The International Journal of Life Cycle Assessment (2026) 31:9
https://doi.org/10.1007/s11367-026-02590-8

LCA OF WASTE MANAGEMENT SYSTEMS

From waste to circularity: the potential of different treatments of poultry manure and forestry residues in a hot-spot production region in Portugal

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Received: 29 July 2025 / Accepted: 2 December 2025

Abstract

Purpose The management of biogenic residues in a way that extends the lifetime of carbon within the systems is a focus of the present work. Different waste management systems are assessed in terms of GHG emissions and removals, aiming to identify that with the lowest impact on climate change.

Methods A life cycle comparative analysis is performed, assessing the mitigation of the impact on climate change of the current waste management system (A) of the top two residues of a Portuguese region – composting of poultry manure and open air burning of forestry residues – considering two bioenergy solutions: biochemical conversion of poultry manure and thermochemical conversion of wood residues (B); biochemical conversion for both residues together (C), implying fungal pre-treatment of the wood residues, which adds a food product to the supply chain. Data were retrieved from literature and from authors' experimental work. Assumptions underlying the methodological framework (e.g., cut offs inherent to comparative assertions) are discussed. A sensitivity analysis covers uncertainties underpinning bioenergy systems assessments (e.g., unperfect substitution and rebound effect phenomena).

Results and discussion The highest impact on climate change is observed with system A, greenhouse gas (GHG) emissions 2 to 3 times higher than those of the other two systems. System A also performs poorly in conserving the biomass, e.g., forestry residues burning results in carbon being directly released to the atmosphere with no valuable intermediate use. In the base scenario, system B results in the lowest GHG emissions of the three systems, producing biochar, which contributes to carbon sequestering, and biodiesel. Nevertheless, system C can result in the lowest GHG emissions, in a scenario considering unperfect substitution with renewable sources being selected to match the biodiesel supply of system B.

Conclusions System A is least preferable among the three options. Between systems B and C, ranking depends on whether unperfect substitution is considered. System B performs better in all scenarios, except with unperfect substitution, where system C outranks B. Moreover, system C achieves a higher yield of digestate, a product providing other ecosystem services. Thus, in future research, the inclusion of other impact categories in LCA can reveal a better overall environmental performance for system C.

Keywords Biomass management · Biomass cascading use principle · Bioenergy systems · Life cycle assessment · Comparative assertion

Communicated by Giovanni Mondello

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1 Introduction

To accelerate the reduction of greenhouse gas (GHG) emissions in a sustainable way, biomass, a renewable but limited resource, should be used in cascading and circular production systems (European Parliament and of the Council 2023). For the implementation of such systems, technology applications are required, together with policy strategies which emphasise a hierarchy of biomass uses where materials and food have priority over energy. The use of biogenic residues, instead of energy crops, as feedstock for bioenergy has been gaining increasing attention, since it does not imply competition for land, fertilisers or water (Osman et al. 2021). Thermochemical and biochemical processes are well established technology options, which could be combined in biorefinery approaches for biogenic residues conversion. These approaches avoid the burdens of bioenergy feedstock production and deliver substitutes for certain goods, also alleviating the burdens of their production (Cherubini and Jungmeier 2010). The choice between thermochemical and biochemical conversion routes depends on multiple factors, such as environmental guidelines, legal frameworks, economic conditions and desired energy carriers, but mainly on the type of biomass (McKendry 2002). Biochemical conversion processes are more suitable for feedstocks with high moisture content (MC) and anaerobically biodegradable organic content, while thermochemical conversion processes are suitable for feedstocks with low MC and high lignocellulosic content, which is hard to decompose by the microorganisms involved in biochemical conversion processes (Yokoyama and Matsumura 2008).

Additional challenges may need to be overcome for the chosen technology. For example, chicken manure is suitable for anaerobic digestion (AD) due to its high anaerobically biodegradable organic content, but its also high ammonia content can inhibit the acetoclastic methanogenesis step of the process (Henze et al. 2000). Anaerobic co-digestion (AcoD) of this bioresidue with substrates with higher values of C: N ratio appears to improve process performance (Ward et al. 2008). On the other hand, AcoD entails its own challenges, the most obvious being an increase in the complexity of substrate management. The adequate operational conditions for the AcoD process may be hard to establish and maintain, for substrates with different MC levels and hydraulic retention time (HRT) requirements.

Forest residues, with its high C: N ratio, could be a complementary substrate in AcoD of poultry manure, but its low MC and high lignin content hinder its hydrolysis and thus render it unsuitable for AD. The latter problem can be overcome with a pre-treatment step, and an extensive review of pre-treatment options for lignocellulosic biomass for subsequent AD is presented by Hashemi et al. (Hashemi et al. 2021), including physical, thermal, chemical, biological and hybrid methods. For forestry residues, thermal pre-treatment methods are those reported to provide the highest increase in biomethane potential, since they break the structure of lignocellulose. However, they can cause the release of by-products inhibiting the subsequent AD, so hybrid methods (e.g., thermal-physical or thermochemical) are recommended to avoid this limitation. Biological pre-treatment methods also minimize the release of inhibitors, having the additional advantages of low energy consumption, low waste production and reduced downstream processing complexity (Hashemi et al. 2021). Moreover, when fungal pre-treatment is used, the necessary adjustment of MC to support mycelium growth, in addition to the breaking of the lignin structure, produces a substrate more suitable for AD. According to (Hashemi et al. 2021), the main setbacks of the fungal pre-treatment methods are the low reaction rate and consequent long residence time values, which increase process costs and space requirements, and introduce the need for substrate sterilisation to prevent the growth of competitor microorganisms. Nonetheless, because this method provides edible mushrooms, a food product that must otherwise be produced with associated GHG emissions, it can be seen as an emission credit instead of a burden.

GHG emissions are a key environmental performance indicator for production systems, and bioenergy systems are no exception. Even when using biogenic residues as feedstocks GHG emissions can occur at the successive stages of the energy production supply chain, and their quantity varies depending on multiple factors, such as those related to unit process layout and technological operating conditions. To assess the impact on climate change of biorefinery and bioeconomy systems, life cycle assessment (LCA) methods have been widely implemented. Several reviews on this subject have been published in peer-reviewed scientific journals, e.g., the review of 100 LCA on bioenergy (Agostini et al. 2020), that of 40 LCA on biofuels (Osman et al. 2021), and that of 83 LCA on bioeconomy (Talwar and Holden 2022). An LCA methodology is thus also applied in the present work, with a Portuguese region (the region of Lafões) as case study and three different waste management systems as a study object.

1.1 The study object

The biomass and bioenergy potential of the biogenic residues of the region of Lafões was characterized in (D'Espiney et al. 2023), considering a system with two separate routes, i.e., the biochemical and thermochemical conversion routes. The biogenic residues of Lafões are mainly poultry manure and forestry residues (jointly representing 92%, 98 kt of dry matter(DM) in a total of 107 kt DM) and so one of the system specifics has to do with the feedstock characteristics, in particular the moisture content heterogeneity between residues, which led to the consideration of two conversion routes. However, the GHG emissions associated to the system were not assessed in (D'Espiney et al. 2023) and this is a useful contribution for the discussion.

To investigate the implications on GHG emissions of considering different operational conditions can also enrich the discussion. As explained in detail by Bridgwater (Bridgwater 2012), pyrolysis processes can be tuned to deliver either more materials or more energy. To optimize it for materials recovery (operation at low temperature and heating rate), implying a higher yield of biochar and lower direct energy yield, may result in a better performance in terms of carbon balance due to the properties of the biochar, e.g., carbon sequestration and reduction of fertilizer use (Bridgwater 2012). However, the system as designed in (D'Espiney et al. 2023) is considered for the present study, namely optimized for energy delivery with a lower biochar yield.

In pursuit of solutions to reinforce the biomass cascading use principle, a system that uses only the biochemical conversion route will also be considered here. Such system may not be suitable for both biogenic residues of Lafões (specifically, it is unsuitable for the forestry residues), but adds a product to the supply chain because it also delivers a substrate for edible mushroom cultivation, which should be considered given the latter's increasing worldwide demand (Robinson et al. 2019). On the other hand, according to (D'Espiney et al. 2023), biochemical conversion routes have a higher chance of being implemented faster, because in the region of Lafões there is more investment capacity along this route. This is because the disposal of poultry manure (suitable for the biochemical conversion route) is a responsibility of private entities with more capacity for the required investments, while non-profit organizations with scarce financial resources are in charge of forestry residues (suitable for the thermochemical conversion route). Moreover, there are challenges in the biochemical conversion route that can be met using integrated flows, as explained in the introduction.

The credits and burdens of these two systems, one considering the two conversion routes and the other relying only on the biochemical conversion route, will be quantified through a comparative assertion (as defined in (Joint Research Centre: Institute for Environment and Sustainability 2010) using the LCA method. In addition, both systems will be compared to the regional management system currently applied to the same residues. Therefore, the study object consists of three systems, for which the main inflows and outflows are depicted in Fig. 1. The systems can be summarized as follows: the current management system representing traditional disposal processes (system A); the system foreseen by the bioenergy potential assessment presented in (D'Espiney et al. 2023), where single flows go through two independent bioenergy conversion routes (biochemical and thermochemical), providing energy, nutrients and soil amending materials (system B); a system that goes beyond that foreseen in (D'Espiney et al. 2023), where flows are regarded as complementary and integrated in a single bioenergy conversion route (biochemical), accompanied by a food production process that adds the edible mushroom value to the supply chain (system C).

In sum, the present LCA framework will be structured aiming at a better understanding of how to improve the regional biogenic residues management system, focussing on the following research questions: Is there a potential for mitigation of the impact on climate change of the current waste management system, when bioenergy solutions are considered? Does a bioenergy system that uses two independent conversion routes (thermochemical and biochemical) have a better performance, in terms of the balance of GHG emissions and removals, than a bioenergy system with only one route (biochemical) that also supplies a food co-product, but requires a pre-treatment stage?

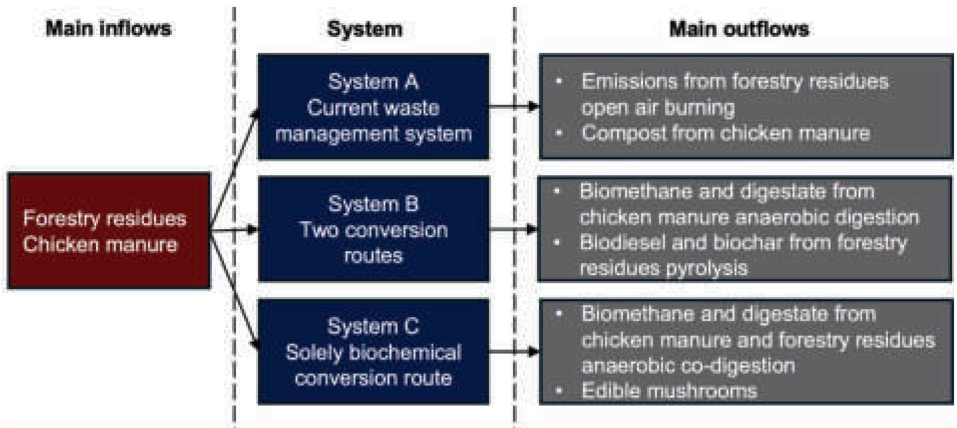

Fig. 1 Systems overview: main unit processes, inflows (same for all systems) and outflows (different in all systems)

2 Methods

The setup of the environmental assessment for the analysed systems follows guidelines from the relevant LCA ISO standard 14067:2018 (International Organization for Standardization 2018), which addresses the quantification and reporting of the carbon footprint of a product system, in line with standards ISO 14040:2006 (International Organization for Standardization 2006a) and the ISO 14044:2006 (International Organization for Standardization 2006b).

2.1 Goal definition

Intended Application. The goal of the present work is to investigate GHG emissions as the central impact category of a comparative LCA of the three management systems for biogenic residues. Climate change has several climate forcers, but it is a common practice to assess it by quantifying only well-mixed GHG (WMGHG), i.e., CO_2, CH_4, and N_2O, neglecting near-term climate forcers (e.g., aerosols and ozone precursors), and biogeophysical forcers (e.g., surface albedo and evapotranspiration). It was the practice in 82 of 90 studies recently reviewed which analyse climate change impacts (Agostini et al. 2020), and it will be adopted here too, yet acknowledging a non-compliance with the completeness principle of LCA studies. It is crucial to acknowledge the significant climate and health impacts of black carbon (BC) emissions. BC is recognised as a major short-lived climate pollutant with a remarkably high global warming potential, 210–1500 fold higher than that of CO_2 over a 100-year period (Agostini et al. 2014). Despite these important impacts, BC emissions are not considered in official greenhouse gas inventories and climate protocols, according to IPCC methods. Quantifying their warming effect is technically challenging due to the wide variability in global warming potential values and the various influencing factors. For these reasons, while BC emissions deserve thoughtful attention and efforts to minimise them can yield immediate climate and health benefits, their inclusion in the numerical analysis of this study is neither feasible nor methodologically robust. Moreover, when focusing on only one impact category, environmental issues other than climate change are overlooked, preventing the use of the results as sole component of a decision-making process.

Reasons for carrying out the study. Concerns with the unsustainability of the processes currently applied to treat forestry residues (open air burning) were expressed by the Associação de Desenvolvimento Rural de Lafões (ADRL), a non-governmental organization certified as a forest management entity responsible for forest management units in the region of Lafões, who commissioned the present study. The need for optimization of the waste management system for livestock production was communicated by the Directorate-General for Food and Veterinary (DGAV), a public entity responsible for the inspection of livestock production and for enforcing the law among producers. These were the main reasons for the implementation of the present study.

Intended audience. The results of the study are to be communicated not only to the two entities mentioned above, but also to any regional or non-regional entity struggling to achieve sustainable standards in forestry and livestock residues management systems. Additional intended audiences are regional decision makers pursuing sustainable solutions for their biogenic residues management systems or producers pursuing optimization of their production process.

2.2 Scope definition

Product systems to be studied. Three waste management systems to treat the two most relevant biogenic residues produced in the region of Lafões, forestry residues and poultry manure, are subjected to comparison. System A corresponds to the current waste management system that uses composting to handle poultry manure and applies open air burning to forestry residues, generating a single product, the chicken manure compost. System B is the one foreseen in (D'Espiney et al. 2023), where both biochemical and thermochemical conversion routes are implemented (anaerobic digestion and pyrolysis, respectively), to handle the poultry manure and forestry residues, respectively. The anaerobic digestion route delivers as co-products biomethane and digestate, while the pyrolysis delivers biodiesel and biochar. System C adopts the biochemical conversion route (anaerobic co-digestion) to handle the two biogenic residues as a joint flow, delivering biomethane and digestate as co-products, as well as the edible mushroom added value as a result of the pre-treatment of the forestry residues before anaerobic digestion.

Main function, *functional unit and reference flow of the product systems.* The main function that the systems need to perform is to treat the two biogenic residues, and the reference flow is defined as one item handled by the systems. That one item enters the systems as two untreated biogenic residues in the mass proportion reported in (D'Espiney et al. 2023), i.e., 63% of forestry residuesand 37% of poultry manure, ad leaves the systems as two treated residues. The functional unit is defined as one item of waste (1 kg dry matter (DM) of forestry residues and 0.6 kg DM of poultry manure) treated at least complying with the minimum requirements as stated in (European Parliament and of the Council 2018a).

Decision context. The decisions are expected to affect only the regional foreground activities, having no impact on market mechanisms and being incapable of triggering structural changes in installed capacity elsewhere in the background.

Systems boundaries. The geographical system boundary is the joint administrative borders of the three municipalities comprising the region of Lafões, namely Oliveira de Frades, São Pedro do Sul and Vouzela, located in the district of Viseu in Portugal. Of the three stages usually included in the supply chain of bioenergy systems, i.e., biomass production, conversion and end-use, only biomass conversion/treatment processes and end-uses are considered within the foreground system boundaries, for the reasons explained in section dedicated to the cut-off criteria below. The main unit processes in the foreground are depicted already in Fig. 1 and are summarized as follows: system A includes forestry residues open air burning (and poultry manure composting, but this is not taken into account in the LCI, due to the reasons explained in the cut-off discussion below); system B considers forestry residues pyrolysis, poultry manure anaerobic digestion and end-use of biomethane, biodiesel, digestate and biochar; system C consists in forestry residues pre-treatment, pre-treated forestry residues and poultry manure anaerobic co-digestion and end-use of biomethane and digestate (and mushrooms, but they are not taken into account in the LCI, due to reasons explained in the cut-off discussion below). Besides these main processes in the foreground, other processes must be imported from the background system, which are introduced next.

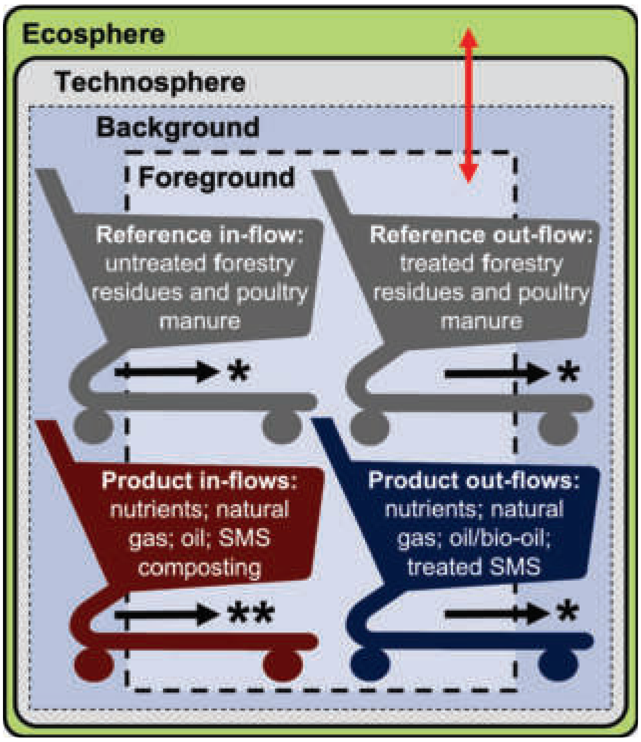

Fig. 2 The mandatory equality of the systems for comparison purposes, illustrated by shopping trolleys, as suggested in [22]. Black arrows: product/waste flows. Red arrow: elementary flows. * The flows are the same for all the systems. ** The flows are different between systems. SMS: spent mushroom substrate

Multifunctionality of the product systems. The analogy used by Fleischer (Fleischer and Hake 2002) for comparison purposes, where systems are assumed to be shopping trolleys containing the same type and quantity of goods, only then capable of being compared, leads to the endorsement of the multifunctionality issue. Systems can deliver goods other than those that they are meant to (e.g., energy or food), while performing the function they have to fulfil (e.g., to treat one item of the waste). This is the case of systems B and C. The issue is solved by expansion of the systems that do not deliver the same co-products, thus adding to their regional foreground system (to the "trolley of the system") the burdens associated with the production of food, energy or nutrients by non-regional background activities. To illustrate this premise, that of the equality of the systems for comparison purposes, the different flows are depicted as shopping trolleys in Fig. 2. The reference flow, illustrated by the grey trolley, must be the same for all systems and is entering the systems as two untreated biogenic residues which are leaving the systems already treated. The co-product outflows (food, energy and nutrients), resulting from the multifunctional character of systems B and C, must also be the same for all systems and are illustrated by the blue trolley. The product (or service) inflows (related to food, energy or nutrients provision), that the systems need to import from outside their regional foreground, in order to match all systems in terms of product outflows, are different for every system and are depicted by the brown trolley.

System A will have to take into account the indirect burdens of background activities associated to the external provision of all co-products of systems B and C (food, energy and even nutrients, since composting was cut-off for the reason presented below in the cut-off criteria section), because it does not generate any of these. Both systems B and C have as co-products biomethane and nutrients and, therefore, only the one that produces less of each will have to consider background activities to fulfil the gap. To match the co-product that only system B produces, the biodiesel, indirect burdens are also to be taken into account in systems A and C, since they do not produce it. Regarding the co-product that only system C produces, the edible mushrooms, systems A and B have to import them from background activities, in order to deliver that product as well. Nevertheless, only burdens related to the spent mushroom substrate (SMS) are considered, for the reasons explained in the cut-off section below. Regarding the SMS treatment, indirect burdens from SMS composting background activities are considered in systems A and B, while in system C SMS treatment burdens are allocated to the energy production in AD. Regarding SMS application, it was set as similar whether in the form of digestate or compost and therefore cut-off, for the reasons explained in the cut-off section below. Regarding transportation, whenever is needed, all systems must envision background services.

Therefore, to provide the entire basket of goods (grey and blue trolleys of Fig. 2), each system sees the system boundary expanded adding different background activities (brown trolley of Fig. 2). Figure 3 depicts the different background activities that were added to the foreground with the expansion of each system (in brown rectangles), as well as the foreground activities (in blue rectangles). The product/service inflows imported by each foreground are illustrated with grey, yellow and orange arrows, for systems A, B and C, respectively. The product outflows are represented by black arrows and the elementary flows (of direct and indirect burdens) are represented by the red arrows. A list of the several co-products from the three systems, synthesizing how they are managed and the reasoning behind the latter, is presented in Table 1.

Cut-off criteria. Figure 3 does not depict similarities between the systems. In systems comparisons, it is accepted, as a cut-off criterion, not to take into account the burdens of the activities that are equal in all systems. For example, the foreground of systems A and B needed to be expanded with the necessary background activities in order to provide the edible mushrooms, since only system C produces it as co-product. Nevertheless, only the SMS treatment (composting and transportation activities) was added to their foreground. This is because it is considered that systems A and B also use residues as substrate for mushroom cultivation and have the same cultivation, distribution and final use processes. The three systems will have to take into account the same burdens from substrate production, and mushroom cultivation, distribution and final use processes, the burdens not varying between the systems. A note is due to the variation of the impact on climate change among mushroom provision processes, depending on substrate used, and the type of mushrooms and cultivation and distribution techniques (e.g., 1.98 kg CO_2e/kg mushroom resulted from a cradle-to-market LCA (Dorr et al. 2021) and 4.42 kg CO_2e/kg mushroom resulted from a cradle-to-farm gate LCA (Leiva et al. 2015). Regarding the substrate used for mushroom growing, in (Dorr 2021) a sensitivity analysis compares the use of spent coffee grains (SCG) with the use of wheat straw. The conclusion is that the use of straw has 5% less impact on climate change, albeit acknowledging that the farm-level scope of the LCA did not allow the modelling of other benefits, such as the diversion of SCG away from incineration. In another study (Robinson et al. 2019), compost is considered as substrate for mushroom growing, but GHG emissions factors for composting are used regardless of the raw material and the technique used for composting. To avoid such simplifications, and since there is no reasonable impediment to consider the same substrate, forestry residues are considered for all three systems in the present study. The same reasoning is applied in all other production stages, namely, the same processes and respective techniques are considered for cultivation, distribution and final use stages in the three systems. Therefore, they have the same burdens and can be cut-off. It must be highlighted that the purpose of this study is not to compare different types of mushroom provision processes, but rather to do a comparison of the overall performances of three systems. When expanding the systems to ensure the same outcomes from all systems, it is a viable option to consider the exact same processes for the system expansion.

Still, systems A and B have compost from SMS as end-product, while in system C the SMS ends up in the digestate.

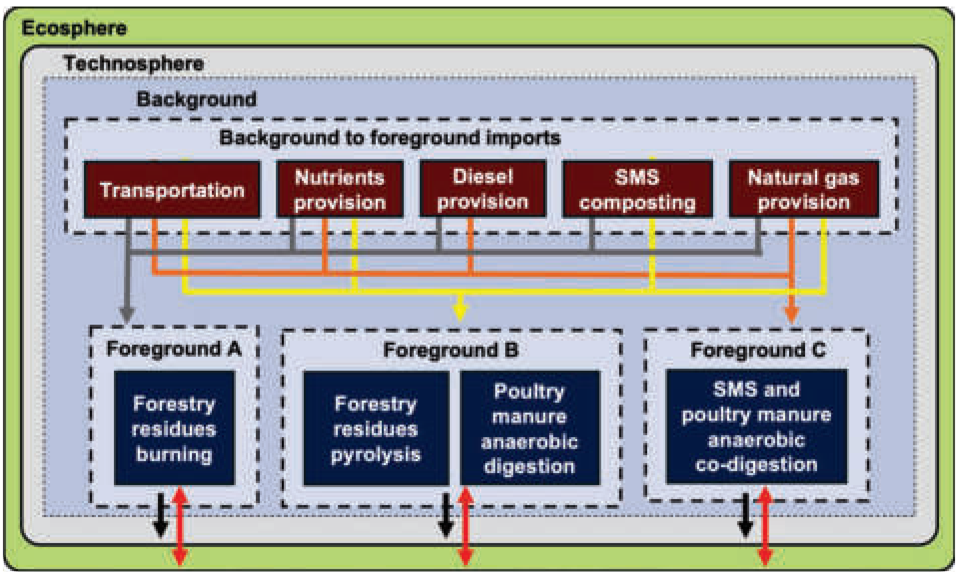

Fig. 3 Systems boundaries. Blue rectangles are foreground activities and brown rectangles are background activities. System expansion for system A, B and C foregrounds is achieved by importing from the background the products/services and associated indirect burdens, represented by grey, yellow and orange arrows, respectively. Black arrows: product/waste flows. Red arrows: elementary flows. SMS: spent mushroom substrate

Table 1 – Co-products allocation methods and reasoning supporting them

Co-product	Allocation method (system)	Reasoning
Poultry manure compost	System expansion (B, C) and cut-off (A, B,C)	Indirect burdens from background activities are allocated to systems B and C to match the co-product poultry manure compost of system A. Nevertheless, the same unit processes are considered, and the burdens are the same in the three systems, therefore, cut-off is applied.
Forestry residues treated	Direct accounting (A) or allocation to other co-product (B, C)	Direct burdens from forestry residues open air burning are allocated to system A. In systems B and C, the emissions of the forestry residues treatment are allocated to their energy production.
Biochar	Production: allocation to other co-product (B); Application: substitution (B)	The emissions of the biochar production in system B are allocated to its energy production process. The carbon sequestration and the reduction in fertilizer needs, resulting of its application, are subtracted from the system.
Biodiesel	Direct accounting (B) and system expansion (A, C)	Direct burdens are accounted in system B due to biodiesel provision. To match it, systems A and C are expanded with allocation of indirect burdens from diesel provision (in the sensitivity analysis, diesel and renewables provision) of background activities.
Biomethane	Direct accounting (B, C) and system expansion (A, B or C)	Direct burdens are accounted in systems B and C due to biomethane provision. To match it, systems A and B or C (depending on which produces less) are expanded with allocation of indirect burdens from natural gas provision (in the sensitivity analysis, natural gas and renewables provision) of background activities.
Digestate	Production: allocation to other co-product (B, C) and system expansion (A, B or C); Application: cut-off (A, B,C)	Direct burdens of the digestate production are allocated to the energy production in system B and C. To match the nutrients in the digestate application, systems A and B or C (depending on which produces less) are expanded and indirect burdens from nutrients provision of background activities are allocated to them. Burdens from application are set as similar and cut-off is applied.
Edible mushrooms	Production: system expansion (A, B) and cut-off (A, B,C); SMS treatment: direct accounting (A, B) and allocation to other co-product (C); SMS application: cut-off (A, B,C)	Systems A and B were expanded to provide edible mushrooms too. The unit processes substrate provision, growing, distribution and end-use are set as equal and cut-off was applied. Direct burdens associated to composting of SMS are allocated to systems A and B. In system C, treatment burdens are allocated to the energy production. Burdens from application are set as similar and cut-off is applied.

Regarding the proper process chain up to application, AD enables reduced emissions and higher nutrient efficiency, when optimally managed. However, management and process choices can cause wide variations in emission risks, nutrient losses and nitrogen efficiency in both AD and composting. Composting can also ensure low emissions with appropriate aeration, C/N ratio, and spreading techniques, despite it typically results in slightly higher NH_3 and N_2O emissions. Due to the wide management related variations in both processes, a good management for both is assumed, justifying a similar treatment in the assessment. The application of digestate and compost are thus set as similar, as both entail the degradation of easy biodegradable carbon substrates, while releasing more stable compost or digestate to be used as organic fertilizers. Therefore, the balance of emissions associated to the application of digestate and compost from SMS are cut-off.

Poultry manure composting is the current treatment process in the region (system A) and again the cut-off criterion was applied. It is assumed that the poultry manure compost outflow of system A is a demand of the market that must be fulfilled. Consequently, systems B and C would have to expand their system boundaries considering background activities in order to deliver it too. Nevertheless, the exact same unit processes are considered for the three systems and (same) burdens do not affect the results of a comparative assertion. Thus, they do not have to be taken into account in the inventory of any system.

The LCA completeness principle implies the consideration of all stages of the supply chain, and for bioenergy conversion systems this means the stages of biomass production, bioenergy conversion and end-uses. Nevertheless, production of the biomasses has no burdens associated to it, since it is considered that biogenic residues fully reached their end-of-waste state and, as secondary material/fuel, are free of environmental burdens, in accordance with the Environmental Product Declaration (EPD International 2021). Even if not, biomass production activities are the same for the three systems and the burdens are thus equal, not affecting the results of the comparison.

Data quality. The data related to the biomass production stage, i.e., the biomass potential of the region, were taken from the previously mentioned biomass potential assessment of the region (D'Espiney et al. 2023) and represent specific data, also referred to as "primary data" or "study-specific data" (EPD International 2021), since it was measured within the system. Because no burdens from the cultivation or breeding are to be taken into account, only the amount of biomass was needed. The biomass transportation process is covered by the non-regional background and therefore generic data (also referred to as secondary or average data (EPD International 2021) are used to quantify the indirect burdens.

In what concerns data related to energy production, generic data from third party sources and not directly measured are usually used (Fazio et al. 2013). For system A, that does not consider bioenergy conversion of the biogenic residues, average data are considered for the emissions to air associated to the forestry residues burning process. To match the energy supply of systems B and C, system A takes into account background activities, where generic data are used to quantify emissions associated to raw material extraction, processing and distribution. For system B that considers the two specific bioenergy conversion systems suggested in (D'Espiney et al. 2023), primary data from that source on the energy yield are used. To the knowledge of the authors, no data are available for the energy yield of the bioenergy conversion system adopted in system C and specific data must be produced. To achieve that, an experimental assay was performed to provide the energy yield of system C and the operational conditions are presented in supplementary material (SM). System C therefore uses specific data on a solution with a Technology Readiness Level (TRL) of 4, i.e., technology validated in the laboratory, according to the classification in (European Commission 2011). The idea that, to be a study object of an LCA, a technology must be developed up to pilot scale (Talwar and Holden 2022), can be questioned. If the results of the preliminary LCA are not favourable, resources spent on TRL development could be saved. To account for the burdens associated to the bioenergy provision of systems B and C, generic data are used to quantify emissions associated to processing, upgrading and distribution.

In what concerns co-products other than energy, for the nutrients delivered by systems B and C, the lowest value of nutrient content of the feedstocks, as reported in the literature (namely, (Borowski and Weatherley 2013) and (Ruangjanda et al. 2022) was used. For the biochar's capacity to reduce fertilizer needs, a review (Matuštík et al. 2020) of several pyrolysis experiments was consulted and the values with the highest statistical evidence were considered. The lowest value of the carbon sequestration capacity of the biochar, as found in the literature (Granatstein et al. 2009), was considered. All the parameters relative to co-products other than energy are therefore quantified using primary data. The burdens associated to the digestate and biochar production are allocated to the energy production stage.

Regarding the energy end-use of the three systems, generic data are used to take into account the combustion of the energy vectors of each system. These were natural gas and diesel in the systems that need to match the energy-product of systems B or C, biomethane in systems B and C and biodiesel in system B. Regarding data related to the end-of-life of SMS, they are addressed in systems A and B with generic background data for composting. Because in system C the burdens associated to SMS treatment are allocated to the bioenergy provision processes, no data were needed.

In short, the WMGHG emissions associated to the several processes included in the three systems are quantified using specific data whenever possible, or generic data when the efforts to measure specific data are not justified. All WMGHG emissions are described in detail in Sect. 2.3 (the life cycle inventory).

Life cycle impact assessment. The impact of every flow on climate change, the single midpoint impact category selected, will be quantified in Sect. 2.4, where the life cycle impact assessment (LCIA) is reported. Regarding the biogenic carbon flows, products from biomass are being dealt by the studied systems and, according to ISO 14,067, carbon removal by the agricultural soils and forest systems (soil plus carbon stock in wood) should be accounted for. Since the biomass (forestry residues and manure) used for the energy products in this study consists of residues from forest and agricultural systems, the carbon removal is allocated to the main product of the biomass cultivation/production process and is not taken into account during the LCIA. Regarding the substrate for mushroom cultivation, all three systems use residues so the carbon removal is again allocated to the main product of the biomass cultivation/production. The biogenic carbon released in the products' end-use is taken into account in every system, namely burning of forestry residues (system A), biomethane (system B and C) and biodiesel (system B). The end-use of the SMS is addressed in systems A and B through composting, and in system B through anaerobic digestion. The digestate and compost are set as similar (for the reasons introduced in section cut-off criteria above) and, therefore, the emissions released from digestate and compost from SMS are cut-off. Regarding fossil carbon flows, emissions and removals during all stages are considered. Unlike that recommended in ISO 14,067, fossil and biogenic GHG emissions and removals are not documented separately, since the goal of the present assessment is to compare the overall impact of the systems on climate change.

The climate change impact has, as indicator, the infrared radiative forcing increase in units of W/m^2 and, as common characterization factor, the Global Warming Potential (GWP) expressed in kg of CO_2 equivalent (CO_2e) emissions to air. In the present LCA study, the time boundary considered is 100 years and the ecoinvent IPCC 2021 GWP 100 impact assessment method was selected and implemented with software OpenLCA version 2.2.0. Nevertheless, the method was adjusted to Directive 2018/2001 by changing the characterization factors of CH_4 and N_2O as suggested in (European Parliament and of the Council 2018b) (25 kg CO_2e/kg CH_4 and 298 kg CO_2e/kg N_2O).

Sensitivity analyses. The completeness, sensitivity and uncertainty checks, as tasks of the interpretation phase, are key factors to guarantee comprehensive, coherent and meaningful results. For example, for addressing the multifunctionality of processes, the ISO standards recommended that system expansion should be prioritised to avoid allocation. Nevertheless, the expansion is often built on subjective choices and done considering perfect substitution of the product replaced (Agostini et al. 2020). In the LCA practice, bioenergy tends to substitute fossil fuels, when there is competition with other renewables or energy sources, which must be considered in a sensitivity analysis or reported as a limitation.

In the interpretation of the results, presented in Sect. 6.3.2, sensitivity analyses will be carried out considering unperfect substitutions of the goods. The replacement of the bioenergy goods will be done not only by fossil fuel in an alternative scenario, but also by 42.5% of renewables, aiming at the share of the Renewable Energy Directive for 2030 (European Parliament and of the Council 2023). In another alternative scenario, the replacement of the bioenergy goods will also be done partially to take into account the rebound effect, replacing only 80% of them, the lower end value suggested in (Semmling et al. 2016) The sensitivity analyses will also consider the limitation of using data from a technology with a low TRL and assume 50% less and more of the energy production level achieved in the exprimental assay. The transportation process, for which a less emission-efficient fleet was first selected taking a conservative approach, is also submitted to a sensitivity analysis, upgrading it to a more modern fleet. A final sensitivity analysis is dedicated to the substitutability of bioenergy products for fossil fuels. Since the emissions are associated to the production and end-use of each energy vector considered in the employed emission factors (see SM), engine efficiency can still raise questions. Therefore, a scenario with a 5% lower efficiency of the biodiesel engine is considered, assumingthe engine efficiency range in (Zhang et al. 2022). The substitutability of biomethane for natural gas is not submitted to a sensitivity analysis, since their engine efficiency is accepted as similar (Olofsson et al. 2014).

2.3 Life cycle inventory

This section is explanatory of the several processes included in each of the defined systems, with their flows and data sources considered for the life cycle inventory (LCI). All the flows are quantified per functional unit (/fu), the latter being one item of waste (1 kg DM of forestry residues and 0.6 kg DM of poultry manure). As mentioned above, the elementary flows quantified in this LCA study are only the WMGHG emissions and emissions from upstream activities (up from cradle) are included, except for biomass cultivation (reasons also mentioned above). All processes, their elementary and their product/waste outflow amounts are presented in summarizing tables in SM and will be explained in the following paragraphs. The parameters and equations used in the calculations are also presented in SM. In the sensitivity analysis, the rebound effect and unperfect substitution of the bioenergy goods are considered, as well as different energy yields from system C, so the flows vary in their amounts, which are also presented in the annexed summarizing table.

System A. According to the scope definition, system A has originally only one foreground process, specifically the one considered for dealing with the forestry residues flow, the open air burning process. The forestry residues flow (1 kg DM of forestry residues/fu) is produced at the same location where the treatment process takes place, so no collection process is required. It is considered that the burning process has no upstream activities associated to it and no other flows are generated, besides the elementary flows associated with the burning of biomass itself. To quantify these elementary flows, average data from a temperate forest burning process, as presented in (Andreae 2019), are used.

Also according to the scope definition, five background processes had to be assigned to the regional foreground of system A to match the product/service outflows of the other systems. To match the bioenergy outflows produced by system B, i.e., 0.8 kWh/functional unit (fu) of biomethane and 2.5 kWh/fu of biodiesel (for the bioenergy amounts of system B, see features of system B below), natural gas and diesel provision within the European background context is considered and the associated indirect burdens are taken into account by adopting the generic data provided in (European Commission 2023). The same data source is used for the renewable energy provision, required for performing the sensitivity analysis considering the case in which fossil fuels only replace 57.5% of the bioenergy producs.

To match the nutrient outflows generated by system C (1.5E-02 kg N/fu, 1.1E-02 kg P_2O_5/fu and 4.1E-02 kg K_2O/fu), average global background data from the market context of nitrogen, phosphate and potassium fertilizer provision are used, taken from the Ecoinvent database version 3 (Wernet et al. 2016). From the Portuguese national inventory report on greenhouse gases (Pereira et al. 2024), generic data from composting of biowaste are obtained, to match the SMS treatment service provided by system C (1.9 kg fresh matter (FM) of treated SMS/fu). For the transportation of the substrate to the mushroom cultivation facility and of the SMS to the composting facility (1.86 kg FM/fu), the European background context is considered and generic data from the Ecoinvent database version 3 (Wernet et al. 2016) are used. Regarding the substrate for mushroom cultivation, a central location of the cultivation facility is assumed, the substrate being collected within a radius of up to 100 km around it, resulting in 186 kg.km/fu, i.e., 1.86 kg FM of substrate/fu transported along 100 km. Regarding the disposal of this 1.86 kg FM of SMS/fu, transportation to a composting facility in Tondela it assumed, located at a distance to the mushroom facility of 36.5 km, resulting in 67.9 kg.km/fu. Transportation with a lorry of 16–32 metric ton (EURO 3 emissions class) is considered, for which the indirect burdens are quantified with average European background data obtained from the Ecoinvent database version 3 (Wernet et al. 2016). For the sensitivity analysis, the same lorry size and data source is used, but the EURO 6 emissions class is considered.

System B. The scope of system B was defined as having two regional foreground activities, namely anaerobic digestion of poultry manure and pyrolysis of forestry residues, and three non-regional background activities, namely the transportation of forestry residues, poultry manure, substrate for mushroom cultivation and SMS, the provision of nutrients and the disposal of SMS.

The forestry residues flow (1 kg DM of forest residues/fu) goes across two unit processes, transportation and pyrolysis, located at the background and foreground, respectively. The background transportation process is as described for system A. To establish the travel distance a central location is assumed for the pyrolysis plant and, since the maximum geographical length of the region is 58.4 km, the flow assumes the value of 16.3 kg.km/fu, i.e., 1.1 kg FM of forestry residues transported an average distance of 14.6 km. The foreground process, pyrolysis, has two co-products, biodiesel and biochar. For quantifying the biodiesel produced by the pyrolysis process (2.5 kWh/fu), fast pyrolysis at 500 °C is selected, with a specific setup as described in (D'Espiney et al. 2023). It takes into account the yield and the LHV of the oil obtained from the two forest species most represented in the region, as well as energy losses during the conversion and oil upgrading steps. The parameters and equations used in the calculations are presented in SM. The emissions generated are quantified using the generic data provided in (European Commission 2023).

The biochar has recognized positive environmental impacts, e.g., soil amendment, increased nutrient availability and crop yield, sorption of pollutants, and reduced methane and N_2O emissions (Matuštík et al. 2020). With relevance for the present study and aiming at WMGHG emissions, carbon sequestration capacity and reduced fertilizer need will be considered, both of which vary with the type of substrate and pyrolysis process. Assuming a conservative approach, the lower end value of the ranges found in the literature was adopted for carbon sequestration, resulting in a credit of 0.3 kg CO_2 sequestrated/fu (calculated from (Granatstein et al. 2009). The capacity to reduce fertilizer needs was set at 10, 5 and 5% for N, P_2O_5 and K_2O, respectively, since thee were the most representative values in the review in (Matuštík et al. 2020). These figures were deducted from the total amounts needed to match fertilizer production in system C, which was the one delivering the highest amounts of nutrients. Pyrolysis also has syngas as a co-product, but since system B is that suggested in (D'Espiney et al. 2023), in which the process is optimized for biodiesel production, syngas production is negligible and is also not considered here.

The poultry manure (0.6 kg DM of poultry manure/fu) began to be collected from poultry production facilities to be delivered to an AD plant at the regional foreground, which is also assumed to have a central location in the region. The transportation process is that described for system A and the distance is that calculated for the pyrolysis of forestry residues, but since the corresponding FM amount is 0.8 kg/fu, the flow assumes a value of 11.8 kg.km. The amount/fu of generated biomethane considers the specific biogas potential of the feedstock and the methane content of the biogas. To quantify the energy losses during conversion and biogas upgrading, the operational conditions as described in (D'Espiney et al. 2023) are considered. Thus, the biomethane outflow assumes the value of 0.8 kWh/fu. To quantify the burdens of the anaerobic digestion processes, generic data from (European Commission 2023) for biogases are used.

The AD has digestate as a co-product, which is recognized as substitute for synthetic fertilizers. Its nutrient contents vary with substrate composition and the implemented technology. It is assumed that the amounts of nutrients in the feedstock are entirely transferred to the digestate, varying only in concentration. The lowest nutrient contents of poultry manure among those presented in (Borowski and Weatherley 2013) (the lowest values found in the literature) were considered. The resultant nutrient outflows/fu are

1.1E-02 kg N/fu, 10.0E-03 kg P_2O_5/fu and 7.2E-03 kg K_2O/fu. The burdens are allocated to the energy flow.

Regarding the non-regional background activities adopted to match the services outflows of system C, i.e., SMS disposal (1.9 kg FM/fu) and transportation of the substrate to the mushroom cultivation facility and of the SMS to the composting facility, the processes and data sources considered for system A were here adopted. For the activities adopted to match the product outflows of system C (the nutrients), the processes and data sources used in system A were again considered here. Even considering the reduction of fertilizer needs from using the biochar, the supply of nutrients provided by the AD process, system B will still have to import 2.0E-03 kg N/fu, 4.3E-04 kg P_2O_5/fu and 3.2E-02 kg K_2O/fu to match system C. When a higher biomethane yield is assumed for system C, system B needs to import 2.6E-01 kWh/fu of natural gas and the processes and data sources considered in system A are again adopted.

System C. System C originally counts with one activity in the foreground, namely the anaerobic co-digestion processes, and with three activities from the background, namely the transportation processes for forestry residues and poultry manure and two activities to match the product and services outflows of system B, namely diesel and natural gas provision.

In the regional foreground, the anaerobic co-digestion process generates two outflows to be taken into account, nutrients and biomethane. The amount/fu of biomethane is calculated from the results obtained in the experimental assays performed to provide data for the present study, the operational conditions of which are reported in SM. A biomethane potential value of 110.5 NL/kg DM was obtained, corresponding to 1.1 kWh/fu. The energy losses during conversion and biogas upgrading as suggested in (D'Espiney et al. 2023) are further considered, resulting in 0.7 kWh/fu of biomethane provision.

The nutrient amounts/fu supplied by the digestate from the AD are calculated using the same assumptions considered for system B. The nutrient contents of poultry manure as in system B are here considered. Nutrient contents of 3.2 g N/kg, 0.9 g P/kg, and 30.8 g K/kg are adopted for the SMS, from (Ruangjanda et al. 2022). The nutrient outflows/fu of system C take into consideration the proportion between the amounts of poultry manure and SMS, resulting in 1.5E-02 kg N/fu, 1.1E-02 kg P2O5/fu and 4.1E-02 kg K2O/fu. The burdens associated to these outflows are allocated to the energy flow. Because of the moisture content correction, a 169.5% increase in FM was reistered, meaning that the amounts of substrate for mushroom cultivation and of SMS which must be addressed by the other systems are also 1.9 kg FM/fu.

Regarding the non-regional background processes adopted to match the biodiesel (2.5 kWh/fu) and the biomethane provision (0.8 kWh/fu) of system B, the processes and data sources used in system A are here considered. Regarding the transportation of poultry manure and forestry residues, the process and flows used in system B (11.8 kg.km/fu and 16.3 kg.km/fu, respectively) are here assumed.

2.4 Life cycle impact assessment

The results of the assessment for the initial comparison (before any variations introduced in the sensitivity analyses) show that, system A is by far the one with more impact on climate change, generating CO_2e emissions 3 and 2 fold higher than those from systems B and C, respectively. The overall balance of CO_2e emissions and removals in system A is 1.9E+00 kg CO_2e/fu, while the values for systems B and C are 5.6E-01 kg CO_2e/fu and 8.5E-01 kg CO_2e/fu, respectively. Figure 4 shows the kg CO_2e/fu emissions and removals in each system, depicting also the contributions of the processes included in them.

Regarding system A, the process with the highest contribution is diesel provision, with almost half of the total emissions of the system (7.8E-00 kg CO_2e/fu; 41.9%). SMS treatment (3.3E-01 kg CO_2e/fu; 17.7%), nitrogen fertiliser provision (2.5E-01 kg CO_2e/fu; 13.6%), natural gas provision (2.1E-01 kg CO_2e/fu; 11.2%) and forestry residues burning (2.0E-04 kg CO_2e/fu; 11.0%) are jointly responsible for over half of the total (53.6%). A small contribution (4.5%) comes from the remaining processes assigned to system A, which are potassium fertiliser provision (4.3E-02 kg CO_2e/fu; 2.3%), mushroom substrate provision (3.2E-02 kg CO_2e/fu; 1.7%), and phosphate fertiliser provision (1.0E-02 kg CO_2e/fu; 0.5%). Treatment of the SMS contributes with emissions mainly from composting (3.2E-01 kg CO_2e/fu; 96.5%) and a small amount from its transportation for disposal (1.2E-02 kg CO_2e/fu; 3.5%). The mushroom substrate provision emissions are all due to the transportation process, since it is the only unit process assigned to it (due to the cut off criterion). The diesel, natural gas and nutrient provisions contribute with all the upstream emissions (such as extraction, refining, transport and end-use), but combined figures for the overall processes were used and it is not possible to discriminate the emissions by unit process.

Concerning system B, half of the emissions are generated in the bioenergy conversion processes (4.7E-01 kg CO_2e/fu; 52.3%), most of them emitted in biodiesel provision (4.3E-01 kg CO_2e/fu;47.5%) and only a small part in biomethane provision. The remaining emissions are almost all generated in the treatment of the SMS (3.3E-01 kg CO_2e/fu; 36.9%) and only a small part in the nutrient provision (6.6E-02 kg CO_2e/fu; 7.3%), in which the main shares are from nitrogen

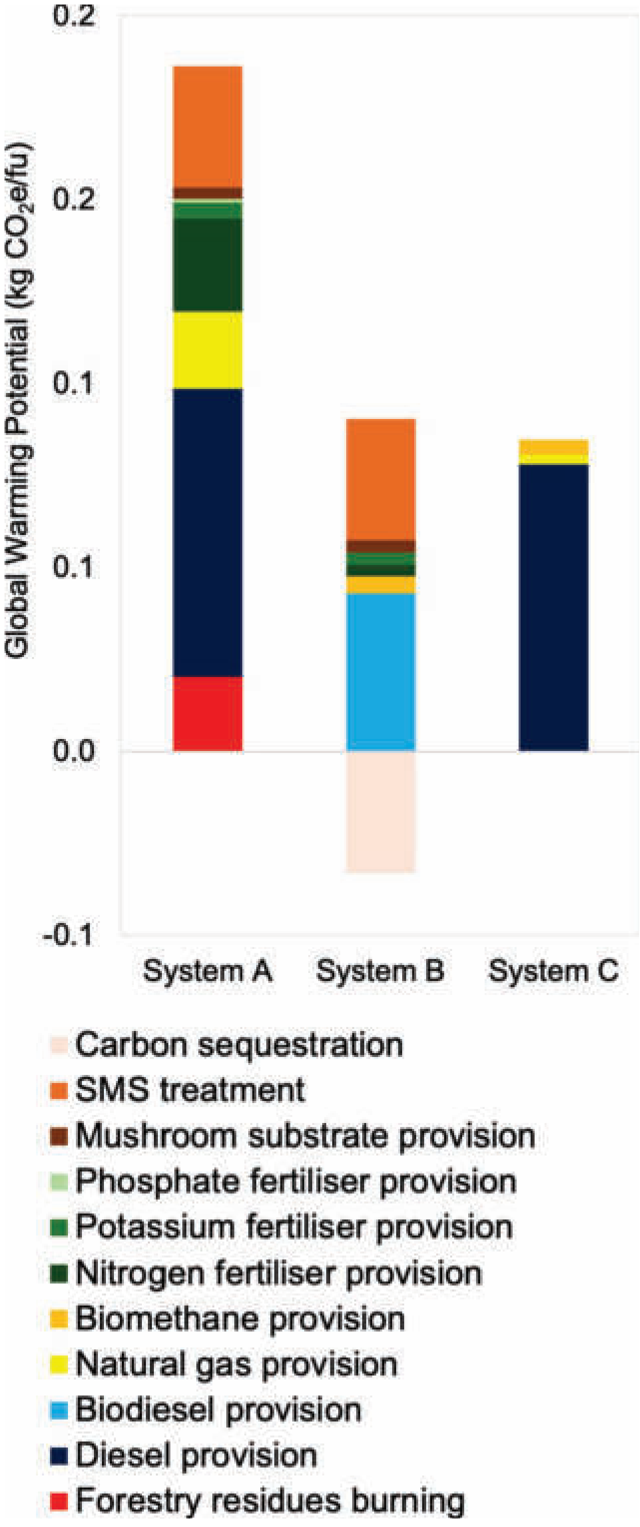

Fig. 4 Contribution of the different processes included in the three systems for the total global warming potential of the latter, per functional unit (fu)

and potassium provision (both contributing with 3.6%). Mushroom substrate provision has the smallest contribution (3.2E-02 kg CO_2e/fu; 3.5%). The mushroom substrate and SMS treatment contribute with the same emissions distribution between unit processes as noted in system A. The emissions from the thermochemical conversion process are mainly due to pyrolysis (4.2E-03 kg CO_2e/fu, 99.4%), which represent the combined emissions of all the upstream processes and end-uses, only a small part being due to the transportation of the feedstock (2.7E-03 kg CO_2e/fu; 0.6%). Emissions from biochemical conversion are mostly generated in the anaerobic digestion process (4.1E-02 kg CO_2e/fu; 95.3%), representing all the upstream processes and end-use emissions combined. The transportation process is accountable for a small part (2.0E-03 kg CO_2e/fu; 4.7%). Only combined figures are provided for nutrient provision.

In system C, almost all emissions come from a single process, diesel provision (7.8E-01 kg CO_2e/fu; 92.2%). The second highest contribution comes from the biochemical conversion process (4.0E-02 kg CO_2e/fu; 4.7%) and the remaining emissions come from natural gas provision (2.6E-02 kg CO_2e/fu; 3.1%). Emissions from the biochemical conversion process are mainly due to the anaerobic digestion process (3.6E-02 kg CO_2e/fu; 88.3%), again representing the combined emissions of all the upstream processes and end-uses. A small contribution for the biochemical conversion process emissions comes from transportation of the feedstock (4.7E-03 kg CO_2e/fu; 11.7%). Again, for diesel and natural gas provision processes, only combined figures can be presented.

3 Discussion

System A, representing the current waste management system operating in the region, presents CO_2e emissions 2 to 3 fold higher than those of the other two systems, and fails miserably in what concerns keeping the biomass in the system. The forestry residues are burned under open air and all carbon is released to the atmosphere, without any temporary storage in the form of some product allowing intermediate usage, so as to extend the carbon lifetime in the system. The products which can be delivered by treating forestry residues, such as biodiesel and biochar (provided by system B) or biomethane, nutrients and edible mushrooms (provided by system C), prolong the carbon lifetime within their systems. These products need to be matched in system A by importing them from background activities which are less carbon-efficient, e.g., the fossil fuels. Thus, in addition to not keeping the carbon within its system, this management option it is adding carbon demand to other systems with worse performance in terms of climate change impact.

When comparative assessments are performed, setting multifunctional systems against more feature-poor ones, the untapped potential of the latter is revealed and thus the shortcomings of system A become obvious. Nevertheless, the conclusion is not straightforward in other comparisons, such as that between systems B and C. An almost negligible difference is observed in terms of total CO_2e emissions. System B is the one with the lowest balance of CO_2e emissions and removals, due to the pyrolysis process it includes. It has biochar as co-product which contributes to its good performance by sequestering carbon, and it also delivers biodiesel thus forcing the other systems to import diesel from carbon-intensive background activities. If delivery of biodiesel by the pyrolysis process is questioned, since its economic viability depends on many factors (needing a deeper investigation into the regional market and legal contexts), system C would not have to import diesel, becoming the one with the best performance in terms of carbon balance. The investigation of the regional market and legal contexts is however out of the scope of the present assessment and must be reported as a limitation.

The merits of system C may also be underestimated due to the selected methodological framework. The nutrients delivered by the digestate in System C are matched in the other systems with synthetic fertilizer (only partly, in the case of system B). Nevertheless, other ecosystem functions attained with providing humus to soils are not accountable in terms of carbon balance. Therefore, the additional benefits of the digestate delivered by system C cannot be captured by assessments using climate change as the sole impact category. Other impact categories should be considered as well, namely the land use impact category which assesses changes in soil quality by measuring product performance in terms of biotic production, erosion resistance and mechanical filtration of the soil.

So, regarding the replacement of the digestate, the appraisal of the added benefits can only be fully understood by observing other impact categories. Being out of the scope of the present assessment, this should be pointed out as a limitation. Regarding the replacement of the energy products (biodiesel and biomethane), there is also the possibility that the actual performance of the systems is being concealed, due to phenomena such as the above mentioned unperfect substitution and rebound effect. This can nevertheless be revealed with sensitivity analyses, which are presented next. In it, the sensitivity analysis done on the energy yield of system B will also be discussed, which was carried out to overcome the uncertainty associated with the results obtained using low TRL experimental data.

To match the bioenergy supplied by systems B and C (biodiesel and biomethane) fossil fuels (diesel and natural gas) are used in the original scenarios. For the sensitivity analysis, a scenario where renewable energy sources compete with fossil fuels is considered, using the 43% share of renewables (the target for 2030 in the Renewable Energy Directive (European Parliament and of the Council 2023) to replace part of the bioenergy products. The remaining 57% were still replaced by the fossil fuels. Tis scenario was called unperfect substitution (US) scenario. Another scenario is assessed, the rebound effect (RE) scenario, that considers the empirical observation that the demand tends to increase when more efficient (or environmentally friendly) products are offered (Semmling et al. 2016). In the RE scenario, only 80% of the bioenergy is replaced. Figure 5a compares the results of thse two scenarios, highlighting the two processes changed as a result of their underlying assumptions, the diesel provision and the natural gas provision.

System A does not become preferable over the other two systems in any of the two sensitivity analysis scenarios. The emissions generated by the processes which remained unchanged are impossible to counterbalance with the reduction of the emissions from the diesel and natural gas provision processes. Regarding system C, because the main contribution for its overall emissions comes from the diesel provision process, when renewable sources are selected for the latter's replacement, system C reveals the best performance in terms of carbon balance. When the RE scenario is considered, system C returns to a performance worse than that of system B. It should be noted that, while in US scenario there is a replacement with another energy source, in the RE there is a decrease in the energy demand. This means that the combination of the processes selected for the US scenario is much less carbon intensive than that selected for the RE scenario, because even having more bioenergy demand to match it still emits less.

A second sensitivity analysis was done to the energy yield of system C, since low TRL experimental data were used. For comparison with the original scenario, two other scenarios were considered, assuming 50% less (C^- scenario) and 50% more (C^+ scenario) energy production when compared to that achieved in the experimental assay. Figure 5b illustrates the performance in terms of carbon balance of the three systems in the three scenarios, namely the original, C^- and C^+. Since a small contribution for the overall emissions of the systems is coming from the biomethane and natural gas provision, in comparison with the emissions generated by the diesel provision, no significant differences are noted. Even when additional emissions are added to system B, to match the surplus in the delivery of biomethane from system C with natural gas (scenario C^+), it is still the system with the best performance in terms of carbon balance. This finding indicates that the uncertainty derived from the use of data from low TRL experimentation can have no influence on the overall results of the LCA.

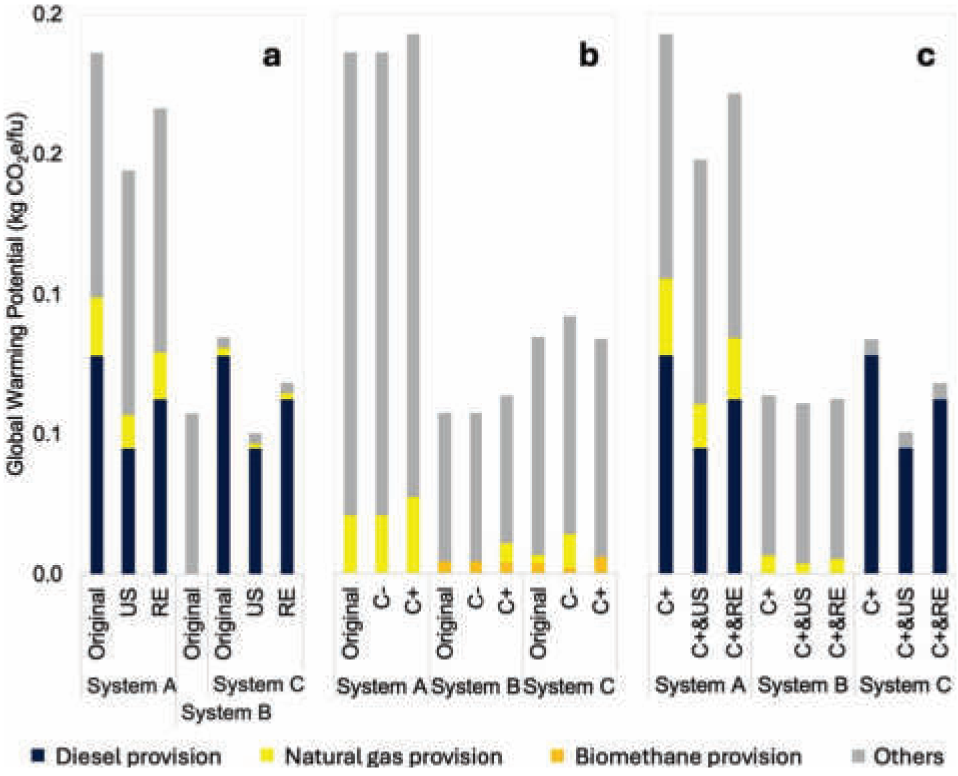

Fig. 5 Global warming potential, per functional unit (fu), in the different sensitivity analyses scenarios: (**a**) original, unperfect substitution (US), rebound effect (RE), with system B (being the one that must be matched) remaining constant in all scenarios; (**b**) using the energy yield value obtained experimentally (original), with less 50% of biomethane delivered by system C (C-) and more 50% of biomethane delivered by system C (C+); (**c**) more 50% of biomethane delivered by system C (C+), C+ assuming unperfect substitution (C+&US), C+ assuming rebound effect (C+&RE). The contribution of the processes included in each system is aggregated (grey bars), except for the processes that suffered changes between scenarios

A third sensitivity analysis was performed, now having scenario C^+ as the reference and considering different options for the replacement of energy goods delivered by that scenario. In comparison with scenario C^+, two other scenarios were studied, where unperfect substitution (scenario C^+&US) and rebound effect (scenario C^+&RE) of the bioenergy goods provided by systems B and C are considered. Figure 5c depicts the carbon balance of the three systems for these three scenarios. Only when considering unperfect substitution, thus replacing the bioenergy with other low carbon intensity energy sources instead of fossil sources, was it possible for system C to present a performance better than that of system B. This was also the outcome of the first sensitivity analysis. However, in that former analysis (considering the US scenario) system C was benefiting from a reduction in emissions by matching the biodiesel with less carbon intensive options. In this last analysis (considering the C^+&US scenario), in addition to that result, system B sees its emissions increased to match the increased biomethane delivery of system C. Thus, the advantage of system C when compared to system B is even higher, the difference between systems B and C in scenarios US and C^+&US being 7.0E-02 kg CO_2e/fu and 1.0E-01 kg CO_2e/fu, respectively.

The fourth and fifth sensitivity analyses resulted in no variation in the ranking of the systems. The fourth sensitivity analysis, where the transportation process was upgraded to a modern fleet (EURO 6), the systems showed a reduction in total emissions between 0.002% and 0.22%, therefore considered negligible and with no implication in their ranking. In the final sensitivity analysis, where a 5% lower efficiency of the biodiesel engine is considered, system A presented a reduction in total emissions between 1.5% and 2.1% and the scenarios in system C presented a reduction in total emissions between 4.2% and 4.6%, again considered negligible and with no implication in the systems' ranking.

4 Conclusions

With the present assessment it is possible to conclude that the current system A (chicken manure composting and forestry residues open air burning) should be discontinued. Both bioenergy solutions here assessed showed a much better performance in terms of impact on climate change, with a GHG emissions and removals balance 2 to 3 fold lower when compared to the current system. Between the foreseen system B (with thermochemical and biochemical conversion routes handling two independent flows) and the solution C beyond (with a solely biochemical conversion route handling a joint flow), the foreseen presents a better outcome, since to match one of its bioenergy co-products, a product from a more carbon intensive background activity must be imported. A deeper understanding of the regional context can reveal that such product is not economically viable, not having market demand or legal framework that supports is commercialization, and in that case system C would have a better performance.

With the chosen methodological framework, having as sole impact category the impact on climate change, it was possible to deliver answers in terms of the expected lifetime extension of the carbon in the systems, which underlies the biomass cascading use principle. However, system C offers a bigger amount of digestate, providing other ecosystem services and the assessment of other impact categories can reveal a better overall environmental performance. That should be reported as a limitation of the present study and can be pointed out for further investigation. Within such assessment, the tuning of the processes towards the biomass cascading use principle (e.g., aiming at higher biochar production, instead of being optimized for biodiesel as was considered here) can be a subject of analysis as well.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-026-02590-8.

Author contributions Ana d'Espiney: Conceptualization, Methodology, Validation, Investigation, Writing - original draft. Bengt Verworner: Investigation, Writing - review & editing. Helena Pinheiro: Methodology, Writing - review & editing. Isabel Marques: Conceptualization, Methodology, Writing - review & editing. Katja: Methodology, Validation, Investigation, Writing - review & editing. Nils Engler: Investigation, Writing - review & editing. Stefan Majer: Conceptualization, Methodology, Validation, Investigation, Writing - review & editing. Walter Stinner: Validation, Writing - review & editing. Daniela Thrän: Conceptualization, Methodology, Validation, Writing - review & editing.

Funding Open Access funding enabled and organized by Projekt DEAL. This research was funded in whole or in part by the Fundação para a Ciência e a Tecnologia, I.P. (FCT, https://ror.org/00snfqn58) under Grant (SFRH/BD/146002/2019). For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript (AAM) version arising from this submission.

Data availability All data generated or analysed during this study are included in this published article or in supplementary material.

Declarations

Ethical approval Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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