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LCA OF WASTE MANAGEMENT SYSTEMS

Prospective LCA of future pathways for used cooking oil valorisation: advancing renewable energy and sustainable materials

Brais Vázquez-Vázquez[1,2] · **Almudena Hospido**[1] · **Ángeles Val del Río**[1] · **Matty Janssen**[2]

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Abstract

Purpose This study aims to evaluate the environmental performance of different valorisation pathways for used cooking oil (UCO). By applying prospective life cycle assessment (pLCA), conventional energy-based routes, such as biodiesel production, cogeneration, and incineration; were compared with novel materials routes such as bioplastic production using PRETENACC technology (TRL = 5). The analysis focuses on identifying the most environmentally favourable long-term option, emphasizing how increasing the market share of bioplastics could shape future UCO recovery strategies.

Methods As the first step of the pLCA, more than 30 parameters related to UCO valorization were identified together with stakeholders with expertise in political, environmental, social, technological, economic and legal (PESTEL) fields. These were used to generate five future scenarios for 2030, 2040 and 2050. Life cycle inventories were developed using experimental and literature data on bioplastics, as well as data from the literature on energy pathways, covering the system boundaries from cradle to grave. The background processes were futurised with Ecoinvent 3.9.1 and scenarios based on IMAGE (SSP2-base and SSP2-RCP2.6). Environmental impacts were quantified using the intermediate categories of ReCiPe 2016, supplemented with indicators of the physical effects of microplastics on terrestrial and aquatic biota.

Results and discussion The pLCA results show that scenario 1 (0% market share for bioplastics) has the lowest initial impacts (2030). Nevertheless, over time (2040 and 2050), only the environmental burden of bioplastics decreases, driven by cleaner electricity production and better waste sorting. Climate change impacts are largely influenced by bioplastics production and end-of-life (EoL) management, with mixed waste disposal accounting for up to 26% of the total impact in 2030, decreasing towards 2050. Terrestrial acidification is dominated by the bioplastics production. Particle formation reflects combustion-related trends, while microplastic impacts depend on poor management, which mainly affects marine environments as the final sink. Energy recovery pathways show limited potential for improvement, while bioplastics offer increasing long-term environmental benefits if appropriate EoL pathways are followed.

Conclusions This study demonstrates that while energy recovery pathways, such as biodiesel, cogeneration, and incineration, contribute marginally to long-term environmental improvements, material valorisation through bioplastics offers a promising and more sustainable UCO management route. Environmental performance of bioplastics is highly dependent on EoL management and the polymer composition. Enhancing waste sorting practices and adopting lower-impact polymer blends are critical to maximizing benefits, enabling a significant reduction in the impacts associated with bioplastics.

Highlights

- pLCA compares future environmental impacts of used cooking oil valorisation routes
- Bioplastics may have lower impacts if their waste is properly managed
- Biodiesel pathways limited by combustion emissions across all time horizons
- The impacts of energy valorisation routes persist over time
- Five scenarios developed integrating technology, policy and stakeholder input

Keywords Stakeholders · Polyhydroxyalkanoate · Bioplastics · Biodiesel · Cogeneration · Incineration

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Extended author information available on the last page of the article

1 Introduction

Fat, oil and grease (FOG) waste, mainly composed of used cooking oil (UCO), are by-products from households and the food industry with significant environmental and processing challenges when not properly managed (Wallace et al. 2017). Improper disposal of FOGs can degrade water resources and urban infrastructure. According to Directive 2008/98/EC (European Union, 2008), UCO and other municipal waste residues must be separated and managed at source, as inadequate separation of UCO can lead to its entry into wastewater treatment plants (WWTPs), where it may clog infrastructure and strain aerobic processes by reducing oxygen transfer efficiency and microbial activity (Wallace et al. 2017). UCO accumulation in sewage systems leads to the formation of fatbergs, causing blockages, sewer overflows, and increased maintenance costs for municipal water infrastructure (Yusuf et al. 2023). Additionally, lipid accumulation in biomass can hinder sludge settlement, exacerbating operational problems such as bulking and foaming, which further disrupt WWTPs efficiency (Wallace et al. 2017). These challenges highlight the need for separation and efficient FOG valorisation to mitigate mismanagement's adverse effects and capitalize on energy and material potential.

Energy valorisation recovers valuable energy resources from FOG while contributing to environmental sustainability and circular economy. Several routes have been developed (Lam et al. 2016), with biodiesel production from UCO being one of the most established.

UCO can be processed into biodiesel through two main routes: fatty acid methyl esters (FAME) produced through alkaline treatment (Ehsan and Chowdhury 2015; Meng et al. 2008), or hydrotreated vegetable oil (HVO) via hydrocracking and hydrogenation of UCO (Ajeeb et al. 2025; Szeto and Leung 2022). Other energy recovery pathways include cogeneration (Lombardi et al. 2018; Winfried et al. 2008) and incineration (Chen et al. 2017; Foo et al. 2021), where UCO is used to produce electricity and heat.

UCO can also be valorised into materials, such as bioplastics (BPs), representing a promising alternative. The ECOPOLYVER project (ECOPOLYVER, n.d.) explores the conversion of UCO into polyhydroxyalkanoates (PHAs), i.e. biodegradable polymers produced by microorganisms from renewable sources (Yadav et al., 2020), using the PRETENACC technology (patent nº ES2908750). PHAs are then used to produce BPs intended to serve as a renewable alternative to fossil-based plastics like polypropylene (PP) and low-density polyethylene (LDPE), only if they achieve market competitiveness (Pizzol et al. 2023). As PHA production via the PRETENACC technology is still in its early development stages (technology readiness level (TRL) 5), scaling up will be crucial for viability.

In this context, prospective life cycle assessment (pLCA) becomes highly relevant, as it allows quantifying the future environmental impacts of emerging technologies at early stages of development (Cucurachi et al. 2018, 2022), such as the PRETENACC technology for PHA production, while allowing for comparisons with other already developed technologies. This approach will help drive positive changes (Arvidsson et al. 2018; Thonemann et al. 2020) and steer technological development towards improved environmental performance (Tsoy et al. 2020). By integrating pLCA with projected scenarios for 2030, 2040 and 2050, this methodology not only forecasts potential environmental outcomes but also promotes the development of innovative solutions that are both economically viable and environmentally friendly. Furthermore, it will enable a comparison of the PRETENACC technology (to produce PHA) with the other UCO valorisation pathways in a future context where all of them will have high TRLs, i.e. TRL 9. A feasible method for assessing future environmental performance is to develop scenarios that project how emerging technologies will evolve (Arvidsson et al. 2018; Bergerson et al. 2020). Nevertheless, the prospective approach inherently entails data gaps and significant uncertainty (Igos et al. 2019). To address this, Langkau et al. (2023) proposed a scenario-based methodology which allows the systematic and well-documented development of scenarios with stakeholders' collaboration.

While the methodology of Langkau et al. (2023) has already been tested in pLCA for PHA production from different wastes (Cucurachi et al. 2022; Saavedra del Oso et al., 2023), UCO valorisation was not performed and requires considering all actors involved, not only PHA producers. The objective of this study is to assess the most environmentally favorable future scenario for UCO valorisation, focusing on how increasing the market share of bioplastics affects the outcomes. Using pLCA as a tool, the study compares the environmental impacts of these pathways (FAME and HVO biodiesel, cogeneration, incineration and PHA production), considering all operational phases of the UCO valorisation, including also the consequences at end-of-life (EoL).

2 Methodology

2.1 Scenarios development

Prospective LCA is a future-oriented variant of traditional LCA that evaluates the potential impacts of technologies or products in future contexts (Arvidsson et al. 2018; Cucurachi et al. 2018). In this study, it is applied as a powerful tool to compare material and energy valorisation pathways of UCO, with a focus on whether PHAs via PRETENACC can be environmentally competitive. By incorporating future TRLs and evolving waste management practices, pLCA enables a robust assessment of potential future outcomes, helping to identify the pathways that best align with environmental sustainability goals. Like conventional LCA, pLCA follows four key stages (Fig. 1): (i) goal and scope definition, which includes the definition of the functional unit, system boundaries, TRL, time horizon, data sources for both foreground and background, and selection of impact assessment methods and categories; (ii) inventory analysis, which involves collecting data and developing future scenarios (Langkau et al. 2023); (iii) impact assessment, where the inventory data is translated into potential environmental impacts; and (iv) interpretation, which involves critically analysing the results and addressing uncertainties and sensitivities (Cucurachi et al. 2022). Within the goal and scope definition, biogenic carbon flows were modelled following a + 1/-1 accounting approach. However, only biogenic CO_2 emissions were considered and not intakes, as the agricultural stages of UCO production were outside of system boundaries of the study. Additionally, biogenic CO_2 emissions were explicitly reported in the life cycle inventory to document their magnitude and distribution across valorisation pathways (Supplementary Material 1, Sect. 5).

The scenario-based inventory modelling for prospective LCA (SIMPL) approach (Langkau et al. 2023), provides a structured methodology for future scenario development by systematically defining assumptions regarding potential social, economic, and technical changes that may affect the system under study. The SIMPL approach consists of four main steps: (i) scenario field identification, (ii) parameters identification, (iii) parameters analysis, and (iv) scenario generation; guiding the development of future scenarios.

(i) **Scenario field identification.** The market shares of material and energy recovery pathways were defined at the stakeholders meeting, whose insights guided the estimation, assuming large-scale implementation. The functional unit was defined as 1 kg of UCO. A cradle-to-grave approach was applied, covering five pathways (Fig. 2). Europe was chosen as the geographical location. The horizon years selected for evaluation were 2030, which aligns with the deadline for Sustainable Development Goals (SDGs) (United Nations, n.d.); 2050, corresponding to the European Green Deal's (The European Green Deal, 2019) target of climate neutrality and limiting global warming to below 2°C; and 2040, as an intermediate point between these two milestones. An explorative scenario approach was adopted to address the question of "how the future could develop" (Langkau et al. 2023). The foreground system was modelled using both own experimental data and data from literature, following the decision tree framework suggested by Tsoy et al. (2020) and the approach outlined by

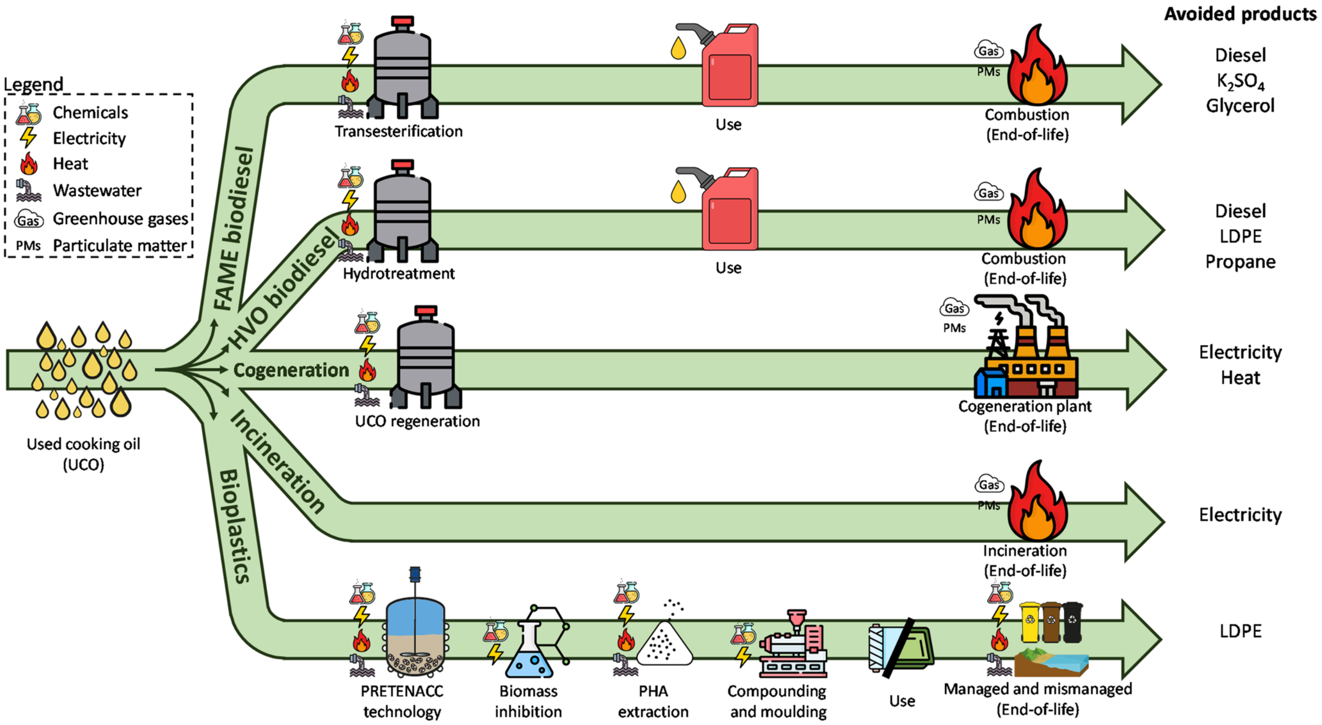

Fig. 1 Valorisation pathways for UCO evaluated: production of bioplastics (PHA), production of biodiesel by transesterification (FAME) or hydrotreating (HVO), cogeneration and incineration

Piccinno et al. (2016). For the background system, a futurized version of the Ecoinvent 3.9.1 database was used, incorporating scenario data from the IMAGE integrated assessment model (Elke Stehfest et al. 2014), based on the Shared Socio-Economic Pathways (SSP) (O'Neill et al. 2014) and Representative Concentration Pathways (RCP) (van Vuuren et al. 2011). Two scenarios were selected: SSP2-base and SSP2-RCP2.6, which represent the 'mid-point' of the SSP framework, i.e. a middle-of-the-road SSP development pathway, but differ significantly in terms of climate change mitigation. The SSP2-base scenario forecasts a 3.5 °C temperature rise by 2100, while the SSP2-RCP2.6 scenario limits warming to below 2 °C (Sacchi et al. 2022). To quantify the environmental impacts across these scenarios, the ReCiPe 2016 v1.03 (H) midpoint method was applied. The foreground and background scenarios were modelled using the superstructure approach (Steubing et al., 2021), implemented in the Activity Browser LCA software (Steubing et al. 2020). As the objective of the study is to compare different UCO valorisation routes, which provide different outputs (energy and materials), a substitution approach was applied. Accordingly, products generated in each pathway were modelled as substitutes for their conventional counterparts. Regarding the impact categories, climate change, terrestrial acidification and particulate matter formation were selected due to the prominent role of combustion processes within the recovery routes evaluated. In addition, the impact category of microplastics physical effects on biota was included, using the characterization factors developed by Corella-Puertas et al. (2023) for the aquatic compartment (marine and freshwater) and Vázquez-Vázquez et al. (2025) for the terrestrial compartment. This ensures that the potential impacts associated with microplastics generated during the production and EoL of PHA-based biopolymers are also captured.

(ii) **Parameters identification.** The identification of both technological and surrounding parameters was initially done by reviewing existing literature and socio-economic policies. Nevertheless, to ensure a comprehensive identification of such parameters without excluding any areas of study, stakeholders were consulted as recommended by Langkau et al. (2023). For this, 58 potential stakeholders were initially identified based on a PESTEL analysis (political, economic, social, technological, environmental and legal) (Achinas et al. 2019; Kansongue et al. 2023). This number was then refined to 15 based on their expertise, gender balance, public/private sector affiliation, and accessibility. After this selection, a hybrid meeting was held, combining in-person and online participation. This meeting was divided into two major blocks: (1) pLCA methodology and challenges and solutions (i.e. valorisation routes) of UCO waste management were presented; and (2) a discussion with all stakeholders to identify the key parameters based on their input and perspectives (see Sect. 1 of Supplementary Material 1 for more details on the stakeholder engagement methodology).

(iii) **Parameters analysis.** After identifying the parameters and relations between them (Sect. 2, Supplementary material), the stakeholders' meeting focused on adopting assumptions regarding their potential future states. Three potential sub-scenarios were formulated for each parameter, although for 6 of them (such as for example "greenwashing"), only binary scenarios (present or absent) could be defined (Sect. 3 of the Supplementary Material 1).

(iv) **Scenario generation.** The large number of possible sub-scenario combinations makes an exhaustive scenario construction unmanageable. To address this, a cross-consistency assessment (Ritchey 1998; Zwicky et al., 1967) of the most relevant parameters (Sect. 3 of the Supplementary Material 1, and Supplementary Material 2) was conducted to discard incompatible combinations by systematically cross-referencing all sub-scenarios (Sect. 3 Supplementary Material). This process enabled a comprehensive evaluation of inconsistencies between the parameters, allowing for the exclusion of unrealistic combinations and streamlining the development of coherent future scenarios. For instance, it is inconsistent to combine tangible environmental and bioeconomy policies with waste management strategies focused solely on disposal. Similarly, low production costs for PHA cannot coexist with poor performance parameters or limited R&D&I investment. Although over 350 combinations were discarded due to inconsistencies, more than 1700 plausible combinations remained, reflecting a wide range of potential future scenarios. To further reduce complexity, and in consultation with stakeholders, all parameters were grouped into four key categories expected to shape the future of UCO valorisation: (i) policies, (ii) environmental awareness, (iii) PHA production yield parameters, and (iv) PHA production process costs (Sect. 4 of the Supplementary Material 1). As UCO valorisation through PHA production (BPs) is the only pathway not yet operating at a large scale, its yield parameters and production costs were identified as key factors in evaluating the future viability of UCO valorisation. Finally, five scenarios were developed (Tables 1 and 2), based primarily on varying market share percentages of bioplastics production (PHA). Consistent market shares for other UCO valorisation

Table 1 Description for the five scenarios of the selected main parameters and the market share percentage of each UCO valorisation process (BAU: business-as-usual; to see the values of low, medium and high parameters see Sect. 3 of the Supplementary material 2)

	Main parameters				Market share for UCO valorisation processes				
	Policies	Environmental awareness	PHA production yield parameters	PHA production process costs	Bioplastics	FAME	HVO	Cogeneration	Incineration
Scenario 1	BAU	Low	Low	High	0%	45%	45%	5%	5%
Scenario 2	BAU	Low	Medium	Medium	20%	36%	36%	4%	4%
Scenario 3	Ambitious	Medium	High	Medium	40%	27%	27%	3%	3%
Scenario 4	Ambitious	Medium	High	Low	60%	18%	18%	2%	2%
Scenario 5	Ambitious	High	High	Low	100%	0%	0%	0%	0%

Table 2 Description of selected scenarios narratives

	Narratives
Scenario 1	The % of PHA yield parameters is low resulting in high operational costs, this occurs under business-as-usual policies and low environmental awareness resulting in a 0% market share of PRETENACC technology.
Scenario 2	Both the % of PHA yield parameters and operational costs are in the range of other PHA production technologies, however, this occurs under BAU policies and low environmental awareness resulting in a 20% market share of PRETENACC technology.
Scenario 3	The % of PHA yield parameters is high, however the operational costs are insufficient to clearly differentiate it from other PHA production and used cooking oil recovery technologies. Besides, the policies are ambitious, and environmental concern is not very high. This results in a 40% market share of PRETENACC technology.
Scenario 4	The % of PHA yield parameters is high, and operational costs are low which makes the PRETENACC technology highly competitive with other PHA production and used cooking oil recovery technologies. Nevertheless, the policies are ambitious, and environmental concern is not very high. This results in a 60% market share of PRETENACC technology.
Scenario 5	The % of PHA yield parameters is high and operational costs are low which makes the PRETENACC technology highly competitive with other PHA production and used cooking oil recovery technologies. Besides, the policies are ambitious, and environmental awareness is high. This results in a 100% market share of PRETENACC technology.

pathways, such as biodiesel production, cogeneration, and incineration, where then incorporated to maintain coherence. One scenario (scenario 5) was included as a best-case for bioplastics valorisation. Although not considered a realistic projection, it was designed to assess the environmental performance of this pathway under optimal conditions. As a result, the potential impacts of 1 kg of UCO (FU) were calculated for each scenario, considering the distribution of UCO across the different pathways.

2.2 Inventory development

The inventory data used to generate the results are provided in Sect. 5 of the Supplementary Material 1, which includes detailed data on the inputs, outputs and processes associated with all UCO valorisation pathways assessed.

For biodiesel production (FAME and HVO), incineration, and cogeneration, data were sourced from existing literature. However, for bioplastics production (PHA from PRETENACC), databases were developed using both experimental and literature data. These databases cover bioplastics' entire life cycle, from PHAs production to EoL stages of managed and mismanaged BPs.

Each inventory was constructed starting from the use of UCO as a feedstock and extending through to the end-of-life treatment of the resulting products, encompassing all relevant processes.

2.2.1 FAME and HVO biodiesel

The LCI for the FAME biodiesel (Table 1 in Sect. 5 of the Supplementary Material 1) was developed based on Gupta et al. (2022). In this process, UCO reacts with methanol (MeOH) and potassium hydroxide (KOH) as a catalyst via transesterification. The resulting mixture is separated into a biodiesel-rich phase and a glycerol slurry using a gravity separator. Biodiesel and MeOH are then separated in a distillation column, while the biodiesel undergoes a final washing stage for purification. The glycerol slurry is treated with sulfuric acid (H_2SO_4), producing additional biodiesel and a mixture containing potassium sulphate (K_2SO_4), glycerol, water, and MeOH. This stream is centrifuged to recover solid K_2SO_4, and the remaining liquids are distilled to separate glycerol (by-product), MeOH (recycled to transesterification), and water (recycled to the biodiesel washing stage).

The production of HVO biodiesel (Table 2 in Sect. 5 of the Supplementary Material 1) involves thermal decomposition of UCO at temperatures between 400 and 500 °C (Yano et al. 2015). This treatment facilitates the breakdown of organic acids present in the oil, promoting their conversion into hydrocarbon chains within a reactor. During this phase, off gases consisting of CO_2, CO, H_2, CH_4, and other hydrocarbons are also produced. The resulting hydrocarbon mixture is then cooled and separated into fractions by boiling point using two condensers. The intermediate fraction (biodiesel) is refined to remove residual acids and subsequently hydrogenated at 150–250 °C with H_2 to improve oxidative and thermal stability. During the process naphtha and propane were also produced as coproducts (Ajeeb et al. 2025).

As both FAME and HVO are biodiesel fuels, the same combustion inventory was applied to their end-of-life phase (Sheehan et al. 1998). This includes emissions of CO_2 (fossil and mainly biogenic), CO, hydrocarbons, SO_x, NO_2, and PM_{10}. The fossil CO_2 emissions originate exclusively from FAME, as its production requires fossil-based methanol, whereas HVO does not involve fossil carbon inputs. Regarding HVO coproducts, bionaphtha was modelled as substituting fossil naphtha as a petrochemical feedstock, and biopropane as substituting fossil propane/LPG. No EoL modelling was applied to these coproducts, as they are assumed to enter the market and displace their fossil equivalents rather than being treated as waste streams.

2.2.2 Cogeneration

For the cogeneration pathway (Lombardi et al. 2018) (Table 3 in Sect. 5 of the Supplementary Material 1), UCO undergoes a regeneration to ensure its suitability as a fuel in an internal combustion engine. This includes pre-heating to adjust viscosity, followed by sieving, sedimentation, and filtration at 50 °C. A water-assisted clarification step further removes fine impurities and reduces volatile fatty acids. After these treatments, the regenerated UCO is used as fuel in a diesel engine for combined heat and power generation, assuming electric efficiency of 39.9% and a thermal efficiency of 40.2%. Electricity is considered the primary output, while the waste heat is fully recovered. Both electricity and heat are treated as avoided products, crediting the system for displacing their conventional generation. The inventory also accounts for water consumption and wastewater generation during the process, as well as emissions of CO_2, CH_4, N_2O, SO_x, NO_x, $PM_{2.5}$, and PM_{10}.

2.2.3 Incineration

For the incineration route, the LCI (Table 4 in Sect. 5 of the Supplementary Material 1) was based on Yano et al. (2015), where UCO was incinerated with municipal solid waste (MSW) to generate electricity. An electricity conversion efficiency of 15% was assumed, and all associated emissions such as CO_2, CH_4, N_2O, SO_x, NO_x, $PM_{2.5}$, and PM_{10} were included. Electricity was treated as avoided product.

2.2.4 Bioplastics

For the bioplastics pathway, the LCI began with the use of UCO as a feedstock for the production of PHAs through the PRETENACC technology (Ucha et al. 2026) (Table 5 in Sect. 5 of the Supplementary Material 1). In this process, PHA is stored inside the bacteria, requiring a posterior extraction. For that, NaClO was used as the inhibiting agent (Lorini et al. 2021) and NaOH as the extracting agent (Salvatori et al. 2023). Once extracted, the PHA was processed in the compounding and shaping stage, where it was formulated into a final bioplastic film, intended for packaging applications, using polylactic acid (PLA) as copolymer and tryethylcitrate (TC) as additive. The final composition followed a 45:45:10 mass ratio of PHA, PLA, and TC, based on ANFACO-CECOPESCA data (ANFACO CECOPESCA, 2025). For PLA production inventory, although more innovative methods are available (Islam et al. 2025; Rezvani Ghomi et al. 2021), the dataset from Ecoinvent was used, as it is based on the world's largest PLA production plant (Vink et al. 2007). The EoL inventory for bioplastics was developed based on plastic end-of-life waste statistics. It was assumed that 4.505% of plastics are mismanaged after use phase (4.500% during production (Ryberg et al. 2018) and 0.005% during EoL stage (Jambeck et al. 2015), where the remaining 95.495% are properly managed.

To model the EoL of managed bioplastic waste, the distribution of bioplastics into the different waste streams was estimated based on data published by Gadaleta et al. (2023) and further developed within the ECOVAL project (*ECOVAL-SUDOE*, n.d.). Additionally, for mixed waste it was estimated that 20% will be landfilled in 2030, 10% in 2040, and 5% in 2050, based on data from the European Parliament (European Parliament, 2024). Based on this, for 2030 it was assumed that 8% of bioplastics will be disposed in the organic bin, 33% in the plastic bin, and the remaining 59% in the mixed bin (47.2% MBT and 11.8% landfill), following the estimates of Gadaleta et al. (2023) for the Italian context. For 2050, a best-case scenario was considered, with 20% entering the organic waste stream, 51% the plastic waste, and 29% the mixed waste stream (26.1% MBT and 2.9% landfill), in line with ECOVAL results indicating that achieving more than 20 is highly challenging. For 2040, a middle-of-the-road scenario was defined, assuming that 16% of bioplastics will end up in the organic waste, 35% in plastic waste, and 49% in mixed waste (46.5% MBT and 2.4% landfill).

Within each stream, specific EoL treatments were assigned:

- Organic waste was assumed to undergo anaerobic digestion prior to composting;
- Plastic waste assumed to be incinerated for energy recovery as bioplastic cannot be recycled; and
- Mixed waste was assumed to be partially treated in MBT plants, while a remaining fraction is directly disposed of in landfill. Within the MBT route, the dry fraction is

sent to incineration after biostabilisation and screening, where thermal and electrical energy are recovered. The resulting ashes are subsequently disposed of in landfill.

The avoided product for bioplastics was assumed to be LDPE. For the EoL modelling of LDPE, similar disposal ratios were assumed, excluding the organic waste stream. It was estimated that in 2030, 50% of the material will enter the plastic bin and 50% the mixed bin (40% MBT and 10% landfill). For 2040, the distribution was projected to shift to 60% and 40% (36% MBT and 4% landfill), respectively, and by 2050 to 70% and 30% (28.5% MBT and 1.5% landfill), based on current data and long-term projections (Dokl et al. 2024). As for bioplastics, the fraction of mixed waste routed to landfill was assumed to decrease from 20% in 2030 to 10% in 2040 and 5% in 2050 (European Parliament, 2024).

Each of these bioplastics waste management routes entails different treatment processes (Gadaleta et al. 2023) with varying environmental implications. In the organic waste stream, bioplastics used for packaging are assumed to undergo anaerobic digestion generating biogas that is converted into energy via a combined heat and power (CHP) system with other organic residues. The remaining digestate is subjected to industrial composting. It should be noted that biodegradability under anaerobic conditions depends on polymer type and process parameters: PHA is generally considered anaerobically biodegradable, whereas PLA exhibits more limited degradation under mesophilic digestion and may partially persist to the composting stage (Cazaudehore et al. 2022). After this non-degraded bioplastic residues are removed and sent to landfill. In the plastic waste stream, bioplastics are processed in material recovery facilities (MRFs) alongside with conventional plastics. Recyclable fractions are converted, while non-recyclable fractions, included bioplastics, are incinerated in a CHP system for energy recovery. When collected as mixed waste, bioplastics are treated in MBT plants or landfilled (it was assumed that of all plastics entering the mixed waste stream, 20% will end up in landfill in 2030, 10% in 2040 and 5% in 2050 (European Parliament, 2024)).

For mismanaged plastics waste, environmental dispersion across compartments was considered. Based on the Plastic Footprint Network report (Quantis and EA, 2020), 75% of bioplastics remain in the terrestrial compartment, while 25% end up the aquatic compartment. To assess the environmental impacts from microplastics ingestion by biota, characterization factors from Vázquez-Vázquez et al. (2025) (for terrestrial) and Corella-Puertas et al. (2023) (for aquatic) were applied.

3 Results and discussion

The pLCA results across the four impact categories (Figs. 2 and 3) evaluated indicate that Scenario 1, where the market share of bioplastics is 0%, exhibits the lowest impacts. However, the sum of the impacts associated with bioplastics shows a decreasing trend over the time horizon (2030, 2040, and 2050). The error bars shown in Fig. 2 correspond to the uncertainty analysis performed for the inventory, based on 5000 Monte Carlo runs, whereas the error bars in Fig. 3 reflect the inherent uncertainty associated with the characterization factors. The LCA results used to construct Figs. 2 and 3, together with the full set of ecoinvent impact categories, are provided in Supplementary Material 3, along with the results of the sensitivity analysis (±20% electricity consumption and ±20% heat consumption). No significant differences were observed across the evaluated impact categories in the sensitivity analysis, with variance remaining below 5% in all cases.

Regarding climate change impacts (Fig. 2a), significant differences arise depending on the horizon year. In the short term (2030), Scenario 1 arises as the best-performing option, with nearly all its emissions stemming from biodiesel (FAME and HVO) combustion being the environmental hotspot of the process (Dufour and Iribarren 2012; Talens Peiró et al. 2010). However, as the market share of bioplastics increases (Scenarios 3, 4, and 5), their contribution to climate change becomes more evident, particularly in 2030. This is mainly linked to BPs EoL management routes, which is mostly disposal in mixed waste rather than in organic waste streams, and to the production processes of the biopolymers themselves, particularly PHA and PLA, which do not always perform better than conventional plastics (Dolci et al. 2025). The main reason is that bioplastics are still unable to realise their potential EoL benefits, since adequate collection systems and treatment infrastructures are not yet widely implemented in Europe (Dolci et al. 2023; Marchelli and Fiori 2025). Over time, the environmental burden associated with biodiesel remains largely unchanged, as its combustion emissions cannot be significantly reduced. In contrast, the impact of biopolymers decreases substantially toward 2050 mainly due to a cleaner electricity mix and better waste sorting, with a higher share of renewable sources and better bioplastics waste sorting. Additionally, a significant presence of biogenic emissions can also be observed, arising from the combustion of UCO (cogeneration and incineration), biodiesel, or bioplastics in scenarios evolving energy recovery (yellow bin and MBT-mixed waste bin). It should be noted that biogenic CO_2 flows were accounted for using a + 1/-1 approach; however, only emissions are reported, as biogenic CO_2 uptake is outside the system boundaries. This is because the agricultural

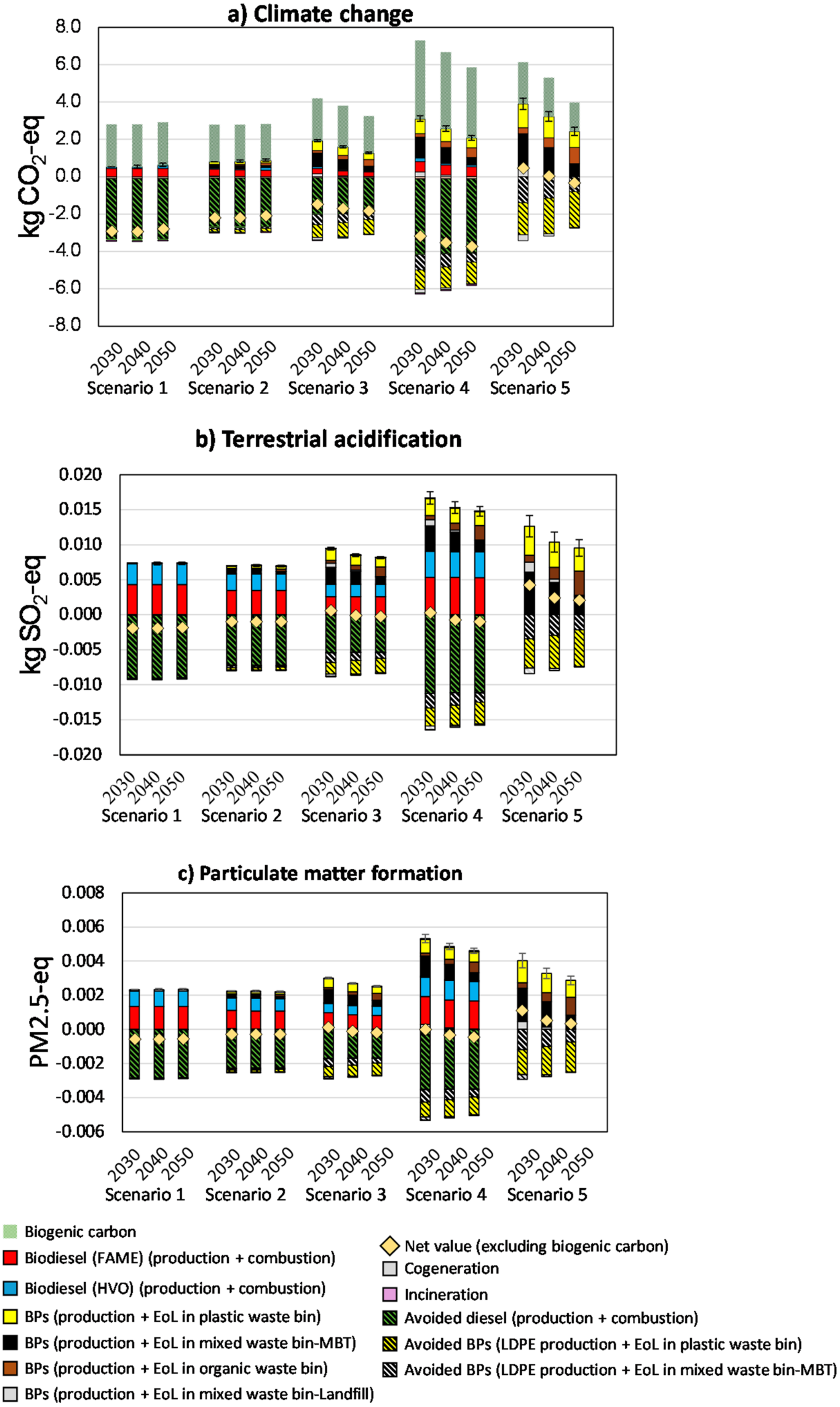

Fig. 2 pLCA results for the climate change and terrestrial acidification impact categories across the five UCO valorisation scenarios. Note that the avoided heat and electricity contributions are so small that they are not visually discernible in the figure

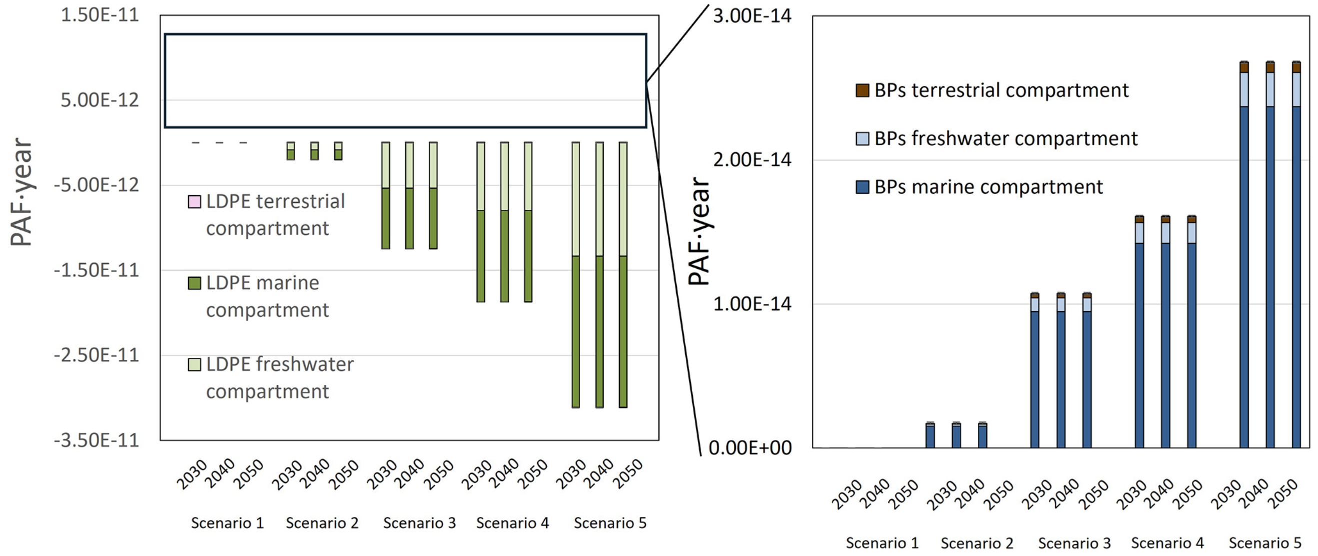

Fig. 3 pLCA results for microplastics physical effects on biota impact category

stage is excluded from the assessment and, consequently, plantations that produce the raw material for vegetable oil, are not within the system boundaries. Regarding terrestrial acidification (Fig. 2b), the most significant differences are observed between the scenarios rather than across the horizon years. Terrestrial acidification is mainly driven by NOx emissions from biodiesel combustion (FAME and HVO), and the emissions associated with PLA production, ammonia emissions from maize cultivation used as feedstock and NOx and SOx emissions from energy generation. Scenario 1 shows the lowest impacts, because most of the impacts related to biodiesel come from its combustion. In contrast, scenario 5 performs the worst due to the emissions from corn cultivation and energy use required for PLA production (45% of the final bioplastic). Additionally, in scenarios with a higher share of biodiesel valorisation (Scenarios 1 and 2), the net values remain consistently negative. This is driven by the relatively larger terrestrial acidification impacts associated with conventional diesel. Although biodiesel tends to exhibit higher NOx emissions due to its higher combustion temperatures (26.14 g NOx/ kg biodiesel compared to 24.0 g NOx/kg diesel (Sheehan et al. 1998), the key factor here is the absence of SOx emissions from biodiesel, in contrast to the significant SOx releases associated with conventional diesel (0.85 g SOx/ kg diesel).

For the particulate matter formation (Fig. 2c), a similar behaviour to that observed for terrestrial acidification was found, as particulate emissions are also strongly related to combustion processes. Scenario 1 again showed the lowest impacts, however, as in climate change and terrestrial acidification, only the impacts associated with the production of bioplastics decrease with increasing time horizon.

Microplastics physical effects on biota (Fig. 3) remain constant across horizon years, as they are not influenced by policy decisions. Instead, these impacts vary only across scenarios, depending solely on the level of bioplastic production and the proportion (4.505%) that is not properly managed after use. Among these, impacts are highest in the marine environment, which acts as the final sink where microplastics accumulate and remain highly accessible to biota. Freshwater serves mainly as a transit pathway from terrestrial to marine, and in the terrestrial compartment limited mobility and lower exposure of microplastics to biota reduce their impacts. The results are three orders of magnitude higher for LDPE than for bioplastics, largely due to the longer residence time of LDPE microplastics and their consequently greater potential to affect biota.

To identify the bottlenecks in the UCO valorisation pathway with the greatest potential for improvement, the valorisation of 1 kg of UCO following a single end-of-life route (mixed-MBT, mixed-landfill, plastic, or organic waste EoL) has been modelled for the years 2030, 2040, and 2050. While energy recovery pathways are currently at higher technology readiness levels (TRLs) compared to bioplastic (BP) production, the latter offers greater opportunities for present-day improvements that could significantly reduce environmental impacts over time. According to Fig. 4a, the climate change impact category is predominantly influenced by three factors: (i) the production and extraction of PHA, (ii) the production of PLA, and (iii) the EoL management pathways that each polymer may follow (i.e., mixed, plastic, or organic bins). Considering that PHA and PLA each represent 45% of the total bioplastic mass, the contribution of PLA production to climate change impacts gradually surpasses that of PHA. This shift occurs because the

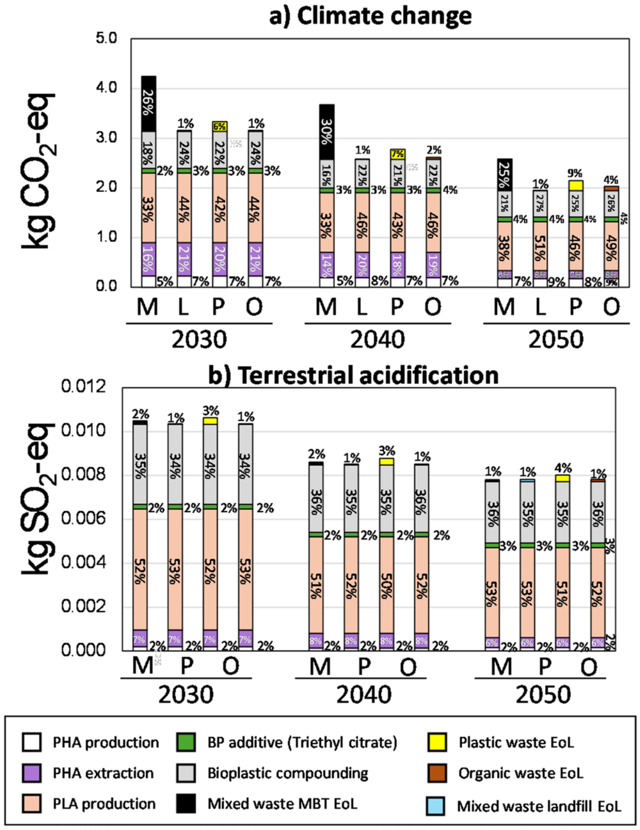

Fig. 4 Contribution of each stage in BPs valorisation to climate change and terrestrial acidification. M: mixed waste stream, P: plastic waste stream, O: organic waste stream

the relative contribution of PHA (production and extraction) decrease over time due to the cleaner electricity production. Regarding production, this difference is mainly due to variations in feedstock origin and inventory data: PHA is derived from UCO, a burden-free by-product valorised using the patented PRETENACC technology, while PLA is produced via microbial fermentation of maize-derived glucose, based on the ecoinvent dataset for the world's largest PLA plant in Nebraska (Vink et al. 2007). Regarding extraction, the impact is driven by the electricity-intensive chlor-alkali process used to produce the NaOH required for PHA recovery. The impacts of this process are decreasing as the horizon year progresses, and energy production is becoming cleaner.

However, the primary environmental hotspot of the system is not the production of PHA and PLA polymers, but rather the EoL stage. The climate change impact of bioplastics is highly dependent on the waste stream they enter after use. When disposed of in mixed waste-MBT, EoL management can account for 25–26% of the total climate change impact, reaching 4.24 kg CO_{2eq}/kg UCO in 2030 and 3.67 and 2.58 CO2eq/kg UCO in 2040 and 2050. In contrast, routing them to the plastic waste stream reduces this contribution to 6–9% (3.31, 2.77 and 2.15 kg COeq/kg UCO in 2030, 2040 and 2050). Nevertheless, with proper disposal in the organic waste stream, the intended and most environmentally favourable pathway, limits the impact to just 1–4%, reaching 3.16, 2.61 and 2.03 kg CO_{2eq}/kg UCO in 2030, 2040 and 2050 respectively. Additionally, a scenario in which the bioplastics end up in landfill from mixed waste EoL was also included. Its contribution would be similar to that of disposal in the organic waste stream (1% of contribution) due to their biodegradable nature and the absence of combustion processes, nevertheless they present the potential risk of uncontrolled fires in landfills. Nevertheless, this is a disposal route that EU aims to progressively reduce and ultimately eliminate in order to increase waste valorization and thereby reduce associated environmental impacts. These results underscore the critical importance of EoL management in determining the environmental performance of bioplastic valorisation pathways. If bioplastics follow the EoL route they were designed for (organic bin) their climate change impacts becomes more competitive with that of the best-case scenario (Scenario 1). In addition, while the end-of-life of other valorisation routes offer limited potential for improvement, the environmental performance of bioplastics can be significantly improved through proper sorting and treatment, making them a more competitive option.

Regarding terrestrial acidification, PLA production is consistently the main contributor, accounting for over 50% of the total impact in most scenarios (Fig. 4b). This is primarily due to its feedstock: PLA is produced from the microbial fermentation of glucose derived from maize, and maize cultivation is the main driver of acidifying emissions. This means that increasing the market share of UCO valorisation via bioplastics leads to higher terrestrial acidification impacts. This translates into PLA becoming a key environmental hotspot in this category.

In addition to polymers production and EoL pathways, the contribution of triethyl citrate (as additive) and the energy used in the compounding and shaping phase were also assessed, showing low but relatively minor contributions to both climate change and terrestrial acidification.

4 Conclusions

This study presents for the first time, to the best of our knowledge, a prospective life cycle assessment comparing the future impacts of UCO valorisation, considering the market shares of their valorisation pathways. These routes include both those already operating at full capacity and others with the potential to reach high TRL in the coming years, like PHA production. The study, conducted in collaboration with stakeholders with extensive national and international expertise, using a PESTEL-based approach to design five future scenarios (Table 1). Given the mandatory nature of UCO valorisation, the following conclusions are drawn:

Cogeneration and incineration currently account for less than 5% of the market share, rendering their contributions to environmental impacts like terrestrial acidification and particulate matter formation almost negligible. These energy recovery pathways are projected to play an even smaller role in the future, as cleaner and more sustainable technologies for heat and power generation are expected to dominate by 2040 and 2050.

Biodiesel, while currently one of the most widespread UCO valorisation pathways, faces major limitations in helping to meet Europe's 2050 carbon neutrality targets. Its climate change impact remains constant over time, due to the inherent emissions from combustion, making it a bottleneck in the decarbonisation process. Its contribution to terrestrial acidification, though less pronounced, is also relevant.

In contrast, material valorisation through bioplastics presents a promising alternative with great potential for improvement if two key factors are taken into account: (i) EoL management, particularly for climate change impacts - the waste stream (mixed, plastic, or organic bin) into which bioplastics are disposed significantly influences their carbon footprint; and (ii) the polymer blended with PHA, PLA in this case, because it plays a decisive role in other impact categories such as terrestrial acidification and particulate matter formation.

To maximize environmental benefits, improving waste sorting practices is critical. Currently, only around 20% of bioplastics are correctly separated into the organic fraction (ECOVAL-SUDOE data). Concurrently, replacing PLA with lower-impact biopolymers in PHA blends could further reduce key environmental burdens. Advancing these strategies through policy, public awareness, and material innovation will be pivotal to ensuring bioplastics fulfil their potential as a viable UCO valorisation pathway.

This study highlights the need for a strategic assessment of UCO residue valorisation pathways to meet long-term sustainability and carbon neutrality goals. While energy recovery pathways present challenges, bioplastics production, contingent on reaching TRL 9, emerges as a promising alternative, dependent on improvements in end-of-life management.

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Data availability The data supporting this article have been included as part of the Supplementary Information.

Declarations

Generative AI and AI-assisted technologies in the writing process During the preparation of this work the authors used ChatGPT-5o to rewrite/edit text sections in a manner that improves the overall understandability of the text. All content generated with this tool was subsequently reviewed, revised, and validated by the authors, who take full responsibility for the final version of the manuscript.

Conflict of interest The authors declare that they have no financial interests or personal relationships that could influence the work described in this article.

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Authors and Affiliations

Brais Vázquez-Vázquez[1,2] · **Almudena Hospido**[1] · **Ángeles Val del Río**[1] · **Matty Janssen**[2]

✉ Brais Vázquez-Vázquez
braisvazquez.vazquez@usc.es

Almudena Hospido
almudena.hospido@usc.es

Ángeles Val del Río
mangeles.val@usc.es

Matty Janssen
mathias.janssen@chalmers.se

[1] Department of Chemical Engineering, CRETUS,
Universidade de Santiago de Compostela,
Santiago de Compostela 15782, Spain

[2] Environmental Systems Analysis, Technology Management
and Economics, Chalmers University of Technology,
Gothenburg 41296, Sweden