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Influence of different LCIA methods on an exemplary scenario analysis from a process development LCA case study

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Abstract
Life cycle impact assessment (LCIA) methods quantify the impact of life cycle inventory data within each impact category by means of classification and characterization. This paper evaluated whether the selected LCIA method influenced the life cycle assessment (LCA) scenario analysis for decision support in process development and its possible reasons. For this study, a scenario analysis was used from a biorefinery LCA case study, as this is a key practice in process development. The analysis was investigated using various LCIA methods for the three midpoint impact categories of global warming potential (GWP, 12 LCIA methods totaling 48 subcategories), eutrophication potential (EP, 9 LCIA methods totaling 18 subcategories), and water assessment (WA, 10 LCIA methods totaling 26 subcategories). The GWP category showed consistent interpretations for the scenario analysis from different LCIA methods. The subcategory of marine EP from the two LCIA methods disagreed on the best-case scenario. Another discrepancy was identified within the three general EP indicators, where the trend of the scenario analysis was inverted in one method because of the sensitivity of a single substance (ethanol). Within the subcategories of WA, the inclusion or exclusion of hydropower water impacts changed the scenario analysis in the blue water use and total freshwater use subcategories, and the general WA indicators also disagreed on the best-case scenario. It is important to understand these influences and the reasons behind the variations for decision support in process development.

Keywords LCIA methods · LCA · Process development · Chemical engineering · Environmental impacts · Sustainable development

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1 Introduction

Life cycle assessment (LCA) is an instrument used to quantify the environmental impacts of a product, service, or system and is standardized by the ISO 14040 series (ISO, 2006a, 2006b). The method is divided into 4 phases: defining the goal and scope; the life cycle inventory (LCI); the life cycle impact assessment (LCIA); and the interpretation. During the LCIA phase, a particular set of methods and models is used to calculate the environmental impacts based on flows into and out of the environment from the LCI. Typically, these methods describe emissions into the environment in terms of impact-related reference indicators by classifying and characterizing each emission. It is critical that this link between emissions and impacts be identified correctly to yield a valid representation of the environmental impact. Therefore, in recent decades, advancements in LCIA methods have been a focus of global research. For instance, the Institute of Environmental Sciences Leiden (CML) method was developed in the Netherlands (Guinée et al., 2002), the Environmental Development of Industrial Products (EDIP) method was developed in Denmark (Hauschild & Potting, 2005), and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method was developed in the USA (Bare, 2011). More impact categories were introduced, as well as further LCIA methods for each impact category, expanding the toolset available to LCA practitioners. Recently, categories have been advanced that quantify the consumption of limited resources, such as freshwater or land. Impact categories are generally divided into midpoint and endpoint groupings, where midpoint categories quantify the environmental impact along with its underlying mechanism and endpoint categories quantify the damage caused in one of the three areas of protection (human health, natural resources, and the natural environment). The results of the midpoint categories are more precise and accurate than those of the endpoint categories, as fewer assumptions are required. Thus, the focus of this study lies on the midpoint categories.

When more than one LCIA method is available for the same impact category, a decision must be made as to which method is the best. Differences between methods should be identified, and more importantly, whether these differences could make a difference to the outcomes should be evaluated. When investigating two LCIA midpoint methods for several impact categories of the same LCA in an investigation of a water-based ultraviolet lacquer, Dreyer et al. (2003) observed minor differences between the EDIP97 and CML2001 methods in all impact categories but two, where major differences were identified. The human and ecosystem toxicity categories showed differences of up to two orders of magnitude for some indicators; furthermore, the results were caused by differences between the methods in the classification and characterization of the causing chemicals. In a more recent study of five different LCIA methods, Bueno et al. (2016) showed, in a comparative LCA of various building materials, that the LCIA method selection could make a difference in the midpoint results. In this instance, the following categories showed the highest discrepancies: acidification, terrestrial and aquatic eutrophication, marine ecotoxicity, and water depletion.

This dependency is problematic, as its general awareness is limited among LCA practitioners. It is a common practice to investigate variation and variability in results by means of a sensitivity or scenario analysis; however, this analysis is performed mostly on the LCI or the technical system and rarely on the selected LCIA method. The focus is often on the LCIA impact category, but the LCIA method is rarely considered, as is apparent in this systematic review by McClelland et al. (2018).

In contrast to the LCA study by Bueno et al. (2016), where different products with diverse materials and frameworks were compared, the focus of LCAs in process development is to compare process variations for the same product within a single technical system. Quantifying the potential environmental impacts of a prospective system based on the technology under development will help further our understanding of the environmental implications of innovative concepts at an early stage. Therefore, environmental advantages and disadvantages can be incorporated into decision support in process development. This early environmental assessment has the advantage of presenting environmental advantages and disadvantages in the process development phase when many commitments and decisions of a technology have not yet been finalized, and changes can be made more easily. Hot spots along the entire process chain and trends embodied in different process variations can be investigated in terms of their environmental impacts. However, this method is not without challenges, as technology at an early stage also implies less data and information to model the LCI of the prospective system and the environmental implications. Consequently, this approach results in more variation and variability within the LCI for this type of LCA, and therefore, even more importantly, variation and variability in other parts of the LCA should be eliminated. For instance, a novel lignin nanoparticle biorefinery was investigated to foster decision support in process development to find an optimum during the purification and ethanol recovery stages across several impact categories (Koch et al., 2020). An LCA for decision support in process development values the relative impact between the scenarios more than the absolute numbers to give a recommendation between the scenarios; therefore, it is important to analyze possible influences from the selected LCIA method not only on one scenario but also on the whole scenario analysis.

The objective of this paper was to evaluate whether the chosen LCIA method could change or influence the conclusion of a scenario analysis in process development. The variability from the LCIA method selection was shown for different products with different life cycle inventory compositions, such as in the study by Bueno et al. (2016). However, this approach has never been used to analyze different scenarios of the same system, having similar life cycle inventories with only changing parameters. If scenario analysis is used for decision support, it is critically important to understand possible influences of the selected LCIA method. Furthermore, the reasons for these possible changes and the influences of the selected LCIA method were identified and discussed. The impact categories of global warming potential (GWP), eutrophication potential (EP), and water assessment (WA) were investigated by utilizing part of the scenario analysis with four scenarios from the lignin biorefinery case study published by Koch et al. (2020). In addition to the GWP and EP, water assessment has not been a common term in the LCA community, but it will be used within this study to summarize the midpoint water impact indicators that are commonly utilized.

2 Case study description and methods

2.1 Case study

For the purpose of this study, part of the scenario analysis from the case study of Koch et al. (2020) was used. When renewable biomass is utilized to produce various chemical products by using integrated extraction processes that separate the components for further treatment, it is called biorefining. Many different approaches exist, one of which focuses on the production of lignin nanoparticles (Beisl, Friedl, et al., 2017), which has great potential for a wide range of possible applications (Beisl, Miltner, et al., 2017). This LCA case study was carried out in a prospective lignin nanoparticle biorefinery that used wheat straw as an input material and ethanol as an extraction solvent to produce nanoscale lignin particles. The biorefinery LCA from which the scenarios were investigated was published in Koch et al. (2020). The purpose of the LCA was to identify an optimized process setup and parameterization regarding its environmental impacts. Specifically, the purification of lignin nanoparticles and the ethanol recovery steps were evaluated, and a scenario analysis with different purification setups and ethanol recovery settings was outlined.

The scope of this case study was set from cradle-to-gate, in which the cradle includes raw material extraction, agricultural processes, and the production of utilities and the gate is the product: lignin nanoparticles in water (Fig. 1). In the first process step, wheat straw was treated by organosolv extraction, where the lignin fraction of the straw was dissolved with parts of recovered and virgin ethanol (depending on the ethanol recovery process). The reaction mixture was further separated into liquid and solid fractions. The solid fractions, including cellulose, hemicellulose, and undissolved lignin, were beyond the scope of this study and were therefore not considered. The liquid phase, with dissolved lignin, was brought into the precipitation steps. Here, lignin nanoparticles were precipitated by adding an antisolvent and shifting the solution pH.

The product dispersion was introduced in the cleaning stage, where the lignin nanoparticle dispersion was separated through membranes from an excessive liquid phase, which contained the bulk of ethanol and was brought back for solvent recovery. During solvent recovery, ethanol was separated from water in a rectification column, and most of it was brought back into the organosolv process, as depicted in Fig. 1. A more detailed description can be found in Koch et al. (2020).

2.2 Life cycle inventory and scenarios

The functional unit for this case study was 1 kg of lignin nanoparticles suspended in water, which was considered the gate of the cradle-to-gate scope. The LCI was compiled from three sources: experimental data, process simulation results, and commercial LCA datasets. Suitable LCA data systems that aim to represent specific technological processes must be composed of two vital types of data: own case-specific technological

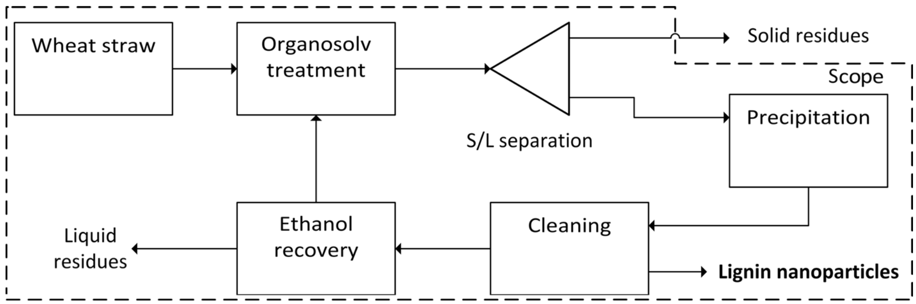

Fig. 1 Scope of the case study, with a simplified scheme of the lignin nanoparticle biorefinery. Solid residues are outside the scope of this case study. Cradle (raw material extraction, agricultural processes, and the production of utilities) to gate (lignin nanoparticles in water)

information (owing to own data measurements, calculations, or collection) and complemented by suitable and up-to-date background data (e.g., of documented and consistent LCI databases). The technological information comprises experimental data (yields, dry mass, etc.) and process simulation results (thermal energy demand for ethanol recovery, mass/energy balances, etc.). For the background data, the latest version of the professional database from Sphera Solutions GmbH was used (thermal energy, wheat straw, process water, chemicals, and solvents). This case study was assessed by means of an LCA corresponding to ISO 14044 and was performed using the LCA software GaBi version 9.2.0.58, schema 8007, with professional database version 8.7, service pack 39. For a detailed description of the life cycle inventory and foreground and background data, see the publication and supplementary material from Koch et al. (2020).

To investigate how the selection of the LCIA method influences a scenario analysis, four scenarios were considered: A, B, C and D (Fig. 2). The setup of the cleaning stage and related changes in ethanol recovery varied across the scenarios. Cleaning was implemented through membrane modules, where the permeate was an ethanol and water mixture, and lignin nanoparticles were suspended in the same mixture as the retentate. In one module, 90% of the volume was passed through the membrane as permeate, and the retentate was refilled with water before the next module. The number of modules increased from one in scenario A to four in scenario D. More modules resulted in more ethanol being brought into the solvent recovery while also increasing the total volume that must be treated in the rectification process step. The goal of this scenario analysis was to provide a recommended number of cleaning modules from an environmental impact perspective as decision support for the process development of a lignin nanoparticle biorefinery.

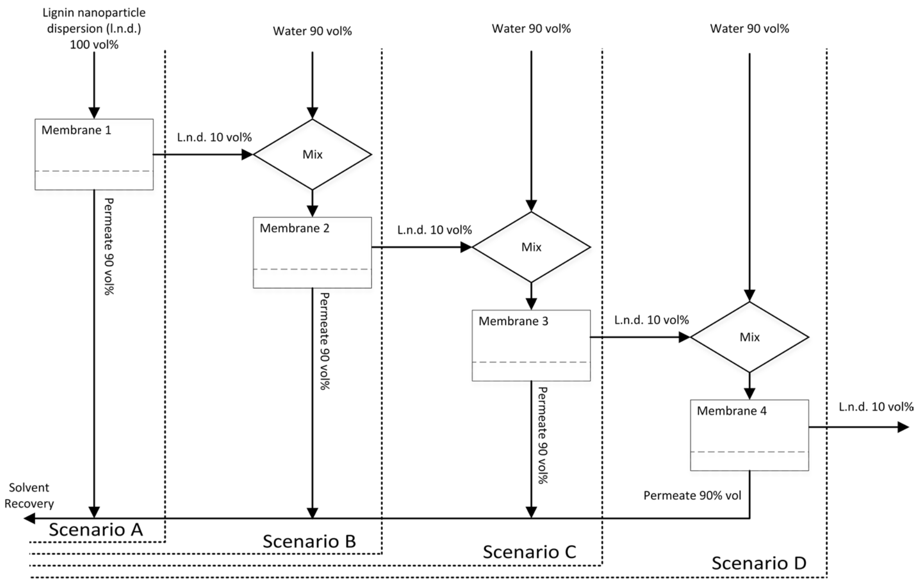

Fig. 2 Cleaning process in detail, with the membrane modules increasing from one in scenario A to four in scenario D

2.3 Methods

Three relevant impact categories were selected for this investigation, namely global warming potential (GWP), eutrophication potential (EP), and water assessment (WA). GWP is essential when assessing renewable resource utilization, and EP is important when considering agricultural processes; therefore, both categories were included, as the cultivation of wheat is part of the LCI's input material. Water is utilized in significant quantities in the cleaning stage and should therefore be included. The term water assessment (WA) was used to summarize the available midpoint water impact indicators in GaBi that were used in this study. The GWP is emission-oriented, and the EP is an effluent-oriented impact indicator; however, the WA is a resource depletion-oriented impact indicator. Alongside the environmentally relevant aspects, the EP and WA categories already demonstrated different results when altering the selected LCIA method in the study by Bueno et al. (2016). However, the GWP should have little to no variation from the selected LCIA method. Other impact categories were excluded for being beyond the scope of this study and will be investigated in future research.

For each impact category, the most common LCIA methodologies available within the GaBi software were included. The LCIA methods investigated for each of the three impact categories used are listed in Table 1. An LCIA method in the impact category of GWP often contains subcategories to present or process certain types of relevant CO_2-equivalent flows in various ways. These are required because not every LCI dataset has information on all types of relevant CO_2-equivalent flows because of outdated data, different approaches, varying system boundaries, or reasons for data gaps. However, depending on the goal chosen and the scope of the LCA, these subcategories may be assigned low or high importance. These subcategories include or exclude biogenic carbon and land use change (LUC). Another subcategory shows only the GWP impact caused by LUC. The LCIA methods of ISO14067, EN15804 (2018), and EF 2.0 also feature a subcategory for biogenic emissions only. ISO14067 uniquely contains a subcategory that summarizes emissions from aviation. Three LCIA methods, namely EDIP, EPD EN15804 (2014), and I02$^+$, contain no information in their description in the software regarding subcategories. However, the results of these methods indicate that they can be assigned to one of the subcategories. This result was further confirmed by reviewing the documentation on these LCIA methods and the flow implementation in the LCA software. These three LCIA methods were identified within the subcategory that includes biogenic carbon and includes or excludes LUC. Although EDIP and I02$^+$ include LUC, EPD EN15804 (2014) does not include LUC. Environmental federal points (UBPs) feature subcategories for LUC but do not clarify biogenic carbon processing. As stated above, the results indicated that biogenic carbon was not accounted for in the UBP method, and the documentation and flow investigation confirmed this conclusion.

As in the GWP category, the EP category can be split into subcategories for different compartments: terrestrial, aquatic, marine, or freshwater. TRACI, EPD EN15804 (2014), and CML have one general EP indicator, with no specification of the compartment. I02$^+$ and EDIP have two EP subcategories for aquatic EP and terrestrial EP. EF 2.0 features the same subgroups as EF 3.0 and EN15804 (2018): the freshwater EP, marine EP, and terrestrial EP. These three LCIA methods also showed the exact same results; therefore, only EF 2.0 was presented. ReCiPe had a freshwater EP and a marine EP subcategory.

Several subcategory indicators existed in the WA and were defined through the terminology and method for the WA following the UNEP/SETAC working group on water

Table 1 Midpoint indicator methodologies for the global warming potential, eutrophication potential, and water assessment

Global warming potential

Method, full name	Version	Documentation	Classification and characterization model	Ref. unit
CML: centrum voor Milieuwetenschappen, Universiteit Leiden	4.7 January 2016	Guinée et al. (2002)	Myhre et al. (2013a) IPCC (2013) AR5, Table 8.A.1, GWP 100[(a)]	kg CO_2 eq.
EDIP: environmental design of industrial products	2003	Hauschild and Potting (2005)	IPCC et al. (2001) + adaptations	kg CO_2 eq.
EF: environmental footprint	2.0	Fazio, Castellani, et al. (2018b)	IPCC et al. (2013) GWP_{100} + adoptions and carbon feedback included	kg CO_2 eq.
EF: environmental footprint	3.0	Fazio, Biganzoli, et al. (2018a)	IPCC et al. (2013) GWP_{100} + adoptions and carbon feedback included	kg CO_2 eq.
EPD: environmental product declaration (EN15804)	2014	NABau (2014)	CML method version 4.1 of October 2012 IPCC et al. (2007) AR4, Table 2.14	kg CO_2 eq.
EN15804: sustainability of construction works, environmental product declarations, core rules for the product category of construction products	2018	NABau (2018)	IPCC et al. (2013) GWP_{100}	kg CO_2 eq.
I02 + : impact 2002 +	2003	Jolliet et al. (2003)	IPCC et al. (2001) GWP_{500}	kg CO_2 eq.
ISO 14067: greenhouse gases, carbon footprint of products, requirements and guidelines for quantification	2019	ISO (2018)	IPCC et al. (2013) GWP_{100} + carbon feedback included	kg CO_2 eq.
IPCC: international panel on climate change 2013	2013	IPCC et al. (2013)	IPCC et al. (2013) AR5, Table 8.A.1, GWP_{100}	kg CO_2 eq.
ReCiPe: GWP 100	2016 (H) v1.1	Huijbregts et al. (2017)	IPCC et al. (2013) AR5, including climate carbon feedback, table 8.7 and supplementary material table 8.SM.15	kg CO_2 eq.
TRACI: tool for the reduction and assessment of chemical and other environmental impacts	2.1	Bare (2011)	IPCC et al. (2007) AR4, Table 2.14	kg CO_2 eq.
UBP: umwelt bundes punkte	2013	Frischknecht and Büsser (2013)	IPCC et al. (2007) AR4, Table 2.14	UBP

Eutrophication potential

Method, Full Name	Version	Documentation	Classification and characterization model	Ref. unit
CML: centrum voor Milieuwetenschappen, Universiteit Leiden	4.7, January 2016	2002Guinée ()	Heijungs et al. (1992), Additional factors are calculated by thinkstep for simple aliphatic hydrocarbons that are characterized stoichiometrically via the CF value for COD	kg phosphate eq.

Table 1 (continued)

Eutrophication potential				
Method, Full Name	Version	Documentation	Classification and characterization model	Ref. unit
EDIP: environmental design of industrial products	2003	Hauschild and Potting, (2005)	CFs for aquatic eutrophication are based on the CARMEN model. CFs for terrestrial eutrophication are based on the RAINS model	Aquatic kg NO_3 eq. Terrestrial m^2 UES
EF: environmental footprint	2.0	Fazio, Castellani, et al. (2018b)	Eutrophication terrestrial: accumulated exceedance Seppälä et al. (2006), Posch et al. (2008) Eutrophication aquatic–freshwater/marine: EUTREND model Goedkoop et al. (2009) as implemented in ReCiPe2008	Freshwater kg P eq. Marine kg N eq. Terrestrial mole of N eq.
EF: environmental footprint	3.0	Fazio, Biganzoli, et al. (2018a)	Eutrophication terrestrial: Accumulated Exceedance Seppälä et al. (2006), Posch et al. (2008) Eutrophication aquatic–freshwater/marine: EUTREND model Goedkoop et al. (2009) as implemented in ReCiPe2008	Freshwater kg P eq. Marine kg N eq. Terrestrial mole of N eq.
EPD: environmental product declaration (EN15804)	2014	NABau (2014)	CML method version 4.1 of October 2012 Heijungs et al. (1992)	kg phosphate eq.
EN15804: sustainability of construction works, environmental product declarations, core rules for the product category of construction products	2018	NABau (2018)	Eutrophication terrestrial: Accumulated Exceedance Seppälä et al. (2006), Posch et al. (2008) Eutrophication aquatic–freshwater/marine: EUTREND model Goedkoop et al. (2009) as implemented in ReCiPe2008	Freshwater kg P eq. Marine kg N eq. Terrestrial mole of N eq.
I02 +: impact 2002 +	2003	Jolliet et al. (2003)	Aquatic: Guinée (2002) + Hauschild and Wenzel (1998) Terrestrial nutrification: Eco99 Goedkoop and Spriensma (2001)	Aquatic kg PO_4 eq. Terrestrial kg SO_2 eq.
ReCiPe	2016 v1.1	Huijbregts et al. (2017)	Freshwater: Azevedo (2014); Azevedo, Henderson, et al. (2013); Azevedo, van Zelm, et al. (2013); Helmes et al. (2012) Marine: Cosme and Hauschild (2017); Cosme et al. (2015, 2018)	Freshwater kg P eq. Marine kg N eq.

Table 1 (continued)

Eutrophication potential				
Method, Full Name	Version	Documentation	Classification and characterization model	Ref. unit
TRACI: tool for the reduction and assessment of chemical and other environmental impacts	2.1	Bare (2011)	Bare (2011); Norris (2002)	kg N eq.

Water assessment				
Method, full name	Version	Documentation	Classification and characterization model	Ref. Unit
EF: environmental footprint	2.0	Fazio, Castellani, et al. (2018b)	AWARE Boulay et al. (2018); Canals et al. (2016)	m^3 world eq.
EF: environmental footprint	3.0	Fazio, Biganzoli, et al. (2018a)	AWARE Boulay et al. (2018); Canals et al. (2016)	m^3 world eq.
EPD: environmental product declaration (EN15804)	2014	NABau (2014)	NABau (2014)	m^3
EN15804: sustainability of construction works, environmental product declarations, core rules for the product category of construction products	2018	NABau (2018)	AWARE Boulay et al. (2018); Canals et al. (2016)	m^3 world eq.
ReCiPe	2016	Huijbregts et al. (2017)	Döll and Siebert (2002); Hoekstra and Mekonnen (2012); Pfister et al. (2009)	m^3
UBP: Umwelt Bundes Punkte	2013	Frischknecht and Büsser (2013)	Frischknecht and Büsser (2013)	UBP
AWARE: available water remaining	2018	Boulay et al. (2018)	Boulay et al. (2018)	m^3 world eq.

[a]The GaBi implemented version is CML Jan 2016. In this version, CML had implemented AR5 with errors. These were corrected in CML Aug 2016. However, the changes were evaluated to be too small to cause a re-implementation in GaBi and the Jan 2016 version with errors therefore remains

and the new ISO standard definitions (Bayart et al., 2010; ISO, 2015; Pfister et al., 2009). Four definitions in particular are important for the results in this category: freshwater, blue water, water use, and water consumption. Freshwater is defined as any water with a low concentration of dissolved solids. Blue water comprises freshwater that is removed from groundwater or surface water bodies, whereas rainwater is specifically excluded. Water use is the total water removal from a freshwater body (only inventory input), and consumption is the total water removal reduced by the water that is returned to the freshwater body (inventory input–output). Subcategories are available that include or exclude the impact of hydropower generation within the electricity mix used in an LCI. Hydropower generation, as a side effect, involves the evaporation of water from water reservoirs, which leads to an impact within the WA. However, there is great variance in the scale of these impacts that stems from their spatial dependency. Therefore, it is recommended to use both water impact indicators in a scenario analysis, including and excluding hydropower impacts (Pieper et al., 2018). The relatively new methods of the available water remaining (AWARE) and water stress index (WSI), in addition to water consumption, account for the availability or scarcity of water in a local area, and this entails characterized water flows with water scarcity-dependent factors [(inventory input–output) multiplied by scarcity (low, average, or high)].

The environmental impacts of the four scenarios were calculated for the LCIA methods (Table 1), and these results were plotted within each impact category. Because of various reference units and to highlight any potential influence on the scenario analysis of the selected LCIA method, the results were normalized within their respective LCIA method by dividing all four scenarios by scenario A. See Formula I, where i can be … A, B, C, or D, depending on the corresponding scenario, y_i … is the relative value of scenario i that is displayed in the figures, x_i … is the result of scenario i in the respective impact category, x_A … is the result of scenario A in the respective impact category, and hence y_A will always have the value of 1:

$$y_i = x_i / x_A \tag{1}$$

3 Results

The results are presented to highlight the differences in the scenario investigation. The reasons for these differences are elaborated in the discussion of this paper.

3.1 Global warming potential (GWP)

Because of the many LCIA methods for the GWP category and its subcategories, the results of the investigated methods are presented in three figures and similar subcategories are colored as follows: green for the total GWP impact including biogenic carbon, red for the land use change related to the GWP impact only, blue for the exclusively biogenic carbon GWP impact, and black for the fossil GWP impacts excluding the biogenic carbon impacts. The single impact subcategory of fossil GWP impact from aviation is colored in gray.

Figure 3 displays all subcategories, including biogenic carbon, with and without LUC. In this case, in the study's LCIA calculation, LUC made a small contribution within the GWP category; therefore, its inclusion or exclusion did not change the results significantly.

The same was found for the subcategories excluding biogenic carbon GWP impacts, including or excluding LUC (Fig. 4). The fossil GWP impact from aviation is displayed in Fig. 4 with little difference from the other fossil-only subcategories.

When looking at the LUC-only subcategories, the differences in the four scenarios were insignificantly small (Fig. 5). In the LUC-only subcategory, all LCIA methods investigated agreed on the scenario analysis, and there was little to no variation.

A similar outcome was found in the GWP subcategory "including biogenic carbon" and the GWP subcategory "excluding biogenic carbon." All the LCIA methods exhibited the same outcome for the scenario analysis and agreed that scenario B was the most favorable of the three subgroups, "including biogenic carbon," "excluding biogenic carbon," and "only LUC."

The three "biogenic carbon only" GWP methods, displayed in Fig. 5, showed similar trends within the subcategory, increasing the CO_2 equivalent from scenarios A to D. However, the EF 2.0 method recorded a substantially larger increase than the other two methods, ISO14067 and EN15804 (2018), and thus, a second axis was used in Fig. 5 to better present the results.

3.2 Eutrophication potential (EP)

Figure 6 displays the EP results for the four scenarios calculated by the EP LCIA methods from Table 1.

The two LCIA methods with the subcategory of freshwater EP presented the same result, favoring scenario A. The results of the terrestrial EP agreed within its subcategory, with minimal variations, but favored scenario B. The subcategory of aquatic EP showed significant divergence for the scenario analysis but still agreed on scenario A as being the most favorable. The two marine EP subcategory methods diverged regarding the most favorable scenario, with ReCiPe identifying scenario A as the best and EF 2.0 identifying scenario B as the best. The general EP LCIA methods showed the strongest divergence. Although CML clearly favored scenario D by some margin and suggested scenario A as the worst scenario, TRACI and EPD EN15804 (2014) favored scenario A and concluded that scenario D was the worst.

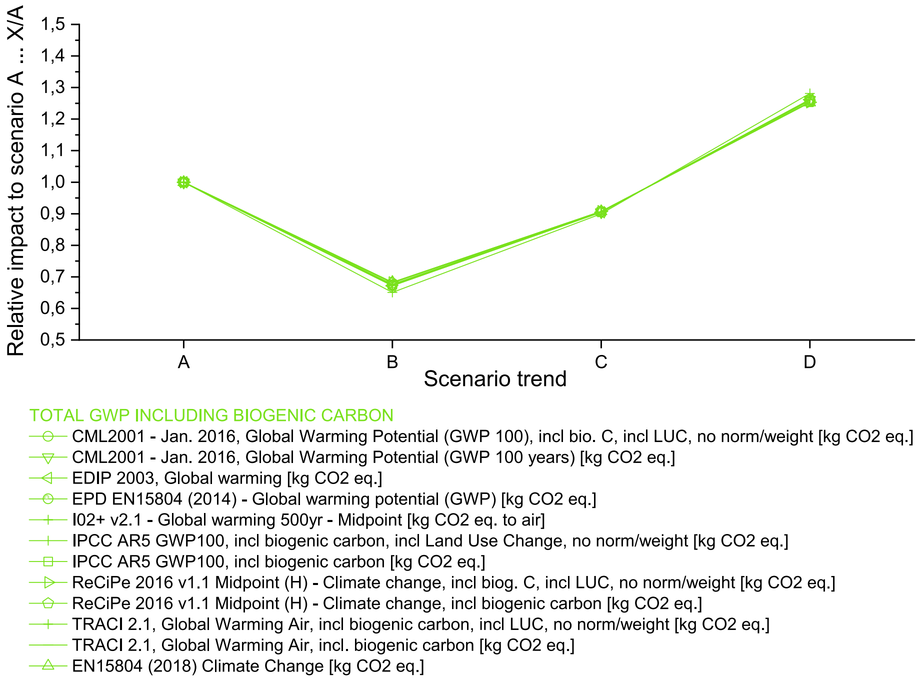

Fig. 3 Environmental impacts in the global warming potential subcategory including biogenic carbon (with and without land use change) calculated using different life cycle impact assessment (LCIA) methods. The results within an LCIA method are related to scenario A, as described in 2.3 Methods

3.3 Water assessment (WA)

Figure 7 displays the results of the water impact calculated for the four scenarios. Three graphs were chosen to provide a better overview of the different LCIA methods, which are represented by abbreviations that are explained in Table 2. The general indicators from the LCIA methods that were also represented in the other impact categories of GWP and EP were displayed in the left graph of Fig. 7: EF 2.0, ReCiPe, UBP, and EN15804 (2014). Again, EF 3.0 and EN15804 (2018) showed the exact same results as EF 2.0; therefore, only EF 2.0 was presented. Water indicators that included characterization, namely AWARE and WSI, were in the middle graph. These methods, in addition to water

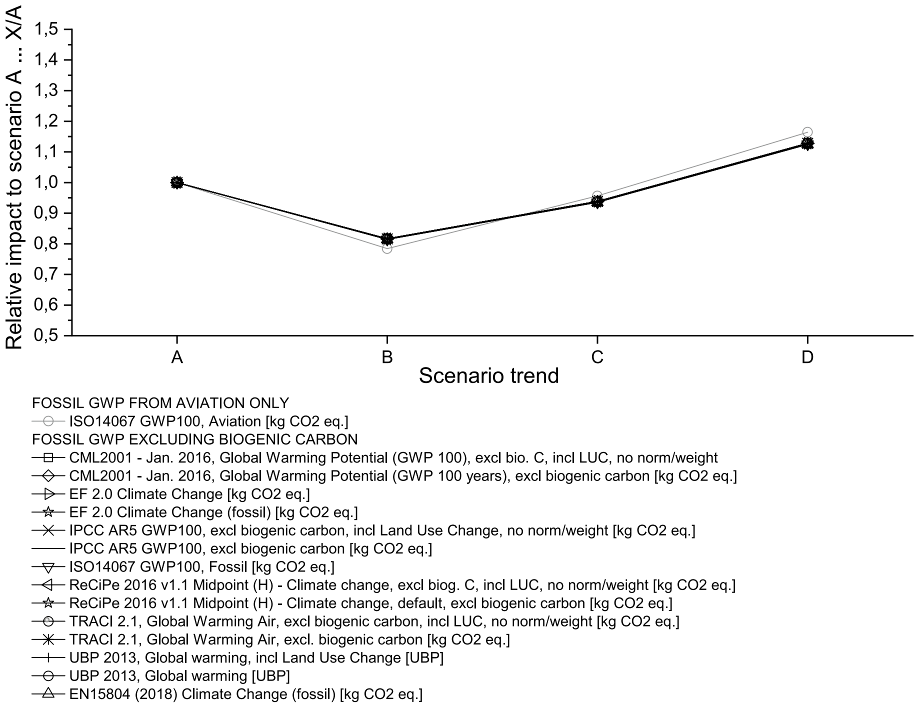

Fig. 4 Environmental impacts in the global warming potential subcategory excluding biogenic carbon (with and without land use change) calculated using different life cycle impact assessment (LCIA) methods. The results within an LCIA method are related to scenario A, as described in 2.3 Methods

consumption, accounted for the local water availability with scarcity factors. Total freshwater and blue water use and consumption methods are presented in the right-hand graph.

Although the EF 2.0 indicator showed minimal changes from scenario to scenario, UBP and, even more so, EN15804 (2014) and ReCiPe exhibited a larger change. Although scenario C had the lowest value for UBP, EN15804 (2014) and ReCiPe, scenario B was the best case for the LCIA method of EF 2.0. The AWARE and WSI methods varied in their scenario behavior only in terms of magnitude. Both methods agreed on scenario B as being the best, but the AWARE method, with a low characterization factor and also including hydropower water utilization, displayed a different scenario as the worst case, namely scenario D instead of scenario A. The average and high characterization factor methods with and without hydropower generation showed little difference. The WSI low characterization factor methods also showed a larger difference in magnitude than did the low characterization factor methods of AWARE. Considering the water consumption indicators, the blue water consumption indicator, excluding hydropower, clearly favored scenario B, whereas the blue water consumption indicator, including hydropower, highlighted scenario C as the most favorable, with only a small margin relative to scenarios B and D. Among the indicators of total freshwater consumption with and without hydropower, there was a minimal difference including and excluding hydropower. The total freshwater and blue water use indicators favored scenario A when hydropower was excluded, whereas the same indicators favored scenario B when hydropower was included.

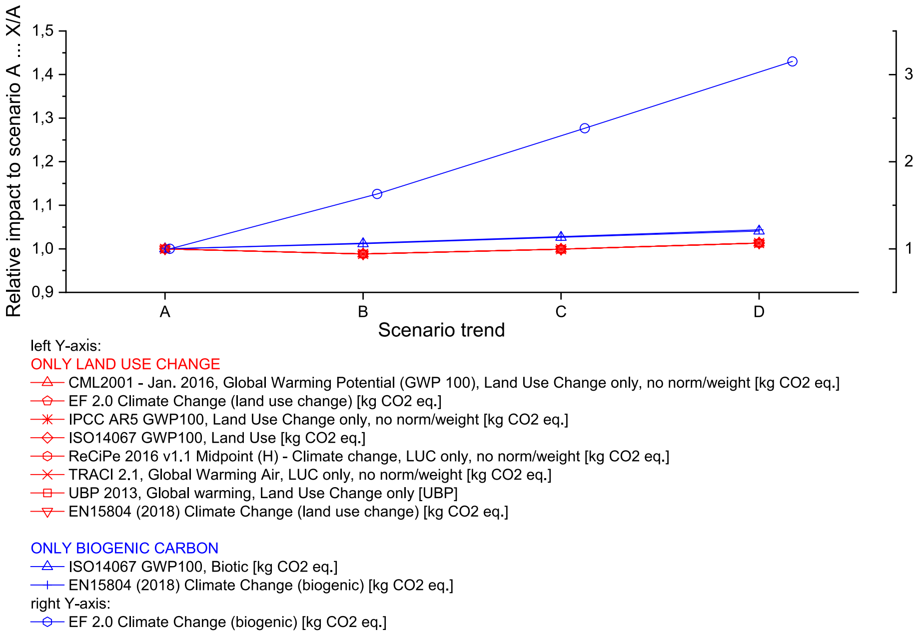

Fig. 5 Environmental impacts in the global warming potential subcategories “only land use change” and “only biogenic carbon” calculated using different life cycle impact assessment (LCIA) methods. The results within an LCIA method are related to scenario A, as described in 2.3 Methods

4 Discussion

The results demonstrated that the selected LCIA method had an influence on certain impact categories or subcategories of the scenario analysis in this case study. LCA scenarios for process development are designed to assess interactions between process variations or different process paths and life cycle inventories with subsequent environmental impacts. When the best-case scenario in an impact category changes in the selection of a different LCIA method, e.g., as was the case with marine eutrophication, it may influence the conclusions and interpretations of the LCA and therefore affect the decision support for the process setup during development. If the reasons for the differences are not assessed and evaluated, even more ambiguous conclusions can arise when opposing trends in the scenario progression are observed in the same impact category on selecting a different LCIA method, as was the case with the general eutrophication indicator of CML and TRACI.

In an interview and assessment with Sphera Solutions (the software and database developers of GaBi), several possible reasons were identified that could potentially cause issues in the LCIA methods and lead to different results across comparable impact categories.

Scientific findings are the basis of the methods in each impact category, and their progress varies in each category. Within the GWP category, which is one of the most agreed upon and least disputed in LCA among method developers and implementers, scientific progress is incorporated continually every 5–7 years using the Intergovernmental Panel on Climate Change (IPCC) reports on climate change (IPCC et al., 2001, IPCC et al., 2007, IPCC et al., 2013). However, not all the LCIA methods investigated always use of

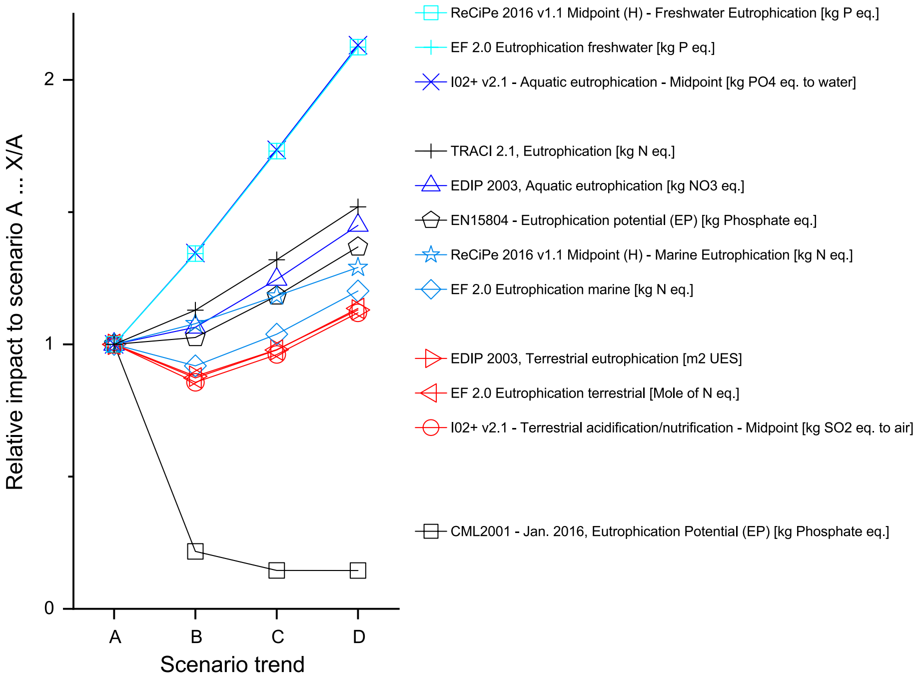

Fig. 6 Environmental impacts in the eutrophication potential category calculated using different life cycle impact assessment (LCIA) methods. The results within an LCIA method are related to scenario A, as described in 2.3 Methods. The LCIA method subcategories are distinguished by the different colors

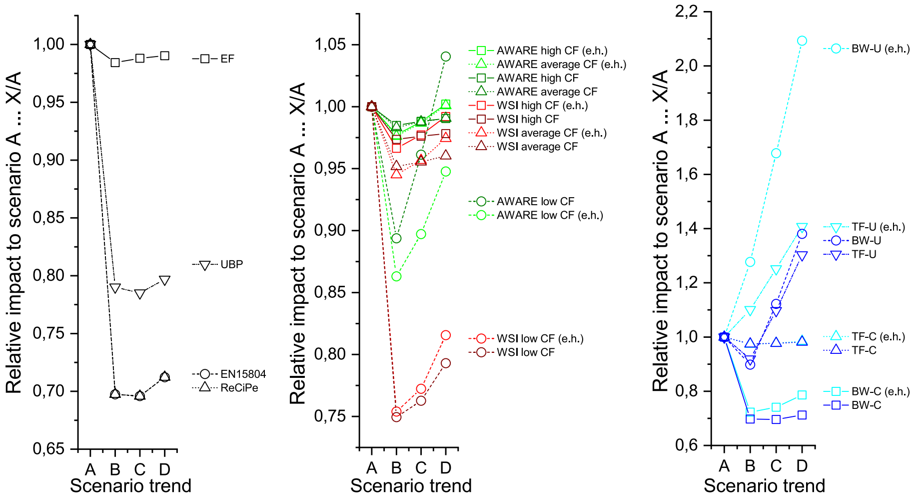

Fig. 7 Environmental impact in the water assessment categories calculated using different life cycle impact assessment (LCIA) methods. The results within an LCIA method are related to scenario A, as described in 2.3 Methods. The LCIA method subcategories are distinguished by color and presented in three different graphs for a better presentation of the results. The general water indicators are presented in the left-hand graph, the AWARE and WSI water indicators are shown in the middle graph, and the freshwater and blue water use and consumption methods are displayed in the third graph

Table 2 Explanation of the LCIA method abbreviations from Fig. 7

Legend short name	Full name
EF	EF 2.0/3.0 Water scarcity
UBP	UBP 2013, Water resources
EN15804	EPD EN15804 (2014)–use of net fresh water
ReCiPe	ReCiPe 2016 v1.1 Midpoint (H)–freshwater consumption
AWARE/WSI	
High CF	High characterization factor for unspecified water
Average CF	OECD + BRIC average for unspecified water
Low CF	Low characterization factor for unspecified water
(e.h.)	Excluding hydropower
BW-U	Blue water use
BW-C	Blue water consumption
TF-U	Total freshwater use
TF-C	Total freshwater consumption

the newest IPCC reports for their impact assessments; even if they use the latest available report, the IPCC publishes many tables with partly different GWP values and no explicit recommendation for which to use in LCAs, e.g., Table 8.A.1 (IPCC et al., 2013) and Table 8.SM.16 (Myhre et al., 2013b). This uncertainty leaves the choice to the method developer, database generator, or software implementer. Impact 2002 + and EDIP derive values from the IPCC report from 2001, and TRACI and UBP utilize values from 2007. Despite using different IPCC reports, these methods agreed on the scenario analysis of this case study LCA, and no major influence was seen on its outcome in the GWP category in terms of the differences in their scientific progress. The EP classification and characterization model sources in Table 1 demonstrate various studies from the last 30 years as the basis for the EP LCIA methods, for example, the CML eutrophication potential method (Heijungs et al., 1992). Fewer resources might be available for the scientific advancement of this impact category compared to the GWP, and thus, global political attention would not be drawn, as EP is a fairly regional or local and spatially significant impact. In addition to the water use and water consumption indicators, more sophisticated and newer indicators, such as AWARE and WSI, seek to further include the spatial aspects that are also important to the WA. Local water body conditions are required to assess the water availability in a region. There is a need to further advance research on how to manage the spatial aspects effectively and efficiently. The spatial importance can be seen in newly developed methods such as the IMPACT World + globally regionalized life cycle impact assessment (Bulle et al., 2019).

The reference unit of the indicator could lead to a different absolute result and might influence the scenario analysis if different impact calculation models are applied. Although all of the GWP methods investigated use the reference unit kg of CO_2 equivalent, apart from the UBP method, seven different reference units were found in the EP LCIA methods included, which may cause differences in the results, as seen in the aquatic EP subcategory. Different methods and their characterization factors are more or less sensitive to different emissions. In the WA conducted, four different reference units were observed. Although we looked at relative values in this study, where no significant influence was measured, the absolute values, which can also be important for process development, might exhibit a different picture and should be investigated in future research.

Each impact category can highlight particular issues in its description of the LCIA model. For the GWP category, biogenic carbon is a special case and is treated in two general approaches that include or exclude biogenic carbon. When included, the uptake of atmospheric CO_2 within the cultivation of biomass is accounted for as a CO_2 incorporation into the biomass (plus the related CO_2 withdrawal from the atmosphere) and, consequently, the emitted greenhouse gases of biogenic origin must be accounted for as well, with the full impact calculated. This method would potentially make biogenic emissions carbon neutral. If biogenic carbon is excluded, CO_2-equivalent incorporation for biomass cultivation and its withdrawal from the atmosphere is neglected, and there is no impact (biogenic carbon CO_2-equivalent) when greenhouse gases that originate from biogenic sources are emitted. However, special attention should be given to the transformation of biogenic carbon, that is, if the CO_2 incorporated is transformed into CH_4 and emitted as such. Methane has a higher GWP than CO_2: 1 kg of CO_2 can be transformed into 0.36 kg of CH_4, and when emitted, it will have an IPCC GWP100 impact of 10.93 kg CO_2-equivalent. This could lead to suboptimal outcomes if biogenic carbon is simply forgotten. The carbon balance is easier to reproduce if all carbon is included, as it can be difficult to separate biogenic carbon from fossil carbon incorporated in products (e.g., composites of wood and plastic, partial biogenic plastics or bioethanol in various fuels blended in with different percentages). Regardless of the selected method, it is important to maintain consistency throughout an analysis to avoid the double-counting of biogenic carbon and consider possible anaerobic transformations to methane. This problem is also recognized in the LCA of buildings, as in the paper investigated by Hoxha et al. (2020). The individual goal and scope of any study should inform a decision to exclude or include biogenic carbon, and therefore, it is an advantage to have both options available. In this case study, where the scope was cradle-to-gate, the selected biogenic carbon management process could have had an effect. However, the scenario analysis indicated some differences but agreed on the best and worst cases. For process development in general, cradle-to-gate is a common scope; therefore, both biogenic carbon management approaches should be investigated. The larger increase in the subcategory "biogenic carbon only" of EF 2.0 could be explained through the characterization table, since EF 2.0 exclusively assesses biogenic emissions from methane, whereas in the other two methods, biogenic methane makes only a small contribution. The dominant flow, next to the other flows, is the biogenic carbon uptake within the renewable resource of wheat straw. As methane increases equally in all three methods, the contribution to the results is low in the ISO14067 and EN15804 (2018) methods and is very prominent in EF 2.0, illuminating the difference. Table 3 displays the flow characterization of the three "biogenic carbon only" subcategories.

EF 3.0 and EF 2.0 featured the exact same results; therefore, only EF 2.0 was presented here. The LCIA method of EN15804 (2018) is based on EF 3.0, with the difference being biogenic carbon. Although the latter method excludes all biogenic carbon flows apart from biogenic methane, the former incorporates biogenic carbon uptake and reemission.

The EP category also exhibited a special issue in that the actual impact of a substance on the EP depends on the nutrients available within the affected area. If nitrogen is the limiting nutrient and phosphorus is emitted, there will be a smaller impact than in the case where phosphorus is the limiting nutrient. Carbon is also required for biomass growth; however, in most cases, it is not the limiting factor. The methodological challenge was also recognized by a case study on farms in New Zealand, which showed that it is necessary to couple the N and P emissions since both can be the limiting factors (Payen & Ledgard, 2017). This issue influenced our results, as the LCIA method of CML takes carbon emissions into account in the EP, whereas other EP LCIA methods do not, which results in different outcomes because of the sensitivity of a single substance. In scenario A, emitted ethanol was responsible for 96% of the environmental impact in the CML LCIA method for EP. In scenarios B, C, and D, more ethanol was recovered and less ethanol was emitted (a reduction of 82–91 mass% of ethanol emissions), reducing the EP drastically in the CML results. This single substance sensitivity is important to highlight and is best identified by utilizing a sensitivity analysis, as suggested in the methodological review on the life cycle interpretation phase by Laurent et al. (2020). In terms of process development, it is not clear, for example, where the biorefinery will be built and which nutrient could be the limiting factor. All EP-relevant substances should therefore be investigated.

For the water impact, a particular issue is water loss when utilizing hydropower. In the modeling principles for the WA in GaBi, it was highlighted that the actual loss of water in hydropower reservoirs depended strongly on the conditions of the location of the hydropower generation (Pieper et al., 2018). A relevant uncertainty—still in discussion among hydroscientists—exists with respect to acceptable amounts of water loss by these hydropower plants, and it is recommended to use both indicators, including and excluding hydropower, for sensitivity analysis (Bakken et al., 2017; Scherer & Pfister, 2016). This case study and the scenario investigation, including and excluding hydropower, showed a significant change in the magnitude of the results of some water indicators. Virgin ethanol production showed a larger impact in the freshwater use and blue water use subcategories when including hydropower impacts due to the use of hydropower within the dataset of virgin ethanol production; therefore, scenario B (where more ethanol is recovered and less virgin ethanol is produced) was more favorable. In scenarios C and D, the water used for ethanol recovery outweighed the savings from virgin ethanol production, and a minimum was found in scenario B. When excluding hydropower, virgin ethanol production had a smaller share of impacts; therefore, in this impact category, the water used for ethanol recovery outweighed the virgin ethanol production savings in each scenario. For the consumption indicators, virgin ethanol production exhibited, for both cases, i.e., including and excluding hydropower, the same smaller share of the impact, and therefore, smaller differences between the methods were observed.

Referring to the source of the classification and characterization model can sometimes be ambiguous, as the IPCC published two tables in its report of 2013: Table 8.A.1 (IPCC et al., 2013) and Table 8.SM.16 (Myhre et al., 2013b). The latter includes the effects of climate–carbon feedbacks for other substances rather than only CO_2. Most methods base their GWP calculation on Table 8.A.1. Although the characterization factors differ significantly for single substances, the scenario analysis in this case study had little influence when comparing two methods that utilized the two different tables: ReCiPe 2016 (h) v1.1 and CML 4.7. A generally recommended table in future IPCC reports would be beneficial to avoid confusion.

The depth of characterization, classification, and scope are important to capture all potentially relevant emissions. More substances are included in each update of the IPCC report for the GWP, from TAR (IPCC et al., 2001) with 42 flows to AR4 (IPCC et al., 2007) with 63 flows to AR5 (IPCC et al., 2013) with 207 characterized flows. In this case study, no uncommon emissions were assessed, and therefore, no influence from the depth of characterization was observed in the GWP category results. However, in the process development of innovative technologies, novel emissions are more likely to occur that are not yet characterized by the LCIA method, which is especially challenging for categories concerning human exposure pathways (Ernstoff et al., 2019). The EP category faces the

Table 3 Characterized flows for the "biogenic carbon only" subcategories from EF 2.0, ISO 14067, and EN15804 (2018)

Flow	1 [flow] = * CO_2 eq		
	EF 2.0	ISO14067	EN15804 (2018)
Carbon dioxide (biotic) [inorganic emissions to air]	0	1	1
Carbon dioxide [renewable resources]	0	1	1
Carbon dioxide, non-fossil [ecoinvent long-term to air]	0	1	1
Carbon monoxide, non-fossil [ecoinvent long-term to air]	0	n.a	1.57
Carbon monoxide, non-fossil [inorganic emissions to air]	0	n.a	1.57
Methane (biotic) [organic emissions to air (group: VOC)]	34	28	36.75
Methane, non-fossil [ecoinvent long-term to air]	34	28	36.75

same challenge, i.e., how to manage limiting and nonlimiting nutrients. Within the marine EP, we noted differences in the scenario results comparing the method of ReCiPe 2016 (h) with 33 characterized flows and the EF 2.0 method with 46 characterized flows. Moreover, a difference in the aquatic EP results between the method of impact 2002+(15 characterized flows) and EDIP (59 characterized flows) was observed, and they also featured different referencing units (PO_4- and NO_3-equivalents) as the indicator. However, similar to water utilization, the EP is highly dependent on local circumstances. Therefore, the depth of characterization (or specification) within the EP category and the WA further included the spatial resolution. Advancements were seen as the characterization factor became available within the AWARE and WSI indicators to consider different water scarcity regions (Boulay et al., 2018; Pfister et al., 2009). In addition to the depth of characterization of an LCIA method, it is important to utilize standardized flow lists; otherwise, implementation in LCA software will be challenging and can lead to an incomplete application of the method. The importance of these lists was also highlighted in the critical review from Edelen et al. (2018).

Human error can always be a source of variation. Errors can be introduced by method developers, database developers, software implementers, and users. First, the error must be detected, then qualified, and, finally, its relevance must be assessed to identify responsibilities and define a suitable way to correct it. For instance, an inconsistency was noticed in the CML version 4.7 January 2016 categorization table for the GWP. The correct values were updated with the CML version 4.8, August 2016 update; however, this was considered too small and insignificant for a new reimplementation by Sphera Solutions GmbH into GaBi, and therefore, the CML 2016 August update was not implemented and distributed immediately but rather was included in the next official release. Considering the scenario analysis, no significant differences were sourced by this variation when considering CML 4.7 2016 January and IPCC, 2013. However, typically, only small errors such as this continued to go unnoticed, and they had no impact on the scenario analysis.

In addition to the selected LCIA method and the issues discussed, implementation within the software also matters, as Herrmann and Moltesen (2015) noted some differences in the results of 100 randomly selected, single-unit processes from the ecoinvent database 2.1 between the LCA software GaBi and SimaPro. In many cases, each software showed identical results, but where differences occurred, there were rarely errors and, more often, different implementations of the LCIA method and the elementary flows used seemed to be the main sources of the deviations.

5 Conclusions

In this study, the influence of the selected LCIA method on the interpretation of LCA within process development was examined critically with the help of scenario analysis that drew on a biorefinery case study. The influence of the LCIA method on certain impact categories and subcategories was identified and enumerated. For the GWP category, the 42 subcategories investigated from 12 different LCIA methods exhibited consistent interpretations in this case study. The depth of characterization and biogenic carbon management were identified as potential issues for LCAs in process development that could influence interpretations and which should therefore be used with care. In the EP category, significant differences were observed within 18 subcategories across nine different LCIA methods. In addition to the variations due to the subcategories, there were differences within the same subcategory of marine eutrophication potential, where scenario A was preferred in the LCIA method of ReCiPe 2016 v1.1 and scenario B was preferred in the LCIA method of EF 2.0. Strong divergence in the EP indicators of CML, TRACI, and EPD EN15804 (2014) was also noted. The problem was partially identified within the characterization of limiting and nonlimiting nutrients in the different LCIA methods. In the WA, 26 subcategories from 10 LCIA methods were compared. The best-case scenario for blue water consumption depended on whether hydropower was included. Although the indicators from EF 2.0/3.0 and EN15804 (2018) showed little variation in the scenario assessments, the indicators from UBP and, even more so, from EPD EN15804 (2014) and ReCiPe, exhibited larger changes.

The influence on the interpretation changed the best and worst cases, showed opposite trends, and changed the magnitudes, which could influence the conclusions of an LCA in process development. Nevertheless, there are many methods to choose from, each of which is derived from a justified environmental impact issue and is, therefore, valuable. As long as it is stated clearly which method is used and interpreted, the variations that arise are comprehensible. The detailed citation of the LCIA method used, including its version and/or publication year, is important to avoid unjustified criticism of LCAs, such as their being ambiguous or even arbitrary. The selection of the LCIA method is equally important to that of the impact category. One or several possible iterations in selecting the LCIA method and comparing the various LCIA methods would enhance and solidify LCA results for process development purposes. To be in agreement with the ISO14040 and ISO14044 standards, it is recommended to examine whether different LCIA methods lead to different scenario results. Furthermore, the "behavior" and specific characteristics of an LCIA method must be understood as being suitable to draw adequate conclusions. Our discussion demonstrated a continuous need for further dialog between the various models and indicated that the impact characterization should be standardized.

We recommend assessing several, if not all, LCIA methods available, which normally entails little extra effort if using any of the available LCA software tools. When differences occur between methods, the following steps can help explain these, and if not, they help to transparently show that they differ:

- What underlying classification and characterization models and versions are used for the categories or subcategories of the used LCIA methods (e.g., utilized IPCC report and table)?
- Is there a difference between the reference unit of each LCIA method and could there be a difference in its implementation (e.g., are carbon emission considered for the eutrophication potential or only nitrogen- and phosphorus-containing substances)?
- Does the depth of characterization differ in the investigated LCIA methods (e.g., comparing the number of characterized flows)?
- Is there a single driver for most of the impact in the investigated impact category or subcategory, and is that one driver handled differently by different LCIA methods?
- Does this impact category or subcategory show special issues that require attention (e.g., GWP biogenic carbon, EP limiting nutrients, water impacts from hydropower)?
- Could the identified variation between two LCIA methods be derived from human error (e.g., wrong value in the implemented flow table)?

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Data availability The described database version and methods were used without alternation.

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Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Consent for publication All authors consent to the publication of the article.

Ethical approval This paper does not contain any studies with human participants or animals performed by any of the authors.

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