help until the step-up to a predominantly renewable energy-based electricity mix is possible. Also, from a Belgian context, this study identified that valorizing residual heat from CHP via district heating networks has the potential to not only reduce natural gas consumption but also mitigate the associated burdens from conveyance of natural gas via long-distance pipelines.

5. Conclusion

Based on the life cycle assessment (LCA) conducted, the findings suggest that co-digestion of roadside grass (RG) with manure offers the most environmentally sustainable approach for managing RG in Northwest European regions, compared to the baseline case of composting. Composting RG alone contributes significantly to biogenic CO_2 emissions, while RG mono-digestion poses environmental challenges due to fugitive emissions and leachate treatment.

Considering the current geopolitical landscape in the energy sector, the processing and utilization of waste biomass, such as RG, play a vital role. In regions heavily reliant on natural gas-based electricity mix, combined heat and power generation emerged as a favourable option in terms of mitigating climate change potential. However, for the efficient utilization of fossil resources, biomethane recovery takes precedence.

In conclusion, the study underscores the environmental advantages of co-digestion as a sustainable approach for managing RG, emphasizing the need for strategic energy planning and utilization of waste biomass to address energy security concerns in the EU and Northwest Europe.

Supplementary information

The supplementary material is categorised into

A: Life cycle inventory: *Life Cycle Inventory.xlsx*

B: LCA code: M*anuscript.ipynb*

Other data files will be made available upon request.

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CRediT

Rahul Ravi: Writing-original draft, Conceptualization, Data curation, Methodology, Visualization, Software

Marcella Fernandes de Souza: Conceptualization, Supervision, Review & Editing

Anne Adriaens: Data curation

Ruben Vingerhoets: Data curation, Review & Editing

Hongzhen Luo: Data curation, Review & Editing

Miet Van Dael: Data curation, Review & Editing

Erik Meers: Review & Editing, Supervision, Project administration, Funding acquisition

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