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Attachment 2

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POLICIES AND SUPPORT IN RELATION TO LCA

LCA standards for environmental product assessments in the bioeconomy with a focus on biogenic carbon: A systematic review

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Abstract

Purpose Climate change mitigation is one of the priorities of the European Bioeconomy Strategy (BES). In this regard, renewable raw materials are a crucial resource, as they help to substitute fossil resources and reduce greenhouse gas (GHG) emissions by storing biogenic carbon (C). To control the environmental impact of the European BES, the life cycle assessment (LCA) is the preferred method. Standards provide guidance for LCA. This review aims to present the state of the art of LCA-related standards, focusing on the assessment of biogenic C and its global warming potential (GWP) to evaluate them for decision-making with regard to the transition to a bioeconomy (BE) and climate change mitigation.

Methods A systematic review is conducted using the database Nautos to reveal the relevant standards guiding LCA in the BE. In an iterative process, criteria for a comparative analysis are defined. The eligible standards are then qualitatively analysed and compared based on criteria previously derived in the iterative process.

Results and discussion In the context of LCA and bio-based products, 13 documents are identified. Differences are revealed in the accounting of biogenic C flows, the calculation of the duration of biogenic C storage and the biogenic C content as well as the consideration of substitution effects. Furthermore, the standards do not provide any information on the assessment of biogenic C in the circular economy so far.

Conclusion The importance of biogenic C aspects in LCA has been reflected in the standards over the last 20 years. However, further research is needed to harmonise the different aspects and integrate new relevant ones related to biogenic C and BE to support decision-making for the transition to a BE. This becomes more important as new legislation refers to LCA standards as the preferred assessment method.

Keywords Life cycle assessment (LCA) · Bioeconomy (BE) · Standards · Bio-based products · Biogenic carbon (C) · Substitution potential · Displacement factor (DF) · Carbon storage

1 Introduction

1.1 Transformation from a fossil to a bio-based economy

It is becoming increasingly clear that a transformation of the global economic system is necessary to ensure the sustainable use of natural resources and achieve sustainable production and consumption. The bioeconomy (BE) has emerged as a strategy highly accepted all over the world to guide this transformation (Aguilar et al. 2019; Ferreira et al. 2022; Vivien et al. 2019). In addition, BE is seen as part of an overall solution for climate change mitigation, which is the focus of this review, as well as biodiversity, defossilisation and resource scarcity (Bröring et al. 2020; Debref et al. 2022; Kuckertz et al. 2020). With regard to climate change mitigation, the importance of bio-based materials or products for the transformation to a BE mostly relates to biogenic carbon (C) (Dees et al. 2023; Kallio et al. 2023; Kundzewicz et al. 2023). Since 2017, interest in research has globally increased, particularly in Europe and Germany, followed by the USA, which made the largest contribution (Ferreira

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et al. 2022). The environmental impact assessment was categorised as the most important, followed by the economic assessment and, to a lesser extent, the social assessment. Thereby, the categories land use (LU) and climate change are focal points in the BE research and policy (Ferreira et al. 2022; Wesseler and Braun 2017). The present review focuses on the climate change impact category and the emission metric global warming potential (GWP) to provide a narrowly defined but in-depth review.

The BE has been comprehensively incorporated into policy. For example, the European Bioeconomy Strategy (BES), which evolved from several previous programmes and strategies, was adopted as a comprehensive framework in 2012 and updated in 2018 (European Commission 2012a, 2018b). The update has placed more emphasis on circular economy (CE) and sustainability rather than on substitution. Climate change mitigation and defossilisation are two of its five main objectives (European Commission 2018b). There are similar developments at the national level, for example, the German BES (BMBF and BMEL 2020). The European and German BES share many similarities, with nuanced variations in focus (Egenolf and Bringezu 2019). Other countries and regions are also moving in the same direction and pursuing BES (Besi and McCormick 2015; Dietz et al. 2018; Meyer 2017; Verkerk et al. 2022). Furthermore, in the construction sector in particular, the use of wood products has been identified as a fundamental part of the European BES and for initiatives such as the New European Bauhaus due to the storage of biogenic C (European Commission 2023d). For the environmental assessment of the BES, the life cycle assessment (LCA) method is recommended for the assessment of bio-based products and systems (European Commission 2019a). To further track progress towards a sustainable BE, the European Bioeconomy Monitoring System has recently been developed (European Commission 2023c).

1.2 Definition of the BE

There are numerous definitions of the BE (Bugge et al. 2016). However, they all have the overarching goal of creating, developing and revitalising economic systems based on the sustainable use of renewable biological resources (Aguilar et al. 2019; Bröring et al. 2020). In line with the OECD definition, BE is understood as an economy in which the basic building blocks for materials, chemicals and energy are obtained from renewable biological resources such as plants and animals (McCormick and Kautto 2013; OECD 2009). Talwar and Holden (2022) identified key elements of the BE as (i) the substitution of fossil with renewable resources to produce bio-based products, (ii) the idea of using renewable biological resources and (iii) the transition to a sustainable economy. It covers a broad range of industries that differ in terms of technological progress and value chains (Bell et al. 2018; Bugge et al. 2016). Recently, the CE aspect has become more prominent in the BE to avoid linear business approaches. This is primarily due to the fact that biogenic C is stored over the product life cycle and can be further retained through a cascade use of secondary raw materials before it is finally utilised for energy production. As a result, the concepts of BE and CE are merged into a circular bioeconomy (CBE) (Jarre et al. 2020; Stegmann et al. 2020). The CE has its origins in waste management and waste hierarchy and focuses on prevention, reuse, recycling and recovery instead of waste treatment or disposal (Kirchherr et al. 2017; Teigiserova et al. 2020). The CE has gained wider visibility with the Ellen MacArthur Foundation's so-called butterfly model, which extends the circular concept to a technical and biological cycle and specifies further pathways such as reprocessing and remanufacturing beyond recycling and recovery (Ellen MacArthur Foundation 2013). Stegmann et al. (2020) have identified three approaches to CBE that differ in terms of the relationship or hierarchy between BE and CE. Some define BE and CBE as part of CE or interpret CBE as an umbrella term for BE and CE, while the definition of CBE as an intersection of BE and CE is more widespread in the literature. Based on the identified key elements, CBE is defined as a sustainable, resource-efficient utilisation of biomass in integrated production chains with multiple production stages, where residues and waste are also used and the value of biomass is optimised over time through cascading (Stegmann et al. 2020). At the product level, the bio-based value pyramid ranks the various product groups pharmaceutical and fine chemicals, food and feed, bioplastics and biopolymers, bulk chemicals and materials and energy, heat and fuels in descending order of volume and ascending order of value for the BE (Stegmann et al. 2020).

A bio-based product is defined as a product that is entirely or partly derived from biomass (EN 2014). With regard to the transition to a BE, the relevance of the product groups of the bio-based value pyramid in terms of value and volume must change. Bioplastics and polymers as well as bulk chemicals and materials are in focus of research and seem to gain in importance and market share (Mitchell et al. 2024; Shah et al. 2020). Energy, heat and fuels from biomass are supposed to be surpassed by other renewable energies not based on biomass (European Commission 2021a). Figuratively speaking, the bio-based value pyramid (Fig. 1a) has to be changed into a bio-based value onion (Fig. 1b) to achieve the goals of the BE. To summarise, the BE is based on the idea of applying biological principles and processes in all areas of the economy and increasingly replacing fossil with renewable raw materials (Dietz et al. 2018).

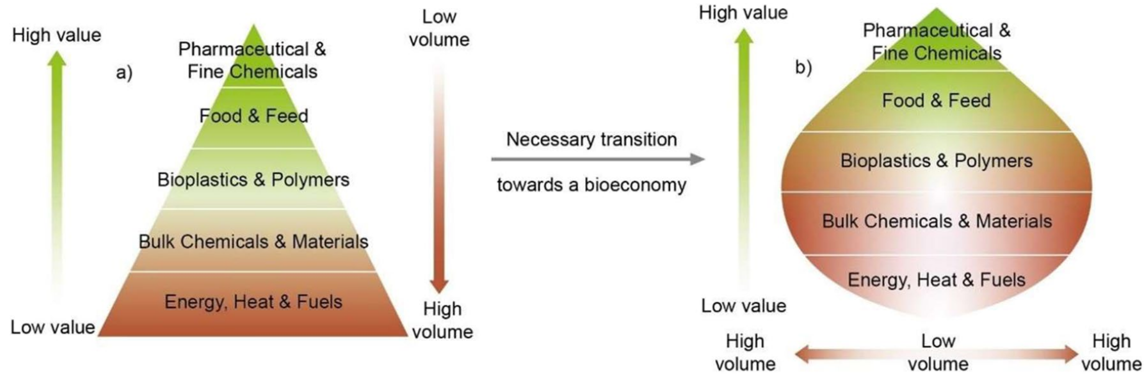

Fig. 1 Transition of the bio-based value pyramid (**a**) (adapted with permission from (Stegmann 2022)) towards a bio-based value onion (**b**) (own illustration) for the BE

1.3 State of research of the assessment of biogenic C

LCA is perceived to be robust and the most appropriate method for assessing the environmental impact of the BE (Ferreira et al. 2022). However, due to the large number of standards and guidelines that have emerged over the last 20 years, the robustness of the LCA as a decision-support tool is partially undermined (Brandão et al. 2024). With regard to BE materials and products, Pawelzik et al. (2013), Ahlgren et al. (2015) and Peñaloza et al. (2016) have illustrated differences in LCA standards before. Their methodological issues focus on allocation in multifunctional processes, land use change (LUC) and storage of biogenic C. Similarly, Klein et al. (2015) address the lack of standardised methods and guidelines based on a review of LCA studies. Consequently, the results of LCA are not comparable. The Product Environmental Footprint (PEF) method is intended to harmonise LCA approaches, but the analysis by Bach et al. (2018) shows that the method and the PEF category rules (PEFCR) cannot guarantee comparability. Referring to construction materials, Tellnes et al. (2017) emphasise that a more differentiated modelling of biogenic C needs to be considered in LCA standards or Environmental Product Declarations (EPD), which in particular takes into account the biogenic C uptake and release during the life cycle phases of a product. This is especially important for the construction sector, as construction materials are intermediate products, of which the C content at the factory gate is of interest in LCA studies. In addition, this information must be made available in the Supplementary Information (SI) beyond the life cycle of the building (EN 2022). Furthermore, Wang et al. (2018) applied different greenhouse gas (GHG) standards to assess a medium-density fibreboard. They mention discrepancies in the carbon footprint of products (CFP) assessment about the cut-off criteria, the system boundaries and the accounting of biogenic C emissions and their storage. Recently, Pinto et al. (2023) pointed out methodological inconsistencies between different standards in terms of C storage and circular systems. Furthermore, they also recommend developing harmonised standards and practices between sectors. Beyond, Tellnes et al. (2017) ask for harmonised definitions of technical and environmental aspects in standardisation to ease the understanding and the use of the standards. The rising need for harmonisation is addressed by the "Biogenic Carbon Project" of UNEP, which aims to produce succinct and harmonised technical guidance on biogenic C in LCA studies of bio-based products and services (UNEP 2023). These considerations prompt an inquiry into the current state of existing LCA standards pertinent to the BE, with a particular focus on the evaluation of biogenic C. In this context, the following research questions (RQ) are to be answered:

RQ 1 Which standards exist and are relevant for LCA in the BE?
RQ 2 Which aspects/criteria are considered in the LCA standards for the assessment of bio-based products in the BE?
RQ 3 What are the differences in the LCA standards for the assessment of BE products?

The aim of the review is to analyse whether the LCA standards provide uniform and cross-sectoral methods and guidance for assessing and understanding the environmental impact of the BE. It also aims to determine whether these provide sufficient information on climate change mitigation and defossilisation to support decisions on the transformation towards a BE. Thereby, particular attention is paid to the assessment of biogenic C, as bio-based resources and products in the BE mostly refer to biogenic C (Dees et al. 2023; Kallio et al. 2023; Kundzewicz et al. 2023).

2 Methods

The analysis of standards, technical regulations and guidelines (hereinafter referred to as standards) is based on a systematic review derived from PRISMA's methodological approach. This approach to systematically reviewing literature is extended to analyse standards (Page et al. 2021). The four successive steps of this approach are (1) search and identification, (2) screening, (3) eligibility and (4) analysis. For the (1) search and identification of the standards, the database Nautos is applied (Nautos 2023). Nautos is a database for standards with approximately 2.6 million data records from 28 countries. It contains standards, technical regulations, German legal regulations with technical reference and VDI (Association of German Engineers) guidelines. Furthermore, it incorporates European (e.g. CEN/CENELEC) and international (e.g. ISO/IEC) standards and regulations, provided that they are also recognised as German standards (e.g. DIN). The database is updated on a monthly basis. In the (1) search and identification, the term "Life Cycle Assessment" is defined to conduct the search as broadly as possible and, in particular, to also include standards that do not deal with bio-based or BE products in LCA. However, the search only takes current standards into account. No further filters or restrictions are set concerning the type of standards, the origin country or the year of publication. The filter "current documents" includes adopted and draft standards. The search is conducted on 6 November 2023 and only considers standards in German or English (Table 1).

In the (2) screening, all documents that occur more than once due to country-specific versions or outdated versions of standards are excluded. In the next step, (3) eligibility, the title and description of the standards are analysed. Hits that deal with the methodology of LCA in standards are included. In addition, hits dealing with EPD and their application such as product category rules (PCRs) or guidelines, which are fed by LCA results, are also included. Vice versa, any standards such as EPD, PCRs and other guidelines that are not related to methodology, BE, CE, bio-based products or biogenic C in LCA are excluded. The list of standards resulting from step (3) has been enriched by standards that are known to the authors and are not listed in the database (Fig. 2). These are ISO 14025 (ISO 2011), the International Reference Life Cycle Data System (ILCD) Handbook (European Commission 2012b), the Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services (PAS) 2050 (BSI 2011b) and the Greenhouse Gas (GHG) Protocol (WRI and WBCSD 2011). These standards are eligible for a full text analysis (4) in order to narrow down the relevant standards and derive the assessment criteria in an iterative process (Table 2) that are applied for the comparative analysis. In the (4) analysis, the remaining standards are first analysed according to the type of standards (e.g. general standard, EPD, PCR or guide), and their relationship to each other or their hierarchy. Then, they are analysed based on the derived criteria that are relevant for the assessment of CBE.

As a fundamental basis, the criteria of the analysis consider the objective, the system boundary of the standards and the accounted resources and emissions in the phase of the Life Cycle Inventory (LCI) (criteria 1–3) (ISO 2021a; Klöpffer and Grahl 2014). For a detailed analysis, the LCI accounting and the impact categories of the Life Cycle Impact Assessment (LCIA) in relation to biogenic C, with a focus on the GWP, are taken into account (criteria 4 and 6). It is also of interest whether and how biogenic C is accounted for in the LCI phases in comparison to fossil C and whether it is considered separately in the impact categories to disclose the effects of biogenic C. Since some standards propose a dynamic accounting of biogenic C (criterion 7) and biogenic C for the allocation between product and by-product (criterion 8), both are selected as additional criteria.

Table 1 Search protocol with description of search criteria, applied filters and restrictions

Criteria	Description
Database	Nautos (formerly Perinorm) and standards known by authors dealing with LCA
Search term	Life cycle assessment
Document type	All documents (e.g. standards, technical regulations), German legal regulations with technical reference including international (e.g. ISO/IEC) and European (e.g. CEN/CENELEC) standards and regulations if approved also as DIN standard
Language	English or German
Period of publication year	No restrictions due to the year of publication
Search date	6 November 2023
Other filters	Filter "only current documents" is applied, no other filters (e.g. country) are applied
Availability of documents	Available online as full text

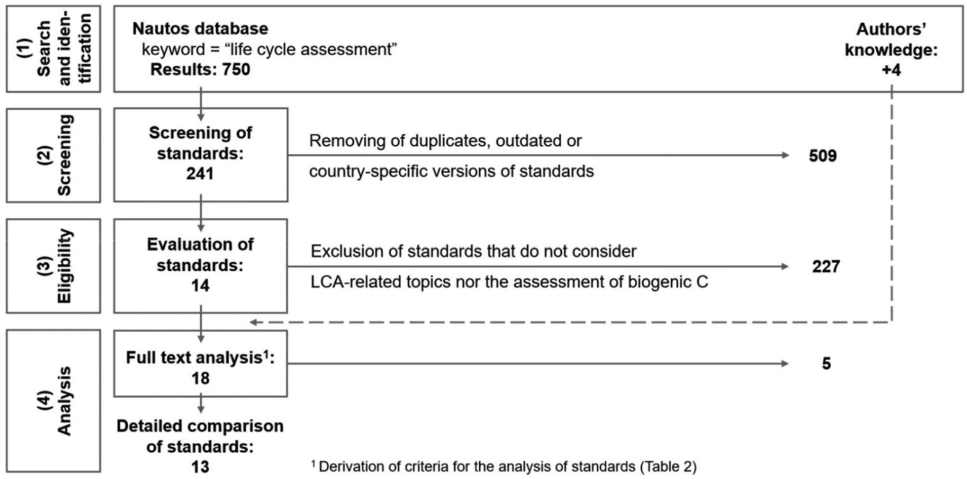

Fig. 2 Results of the systematic review on LCA standards (own illustration following a systematic literature review (Page et al. 2021))

Table 2 Criteria for the qualitative analysis of biogenic C in LCA-related standards

No	Criteria	Definition
1	Objective	The objective describes the purpose of the standard, framework, PCR or guideline
2	System boundary	The system boundary defines the life cycle phases and process modules that are analysed in the LCA. Ideally, these extend from the cradle to the grave, and the input and output at the border are elementary flows. But other system boundaries are also possible, e.g. cradle-to-gate and gate-to-gate. It is determined depending on the objective and the scope of the study
3	LCI: Accounted resources and emissions	Elementary flows (resources and emissions) that are taken into account in the LCI
4	LCI: Accounting of biogenic C	Elementary flows of C and biogenic C that are accounted separately in the LCI
5	Calculation of biogenic C content	Requirement of the standard, framework, PCR or guideline for a method for calculating the biogenic C content of a product, intermediate product or by-product
6	LCIA: Climate change	The assessment of non-biogenic and biogenic C within the impact category climate change
7	Temporal duration of biogenic C storage and delayed emissions	Emissions not occurring at time $t=0$ within a given TH (or those that are assumed not to occur at this time) are considered as delayed emissions. The time between the beginning of the TH and the actual emission describes the duration of the biogenic C storage
8	Allocation of biogenic C to products/by-products	Proposed attribution approach(es) for the allocation of environmental burdens to (intermediate) products and by-products during the life cycle, for co-production, recycling and disposal
9	Substitution effects/DF	The potential of using bio-based products instead of fossil alternatives to reduce GHG emissions. The DF indicates the amount of fossil emissions that may be avoided by using one unit of bio-based products in a specific end use
10	Reporting of biogenic C	Requirement of the standard, framework, PCR or guideline how biogenic C emissions and uptakes or the content of biogenic C shall be reported

Particularly with regard to the effect of biogenic C on climate change mitigation and defossilisation, it is analysed whether the standards quantify the biogenic C in the (intermediate) product (criterion 5) and the substitution effect of biogenic C (criterion 9). The C content of products indicates how much biogenic C is stored in a product. It is therefore an indicator of the extent to which the atmosphere is relieved of carbon dioxide (CO_2). The mass and temporal duration of storage are also relevant here (Bergman et al. 2014; Brandão et al. 2013). The substitution effect or displacement factor (DF), which is used as a synonym, quantifies the impact of substituting fossil with bio-based products. Often it is related to wood products substituting fossil ones (Hurmekoski et al. 2021; Leskinen et al. 2018; Myllyviita et al. 2021; Sathre and O'Connor 2010), but it can apply to other bio-based products. Finally, it is analysed whether the standards require separate reporting of biogenic C uptakes and emissions over the life cycle phases (criterion 10). The latter is primarily used for communication and corporate reporting purposes.

3 Results

3.1 LCA standards for an environmental product assessment in the BE

Based on a total of 750 standards identified in the first step of the review using the Nautos database, 241 standards resulted from the screening step (Fig. 2). A total of 509 standards are removed due to duplicates, outdated standards or country-specific versions of standards already included. In the next step of the eligibility, 227 out of 241 standards are excluded as they do not take into account LCA issues or biogenic C of products in BE. The remaining 14 standards are enriched by four additional standards known to the authors. Ten assessment criteria are derived in an iterative review of the standards (Table 2). Most of these 18 standards deal with LCA as a method, while guidelines and recommendations explain the application of the method in detail. In addition, EPD and PCRs provide basic rules for the LCA of product categories to provide quantified environmental information on products on a scientific basis for third parties. Concerning the BE sectors, most standards focus on construction products and bio-based products. However, there are also specific standards for plastics and bioplastics, as well as biofuels (Table 3).

As a result of the full text analysis, 13 standards are selected for a detailed comparison (Table 3, RQ 1), whereas ISO 14040 and ISO 14044 are counted as one standard due to their close connection. Five standards are excluded. These are quite rudimental or preparatory standards and do not provide further method- or product-specific LCA requirements. ISO 14025 (ISO 2011), ISO 14027 (ISO/TS 2018) and CEN/TR 16957 (CEN/TR 2018) pose only LCA-supporting standards, while EN 16785–2 (EN 2018) and EN 16449 (EN 2014a) guide the calculation of the biogenic C content. The remaining 13 standards provide guidance for LCA (Table 3) but differ in the criteria analysed (Sect. 3.2, Table 4a, 4b, 4c, 4d, RQ 2 + 3).

3.2 Comparative analysis of LCA standards in the BE

3.2.1 Objective (criterion 1)

Fundamental guidelines for the LCA methodology are given by the standards ISO 14040 and 14044 (ISO 2021b, a). Several standards complement or build upon ISO 14040 and 14044. ISO 14067 (ISO 2018) uses the standards to guide the assessment of GHG emissions in order to quantify the

Table 3 LCA-relevant standards for the environmental product assessment in the BE

Standard	Title	Nautos database	Authors' knowledge	focus of standards: method	EPD/Label	PCR	Guidelines/Rec.	relation to product: in general	biofuel	bio-based product	(bio-) plastic	construction product
	Remark: Standards that are written in bold and marked with a bold "**X**" in the column "Nautos database" or "Authors' knowledge" are eligible for detailed analysis.											
ISO 14040: 2006 + A1:2020 **ISO 14044: 2006 + A1: 2018 + A2: 2020**	Life cycle assessment – Principles and framework Life cycle assessment – Requirements and guidelines	**X**		x				x				
ISO 14025:2006	Environmental labels and declarations – Type III environmental declarations – Principles and procedures		x		x			x				
ISO 14027: 2018	Environmental labels and declarations – Development of product category rules	x				x		x				
ISO 14067 (2018)	Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification	**X**		x				x				
DIN EN 16760 (2015)	Bio-based products – Life Cycle Assessment	**X**		x						x		
DIN EN 16785-2:2018	Biobased products – Biobased content – Part 2: Determination of biobased content using the material balance method	x		x						x		
DIN CEN/TR 16957: 2016	Biobased products – Guidelines for Life Cycle Inventory (LCI) for the End-of-life phase	x					x			x		
DIN EN 18027:2023	Bio-based products – Life cycle assessments – Additional requirements and guidelines for comparing the life cycles of bio-based products with their fossil-based counterparts (draft)	**X**		x						x		
DIN EN 16214-4: 2013 + A1: 2019	Sustainability criteria for the production of biofuels and bioliquids for energy applications – Principles, criteria, indicators and verifiers – Part 4: Calculation methods of the greenhouse gas emission balance using a LCA (RED)	**X**		x					x			
DIN EN ISO 22526-3:2022	Plastics – Carbon and environmental footprint of bio-based plastics – Part 3: Carbon footprint of the process, requirements and guidelines for quantification	**X**		x							x	
DIN EN ISO 22526-4:2023	Plastics – CO_2 and ecological footprint of bio-based plastics – Part 4: Ecological (total) footprint (life cycle assessment)	**X**		x							x	
EN 15804:2012+A2:2019 + AC:2021	Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products	**X**			x							x
EN 16485 (2023)	Round and sawn timber – Environmental Product Declarations – Product category rules for wood and wood-based products for use in construction	**X**				x						x
DIN EN 16449: 2014	Wood and wood products – Calculation of biogenic carbon content in wood and conversion to carbon dioxide	x		x								x
PEF (EURec2021/2279:2021)	Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the application of the environmental footprint calculation methods for measuring and disclosing the environmental performance of products and organisations along their life cycle	**X**						x				
Annex I	PEF method				(x)							
Annex II	PEFCR Part A: Requirements to develop PEFCRs and perform PEF studies in compliance with an existing Product Environmental Footprint Category Rule; Part B: PEFCR Template; Part C: List of default CFF parameters					x						
ILCD Handbook	ILCD Handbook (2012) – Towards more sustainable production and consumption for a resource-efficient Europe		**X**									
General Guide for LCA	ILCD Handbook (2010) – General guide for life cycle assessment – Detailed guidance			(x)			x	x				
Specific Guide for LCI	ILCD Handbook (2010) – Specific guide for Life Cycle Inventory data sets			(x)			x					
PAS 2050 (2011) **The Guide (2011)**	Specification for the assessment of the life cycle greenhouse gas emissions of goods and services		**X**	x			x	x				
GHG Protocol (2011)	Product Life Cycle Accounting Reporting Standard - Product Standard.		**X**	x				x				
		14	4					8	1	4	2	3

CFP. Additionally, ISO 14067 is concretised by ISO 22526–3 (ISO 2022), which provides requirements and guidelines for the partial CFP for bio-based plastics. EN 16760 (EN 2015) builds upon ISO 14040 and 14044 and gives guidance to assess resources and emissions in LCA of bio-based products in general, while ISO 22526–4 (ISO 2023) provides guidance specifically for bio-based plastics. The draft standard prEN 18027 supplements ISO 14040 and 14044, ISO 14067 and EN 16760, and supports the preparation of LCA studies comparing fossil and bio-based product systems. Other standards building upon ISO 14040 and 14044 are not related to the origin of the product (fossil/bio-based), but to the overarching sector. For instance, EN 15804 (EN 2022) provides the core rules for EPD exclusively for construction products. These core rules are taken up and specified within PCRs referring to specific product categories, such as the draft PCR prEN 16485 (prEN 2023a). This draft specifically guides the EPD preparation for wood and wood-based products. For the energy sector, EN 16214–4 (EN 2020) is guiding the assessment of GHG emissions arising from biofuel or bioliquid production and the corresponding transport chain up to the consumer. The standard is related to the Renewable Energy Directive I (RED I) (European Commission 2009), which has been substituted by RED II (European Commission 2018a), and recently further revised by RED III (European Commission 2023a). While RED II mandates the assessment of GHG emissions from renewable energy for the achievement of emission targets, RED III encourages EU Member States to promote the cascading use of wood to fully realise its climate change mitigation potential and refers to ISO 14067 and the PEF for product certification.

Besides, the ILCD Handbook with its umbrella document (European Commission 2012b) and several guides like the General Guide for LCA (European Commission 2010a) and the Specific Guide for LCI (European Commission 2010b), the PAS 2050 and the Guide to PAS 2050 (BSI 2011a), the GHG Protocol and the PEF (European Commission 2021b) build upon ISO 14040 and 14044. The ILCD Handbook aims to provide guidance for greater consistency and quality assurance in applying LCA accounting for emissions and resources (European Commission 2012b). Whereas the PAS 2050 and the GHG Protocol only focus on GHG, guiding their quantification and assessment (BSI 2011b; WRI and WBCSD 2011). The PEF has been developed over the past decade with the objective of establishing a uniform method for carrying out LCA, and it is anticipated that its transition phase will be completed by the end of 2024 (European Commission 2021b; Lena Nickel 2024).

3.2.2 System boundary (criterion 2)

Even though the standards mentioned have in common that they quantify environmental impacts, they differ in several criteria (Table 2). Except ISO 22526–3 and EN 16214–4, all standards advocate for a cradle-to-grave system boundary, which includes all stages of a product's life cycle from raw material extraction to disposal (Table 4, criterion 2). Other system boundaries, such as cradle-to-gate or gate-to-gate, may be acceptable if they are properly justified or meet specific requirements. Only EN 16214–4 prescribes a cradle-to-gate system boundary. This includes all steps from the biomass production to the delivery to the consumer. Thus, End-of-Life (EoL) emissions are not considered. This may also be due to the fact that the standard sets biogenic C flows to zero. EN 15804 specifies requirements for the life cycle stages to be calculated for products containing biogenic C. Thus, to be in line with the standard, for bio-based products, the product stage, the EoL stage and the SI for benefits and loads are mandatory. Closely connected to the selected system boundary, the biogenic C content is to be reported differently depending on the standard (Table 4, criterion 10). ISO 14040 and 14044, ISO 22526–4 and the ILCD Handbook do not refer to the biogenic C content. Considering ISO 22526–3, it *can* be reported for intermediate products *if calculated*, and *can* be documented for both intermediate and final products following ISO 14067. The Guide to PAS 2050 and the PEF *mandate* its reporting for intermediate products, while the PEF specifies that for intermediate products from native forests, the biogenic C content (physical and allocated content) *shall* be recorded and reported as *additional technical information*. The GHG Protocol *mandates* the reporting for intermediate products, while for final products, the reporting *can* be done *when applicable*. Regarding the draft standard prEN 18027, the biogenic C content *shall* be reported for both intermediate and final products. EN 15804 and its related PCR prEN 16485 *mandate* the reporting of the biogenic C content for intermediate products, unless it is <5 weight-%. EN 16760 prescribes a transparent documentation of the biogenic C content without specifying whether for intermediate or final products.

3.2.3 Accounted resources and emissions in the LCI (criterion 3)

Concerning the LCI, the fundamental standards ISO 14040 and 14044 provide few instructions and specify that resources and emissions to air, water and soil can be assessed depending on the objective and scope of the LCA (Table 4, criterion 3). Most comprehensive LCI are required by ISO 22526–4, EN 16760, EN 15804, prEN 16485 and the ILCD Handbook, prescribing all emissions and resources associated with the life cycle to be assessed. Thereby, ISO 22526–4 and EN 16760 put emphasis on resources, land use and land use change (LULUC), forestry and water. Other standards only mandate all emitted and removed GHG emissions to be assessed (ISO 14067, ISO 22526–3,

Table 4a Comparison of standards for LCA and CFP/GHG assessments concerning essential characteristics related to biogenic C

Criteria	ISO 14040 and 14044 (2021)	EN 16760 (2015)	prEN 18027 (2023)
2	Cradle-to-grave (other boundaries such as cradle-to-gate, gate-to-gate, or specific parts of the life cycle *shall* be adequately justified).	Cradle-to-grave (other boundaries such as cradle-to-gate, gate-to-gate or EoL *shall* be justified; the LCA of a bio-based product *shall* take into account the entire product, not just the bio-based portion)	Cradle-to-grave or cradle-to-gate
3	Resources and emissions to air, water and soil can be assessed depending on the objective and scope of the LCA	All resources and emissions. Emphasize is put on resources, LULUC, forestry, water.	All GHG emissions and removals arising from fossil and biogenic C sources and sinks.
4	Not specified.	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. Two approaches are provided: (1) CFs = –1/+1; (2) CFs = 0/0 Other biogenic GHG emissions than CO_2 *shall not* be set to zero.	As defined in EN 16760, two approaches are valid. PrEN 18027 specifies that the 0/0 approach may be applicable to biofuels/incineration but mandates the –1/+1 approach for bio-based products as complete oxidation of the biogenic C is not ensured. CFs = –1/+1
5	Not specified.	Radiocarbon and elemental analysis, measurement of stable isotope ratios or material balance (CEN/TR 16721) is proposed; (the biogenic C content is considered an inherent characteristic)	No specific guidance on the calculation is addressed.
6	No default metric to assess climate change is specified.	No default metric to assess climate change is specified.	GWP_{100} using the IPCC CFs. Two exemplary sub-categories are given: biogenic and fossil. (Reference is made to other sub-categories described in other standards.)
7	Not specified.	*If required*, a time-dependent CO_2 emissions calculation based on ISO 14067 and the ILCD Handbook *can* be reported separately. *Its benefit is subtracted from the* CFP_{total}. Permanent C storage *can* be reported separately (permanent storage after 100 years).	*If required*, a time-dependent CO_2 emissions calculation based on the ILCD Handbook *can* be reported separately. *Its benefit is subtracted from* CFP_{total}. DLCA *can* be applied. Permanent C storage *can* be reported separately (permanent storage after 100 years).
8	In line with the allocation hierarchy (1)-(3). (Biogenic C is not specifically addressed.)	In line with the allocation hierarchy (1)-(3) with the addition: For bio-based products, it can be viable to use the content of biogenic C as a basis for the allocation method.	In line with the allocation hierarchy (1)-(3). It is noted that allocation introduces problems, as the modelled biogenic C flows might not reflect the actual physical content and flows.
10	Not specified.	Biogenic and non-biogenic emissions/uptakes *shall* be reported separately. The biogenic C content *shall* be reported transparently. (Not specified, whether for intermediate or final products or separately.)	Biogenic and non-biogenic emissions/uptakes *shall* be reported separately. Biogenic C content *shall* be reported separately for final and intermediate products.

Table 4b Comparison of standards for LCA and CFP/GHG assessments concerning essential characteristics related to biogenic C

Criteria	ISO 14067 (2018)	ISO 22526-3 (2023)	ISO 22526-4 (2023)
2	Cradle-to-grave (= CFP) and cradle-to-gate, gate-to-gate, other partial life cycle (= partial CFP) possible.	Cradle-to-gate (= partial CFP; by adding partial CFPs, that were created under the same conditions, also cradle-to-grave possible).	Cradle-to-grave (other boundaries as cradle-to-gate, gate-to-gate or specific parts of the life cycle (e.g. waste management, components of a product) *shall* be justified).
3	All emitted and removed GHG emissions that make a significant contribution to the CFP or partial CFP in the product system	All emitted and removed GHG emissions that make a significant contribution to the partial CFP (in line with ISO 14067).	All resources and emissions. Emphasise is put on resources, LULUC, forestry, and water.
4	Biogenic and non-biogenic emissions/uptakes *shall be* inventoried separately. CFs = –1/+1	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. CFs = –1/+1	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. CFs = –1/+1
5	No specific guidance on the calculation is addressed (the biogenic C content is considered equal to the removal during biomass growth).	No specific guidance on the calculation of the biogenic C content is addressed.	Stoichiometry or the radiocarbon analysis (ISO 16620-2 (ISO 2019)) is proposed; (the biogenic C content is considered an inherent characteristic).
6	GWP_{100} (for short-term impacts) and GTP_{100} (for long-term impacts) using the IPCC CFs. No sub-categories provided.	As defined in ISO 14067.	GWP is recommended. Two sub-categories are defined: GWP incl. and excl. biogenic C. No TH is prescribed. It *shall* be selected to cover the relevant period in the life cycle of the product.
7	Delayed emissions *shall not* be taken into account *unless* emissions/uptakes from the use phase and/or from the EoL phase occur > 10 years after the start of use. Then delayed emissions *shall be* recorded separately. *No* methods are provided.	*NO*. Delayed emissions are not taken into account.	*If required*, a time-dependent CO_2 emissions calculation based on ISO 14067 *can* be provided separately.
	Permanent C storage *can* be reported separately (*no* minimum storage period provided).	Permanent C storage is not specified.	Permanent C storage *can* be reported separately (*no* minimum storage period provided).
8	In line with the allocation hierarchy (1)-(3). (Biogenic C is not specifically addressed.)	Not specified. It is assumed to be in line with ISO 14067.	In line with the allocation hierarchy (1)-(3) with the addition: For bio-based products, it can be viable to use the content of biogenic C as the basis for the allocation method.
10	Biogenic and non-biogenic emissions/uptakes *shall be* recorded separately. Biogenic C content *shall* be recorded separately for both CFP and partial CFP *if calculated*. Guidance is provided in section 6.4.9.8.	Biogenic and non-biogenic emissions/uptakes *shall* be recorded separately. Thereby, non-CO_2 emissions/uptakes shall be recorded in the LCI but are *not mandated* to be reported separately. The GHG emissions/uptakes that occur in the cradle-to-grave phase *shall* be calculated and reported even for the partial CFP. Biogenic C content *shall* be recorded separately *if calculated*.	Biogenic and non-biogenic emissions/uptakes *shall* be recorded separately. (No information on separate reporting of biogenic C content.)

Table 4c Comparison of standards for LCA and CFP/GHG assessments concerning essential characteristics related to biogenic C

Criteria	EN 15804: 2012+A2:2019+AC:2021	prEN 16485 (2023) Product Category Rule (PCR)	EN 16214-4
2	Different boundaries are possible: cradle-to-grave and different options of cradle-to-gate; for products containing biogenic C, the product stage, the EoL stage and the SI beyond building life cycle are mandatory.	As defined in EN 15804 with the following addition: All technical processes related to forestry operations intended to produce timber, are considered within the system boundary.	Cradle-to-gate (from biomass production to final transport and distribution)
3	All resources and emissions.	As defined in EN 15804.	CO_2, CH_4 and N_2O.
4	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. CFs = –1/+1	As defined in EN 15804, with the specification: (a) wood from non-native forest: $GWP_{biogenic}$ (–1/+1) (b) wood from native forests: GWP_{LULUC} (0/+1) (c) recovered wood: $GWP_{biogenic}$ (–1/+1)	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. However, biogenic CO_2 *shall* be set to zero, while biogenic CH_4 and N_2O *shall* be assessed in the LCIA. $CO_2 \rightarrow$ CFs = 0/0 $CH_4 \rightarrow$ CFs = –1/+1 $N_2O \rightarrow$ CFs = –1/+1
5	The calculation of the biogenic C content and its conversion to CO_2 specifically for wood as defined in EN 16449 is proposed. (the biogenic C content is considered an inherent characteristic)	As defined in EN 15804.	The biogenic C content can be calculated based on the mass of the non-biogenic and biogenic components and their calorific values (formula provided).
6	GWP_{100} using the IPCC CFs. Three sub-categories are defined: fossil, biogenic, LULUC. They *shall be* assessed separately.	As defined in EN 15804.	GWP using the outdated CFs defined in RED I. No sub-categories provided. No reference is made to the TH.
7	*NO*. The time-dependency of C emissions and permanently stored biogenic C *shall* not be inventoried. Permanent C storage is *not* considered. Thus, any remaining biogenic C is treated as an emission.	As defined in EN 15804. However, separate documentation is supported, as WFs for delayed emissions related to a 100-year time frame are provided. Further, it is referred to the methods provided by PAS 2050 and the ILCD Handbook.	*NO*. The time-dependency of C emissions is not referred to. Permanent C storage is considered as CCS technologies are mentioned. Any credits from CCS *shall* be subtracted from the total GHG emissions for the biofuel or bioliquid.
8	In line with the allocation hierarchy (1)-(3) with the addition: The biogenic C content *shall* be allocated physically, irrespective of the allocation chosen for the product system.	As guided in EN 15804, with the addition. For wood-based multiple output product systems and the biogenic C content, physical allocation *shall be* used.	Allocation by calorific value. Products with negative calorific values *shall* be set to zero. Thus, *no allocation* of GHGs *shall* be done.
10	Biogenic and non-biogenic emissions/uptakes *shall* be reported separately *per life cycle stage*. Separate reporting of GWP_{LULUC} may be omitted if its contribution is < 5 % of the total GWP of the declared modules, except module D. The biogenic C content *shall* be reported separately, unless it is < 5 weight-%.	As defined in EN 15804.	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately in the LCI. In the LCIA, the biogenic CO_2 emissions *shall* be set to zero. For intermediate products, the biogenic C content *shall* be reported separately. It is not determined, whether credits from CCS or CCR shall be reported separately.

Table 4d Comparison of standards for LCA and CFP/GHG assessments concerning essential characteristics related to biogenic C

Criteria	ILCD Handbook (2012) General Guide for LCA (2010) Specific Guide for LCI (2010)	PAS 2050 (2011) The Guide to PAS 2050 (2011)	GHG Protocol (2011)	PEF (2021) Annex I: PEF method Annex II: Requirements (PEFCR, PEF study)
2	Cradle-to-grave or cradle-to-gate (cradle-to-gate requires a list of all types of activities, processes, flows etc. that are excluded from the analysed system).	Cradle-to-grave (for cradle-to-gate, exact reporting of included phases is required).	Cradle-to-grave (cradle-to-gate for intermediate products; then use and EoL stage *shall be* excluded; justification required).	Cradle-to-grave (default life cycle stages provided); cradle-to-gate for intermediate products (then the following life cycle stages *shall* be excluded: distribution; use; EoL).
3	All emissions and resources associated with the life cycle of the analysed process or product.	All GHGs declared by the IPCC.	CO_2, CH_4, N_2O, SF_6, PFC and HFC. Other gases are optional and *shall* be listed in the inventory report.	All material, energy and waste inputs and outputs and emissions to air, water and soil within a product supply chain.
4	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. Uptakes of CO_2 by plants *shall* be accounted under "resources from air". CFs = –1/+1	Biogenic and non-biogenic emissions/uptakes *shall be* inventoried. Separate accounting is *not explicitly mandated*. CFs = –1/+1	Biogenic and non-biogenic emissions/uptakes *shall be* inventoried separately *if applicable*. CFs = –1/+1	Biogenic and non-biogenic emissions/uptakes *shall* be inventoried separately. It *shall* be reported as follows: (a) aboveground biomass: $GWP_{biogenic}$; (b) native forest: GWP_{LULUC}. CFs = 0/0
5	No specific guidance on the calculation is addressed.	No specific guidance on the calculation is addressed in the PAS 2050. *The Guide* specifies: For intermediate products, the biogenic C content *shall* be recorded.	No specific guidance on the calculation is addressed. For intermediate products, the C content of the products and the C content that is not released again in the EoL phase *shall* be recorded.	No specific guidance on the calculation is addressed. For intermediate products from native forests, the biogenic C content (physical and allocated content) *shall* be recorded as *additional technical information*.
6	GWP_{100} using the IPCC CFs. No sub-categories provided.	GWP_{100} using the IPCC CFs. No sub-categories provided.	GWP_{100} using the IPCC CFs. No sub-categories provided. GTP_{100} may additionally be calculated, but *shall* be reported separately.	GWP_{100} using the IPCC CFs. Three sub-categories are defined: fossil, biogenic, LULUC.
7	*Only if* "temporary C storage in bio-based goods" is considered; then it *shall* be recorded separately (linear discounting over 100 years; *its benefit is subtracted from CFP_{total}*). Permanent C storage *shall* be inventoried separately (permanent storage after 100,000 years).	WFs for delayed emissions and offsets are *not* included *by default*. Separate recording *can* be done (methods to calculate WFs (single/gradual release) are provided). Permanent C storage *shall* be reported separately (permanent storage after 100 years).	WFs for delayed emissions, offsets and avoided emissions are *not* included *by default*. Separate reporting possible. Permanent C storage *shall* be inventoried and reported separately wh*en applicable* (permanent storage after 100 years; other periods possible).	*NO*. Delayed emissions *shall not* be considered. Offsets *shall* be recorded separately as *additional environmental information*. Permanent C storage *shall not* be considered. Thus, all emissions and removals *shall* be considered as emitted "now".
8	In line with the allocation hierarchy (1)-(3) with the addition: (4) allocation due to quality *shall* be used. (Biogenic C is not specifically addressed.)	In line with the allocation hierarchy (1)-(3). (Biogenic C is not specifically addressed.)	In line with the allocation hierarchy (1)-(3). (Biogenic C is not specifically addressed.)	In line with the allocation hierarchy (1)-(3) with the addition: (4) allocation based on some other relationship *shall* be used. Biogenic C *shall* be allocated by mass.
10	Biogenic and non-biogenic emissions/uptakes *shall be* reported separately *when applicable*. LCIA results of short-term (> 100 years) and long-term (< 100 years) emissions *shall* be calculated and reported separately. (No information on separate reporting of biogenic C content.)	Biogenic and non-biogenic emissions/uptakes *shall be* assessed. Separate reporting is *not explicitly mandated*. *The Guide specifies*: For intermediate products, the biogenic C content *shall* be reported.	Biogenic and non-biogenic emissions/uptakes *shall be* reported separately *when applicable*. For final products, the biogenic C content *shall* be reported *when applicable*. For intermediate products, it *shall* be reported.	Biogenic and non-biogenic emissions/uptakes *shall* be reported separately if one GWP sub-category accounts for > 5 % of the total. For intermediate products, the biogenic C content *shall* be reported as *additional technical information*.

prEN 18027). The PAS 2050 mandates all GHG declared by the Intergovernmental Panel on Climate Change (IPCC) to be considered. The GHG Protocol is limited to CO_2, CH_4, N_2O, SF_6, PFC and HFC, while other gases are optional to report. Furthermore, EN 16214–4 limits the assessment to CO_2, CH_4 and N_2O only. This restriction in the energy sector may lead to an incomplete assessment in comparison to other standards aiming to guide comprehensive assessments or at least to take into account the relevant GHG emissions determined by the IPCC.

3.2.4 Accounting of biogenic C in the LCI (criterion 4)

Regarding the accounting of biogenic C, almost all standards separately consider biogenic and non-biogenic C in the LCI, except the fundamental ISO 14040 and 14044 (Table 4, criterion 4). The accounting is done according to the following approaches: (1) the uptake or sequestrated biogenic C, as well as its emission is accounted for; (2) biogenic C is not accounted for. Thereby, the uptake of biogenic C can be considered with negative and the emissions with positive flow values (EN 16760). The same applies via the characterisation factor (CF) (ISO 14067, EN 18027, EN 15804 and prEN 16485). However, some standards do not define whether the flows or the CF contribute the signs (ISO 22526–3, ISO 22526–4, the PAS 2050 and the GHG Protocol). These two approaches can be described as the (1) $-1/+1$ or (2) 0/0 approach as well as with the (1) CF $= -1/+1$ or (2) CF = 0/0 leading to the same LCIA results.

While the fundamental standards ISO 14040 and 14044 do not mention these approaches, ISO 14067, ISO 22526–3, ISO 22526–4, EN 15804 and the GHG Protocol refer to the $-1/+1$ approach. Thereby, ISO 22526–3 mandates a separate LCI exclusively for fossil and biogenic GHG emissions and removals from direct LUC. In the PAS 2050, it is not clear which approach to choose, however, EN 18027 infers it as CF $= -1/+1$. EN 16760 and prEN 18027 leave the choice open. Furthermore, prEN 18027 specifies that the 0/0 approach *may* be applicable to biofuels and incineration, but mandates the $-1/+1$ approach for bio-based products as complete oxidation of the biogenic C is not guaranteed. Similar to prEN 18027, EN 16214–4 also mandates the 0/0 approach for the assessment of biofuels and bioliquids. The PEF does not deal exclusively with energy products, but prescribes the 0/0 approach. However, it mandates separate accounting of non-biogenic and biogenic C, but prescribes that the CF are set to zero. The acceptance of the 0/0 approach for bioenergy may be due to the fact that energy products have a very short life cycle. Energy products are often biomass with short cultivation phases and the re-emission of biogenic C occurs at a single point in time that of combustion or utilisation. However, this does not apply to biomass with longer growth phases, such as forests. In this case, the sequestration of biogenic C is taking place over several years, which significantly influences the environmental impact (Cherubini et al. 2011). Furthermore, the 0/0 approach seems to be even less applicable for the assessment of other products with long use phases, as the storage period and the type of emission (single/gradual release) also significantly influence the environmental impacts (Kirschbaum et al. 2024; Levasseur et al. 2010). As the $-1/+1$ approach ensures transparency for LCI and LCIA and the underlying biogenic C flows, it may have been included in most of the standards analysed, except the PEF, which solely mandates the 0/0 approach and ISO 14040 and 14044, which do not address any approach (Table 4).

Up to the revision of EN 15804 (EN 2012) in 2022, the C neutrality, which is reflected in the 0/0 approach, has been standard practice in LCA for the construction sector (Hoxha et al. 2020). However, in its revision and in the BE in general, the transparency of biogenic C flows over the life cycle phases has gained importance. Particularly in the case of biofuels and bioliquids and process chains with by-products or EoL options, essential information for the assessment is lost when biogenic C is not accounted for. This especially applies to intermediate products with a cradle-to-gate system boundary. The amount of sequestered and stored biogenic C is valuable information concerning its contribution to climate change mitigation. However, it has to be reported transparently to avoid overestimation, as re-emission at the EoL is excluded from the system boundary. As the (biogenic) C content is not mandatory for all standards, the transparent reporting of biogenic C flows over the life cycle is essential (Table 4, criterion 10). In addition, the accounting of biogenic C is equally important when considering imports of biomass or bio-based products from countries that do not include biogenic C in their national C accounting (Liu et al. 2018). Here, the transparency of the biogenic C flows is lost. Although a distinction must be made between C accounting at the macro level (national C accounting) and assessment using LCA at the micro level (product), the issue of C leakage can exist. Furthermore, Wiloso et al. (2016) deplore “that the assumption of biogenic C neutrality introduces a bias to the ‘true’ values based on a complete inventory”. Additionally, in the case of the destruction of C reservoirs such as peat extraction or cutting of primary forests, the $0/+1$ approach, as defined in prEN 16485, would be easy to implement.

3.2.5 Calculation of biogenic C content (criterion 5)

The biogenic C content describes the amount of C stored in a bio-based product. When referring to biofuels or intermediate products with a system boundary from cradle-to-gate, it is important to show the biogenic C flows and biogenic C content. This makes it transparent under which conditions sequestration has taken place and how much biogenic C has been sequestered during the growth phase of biomass and stored in the bio-based product. This is even more important for intermediate products than for biofuels, as it is not possible to assume complete oxidation at the EoL (prEN 2023b). A cradle-to-gate system boundary requires explicitly stating the stored biogenic C content separately. Otherwise, there is the risk of biased LCA results (Pawelzik et al. 2013), which may even indicate a CO_2-negative product.

However, different methods for the calculation of the biogenic C content exist (Table 4, criterion 5). Some standards refer to the stoichiometry, radiocarbon or elemental analysis (EN 16760, ISO 22526–4) to determine the biogenic C content. Other standards use the mass of the non-biogenic and biogenic components and the calorific values (EN 16214 4), or consider the content of biogenic C in wood products (EN 16449). These different methods could, in turn, lead to different results and cause different efforts. Methods using mass and molecular weights seem to be the most suitable in terms of accuracy and effort to calculate the (biogenic) C content.

3.2.6 The impact category climate change in the LCIA (criterion 6)

Biogenic C is considered in the impact category climate change and is assessed using the metric GWP or the global temperature potential (GTP). Thereby, he GWP quantifies the relative contribution of emissions to climate change by integrating its radiative forcing over a chosen time horizon (TH), compared to that of CO_2, while the GTP measures the ratio of change in global mean surface temperature at a chosen point in time (IPCC 2013). The standards ISO 14040, 14044 and EN 16760 do not prescribe a specific one to be assessed. The other standards provide a metric that *shall* or *may* be applied (Table 4, criterion 6). Only ISO 14067 and the GHG Protocol refer to the GTP. ISO 14067 even prescribes the GTP for the assessment of long-term impacts, while the GHG Protocol only permits the metric as an addition to the GWP, which *may* be calculated and reported separately. This shows that the GWP is more widely used than the GTP for the assessment of biogenic C in science and practice. Consequently, the GWP is the method of choice in policy (IPCC 2013). Nevertheless, the GTP may also be of interest, depending on the particular application and which aspects of climate change are considered.

To properly assess non-biogenic and biogenic C, the GWP is divided into sub-categories. However, there is no consensus in the standards on whether it should be divided into two or three sub-categories, nor on the designation of the impact categories (fossil, biogenic, inclusive and exclusive biogenic C). Additionally, the impact category GWP_{LULUC} is partially accounted for and reported as a separate sub-category. It comprises emissions and uptakes of C resulting from LULUC including native forests and excluding short-term forests, degraded forests, managed forests or forests with short-term or long-term rotations (European Commission 2021b; prEN 2023a). Most detailed are the requirements of the prEN 16485 and the PEF, where C flows are to be considered in the sub-categories. Although the PEF prescribes applying the 0/0 approach, it still mandates recording biogenic and non-biogenic C separately. Thus, it prescribes considering the aboveground biomass, including emissions from combustion, digestion, composting, landfilling and uptakes through photosynthesis, within the category $GWP_{biogenic}$. The draft PCR prEN 16485 for wood and wood-based products takes up an even more differentiated approach. In the draft, the type of the forest is considered, and a distinction is made between three cases that differ in the accounting of sequestration: (a) for non-native forests, including short-term forests, degraded forests, managed forests or forests with short-term or long-term rotations; sequestration *shall* be recorded and impacts *shall* be reported $(-1/+1)$ in the category $GWP_{biogenic}$; (b) for native forests; sequestration is *not* recorded and impacts are reported $(0/+1)$ in GWP_{LULUC}; (c) for recovered wood, including all kind of wood material that is made available for re-use, recycling or energy recovery at the EoL in wood products; sequestration *shall* be recorded and impacts *shall* be reported $(-1/+1)$ in $GWP_{biogenic}$. This detailed guidance on the attribution and assessment of biogenic C in the sub-categories maximises the opportunity for a consistent assessment within LCA studies.

Diving deeper into the methodology of the GWP, it is assumed a one pulse emission at time $t=0$ (IPCC 2013). This indicates all emissions occurring over the whole TH to be summed up to one emission being emitted at the beginning of the TH. The 100-year TH is preferred in many standards and LCA studies, although there is no scientific reason compared to other TH (IPCC 2013). Thus, provided that no supplementary requirements or guidance exist, a TH of 100 years (GWP_{100}) using CF of the IPCC is recommended by ISO 14067, ISO 22625–3, prEN 18027, EN 15804, prEN 16485, the ILCD Handbook, the PAS 2050, the GHG Protocol and the PEF (Table 4, criterion 6). ISO 14067 and the GHG Protocol state that other TH may additionally be calculated, but *shall* be reported separately. As a TH of 100 years is common practice but not mandatory, ISO 14040, 14044 and EN 16214–4 do not prescribe any TH. EN 16760 does not prescribe one either, but applies a TH of 100 years in a calculation example and refers to the guidance of the ILCD Handbook. ISO 22526–4 notes that the TH shall be selected to cover *the relevant period* in the life cycle of the product. Since a TH of 100 years has already been established both in science and in most standards, this should be consistently required to improve the harmonisation of LCA studies. However, this could only apply to the application of the GWP, as briefly taken up and explained in the following section.

3.2.7 Temporal duration of biogenic C storage and delayed emissions (criterion 7)

The GWP assumes a one pulse emission at time *t = 0*, regardless of whether this is the case or a gradual emission over several years occurs (IPCC 2013). Thus, benefits and burdens resulting from temporarily stored biogenic C or delayed emissions are not taken into account. As most of the standards refer to the GWP metric, these benefits and burdens are not considered within the main assessment. In this context, the draft standard prEN 18027 recommends dynamic LCA (DLCA) approaches for a more accurate assessment. It uses variable TH that relate to each individual emission and its specific time of release. Thus, the TH for the entire assessment is extended with each emission that occurs later than at time *t = 0* (Albers et al. 2020; Levasseur et al. 2010). Another possibility to discount the benefits and burdens of biogenic C storage is to calculate C credits, which can be related to weighting factors (WF). WF are applied to the quantities of emitted biogenic C or their environmental impact, taking into account the duration of storage, and resulting in a credit. However, calculating credits or in general the consideration of delayed emissions is either not referred to or prescribed by default in the standards (Table 4, criterion 7). Rather, delayed emissions *shall* be excluded, as determined in the PEF, ISO 22526–3 and EN 15804 (provided that a PCR does not include specific guidance), or it *shall* be reported separately as SI. In this context, the standards do not provide a uniform approach for such an SI (for the respective formulas, see Appendix). ISO 14067 and ISO 22526–4 allow separate reporting for delayed emissions, provided that the storage period is > 10 years, but do not provide a method to calculate them. In contrast, the ILCD Handbook and EN 16760 describe a method without such a temporal limit. The draft PCR prEN 16485 provides a table of WF. The PAS 2050 even specifies methods, especially for single releases within the first 25 years of storage, single releases in the subsequent years or gradual releases. This already indicates that the assessment of delayed emissions inevitably leads to different results depending on which standard is used. For example, using ISO 14067, ISO 22526–3 and ISO 22526–4, no credit is given for biogenic C that has been stored for 5 years, whereas the PAS 2050 even provides separate methods for the assessment of single and gradual releases. Diving even deeper into methodological issues, Pawelzik et al. (2013) remark inconsistencies regarding the two formulas provided by the PAS 2050. Following the formulae for single releases within the first 25 years, only 76 % of the emitted C is considered, as the natural uptake of C in oceans and soils is discounted. However, following the formulae for single releases after 25 years or gradual releases, this natural uptake is left out and the whole amount of C emission is considered. Thus, single releases in the first 25 and subsequent years, as well as gradual releases, are treated differently. Nevertheless, the approaches of the ILCD Handbook and PAS 2050 (formula for single releases after 25 years or gradual releases) lead to identical results with regard to the relative effects of delayed emissions, as Brandão et al. (2013) have illustrated.

A similar inhomogeneity can be observed when considering the permanent C storage (Table 4, criterion 7). The PEF, ISO 22526–3 and EN 15804 do not consider permanent C storage. Following ISO 14067 and ISO 22526–4, permanent C storage is considered, but no specific period after which C is considered as permanently stored is provided. In EN 16760, the permanent C storage is considered, when stored C has not been re-emitted within a 100-year time period and *can* be reported separately. The draft standard prEN 18027, the PAS 2050 and the GHG Protocol are in line with EN 16760. The ILCD Handbook only considers permanent C storage when it can be guaranteed that stored C is not re-emitted within a 100,000-year time period. Consequently, the different time limits before a permanent C storage is assumed result in varying amounts of biogenic C being considered as either remaining in the product or emitted, depending on the TH. EN 16214–4 occupies a special position in this context, as it is the only standard explicitly referring to carbon capture and storage (CCS) and reuse (CCR) technologies. To the authors' best knowledge, these technologies are not named in the analysed standards. However, methods described in the standards may be applicable to them, or it may be included in updated standard versions. According to EN 16214–4, credits can be calculated if long-term geological storage is confirmed, although no exact storage period is defined. When claiming the credit from CCR, proof of the source of the replaced CO_2 must be provided.

3.2.8 Allocation of biogenic C to products/by-products (criterion 8)

To allocate environmental burdens to (intermediate) products and by-products during the life cycle, the standards provide allocation approaches and a hierarchy that should be followed (Table 4, criterion 8). In general, (1) allocation *shall* be avoided by subdivision of processes or system expansion. *If not possible*, (2) physical or (3) economic allocation *shall* be applied (this is referred to as "allocation hierarchy (1)-(3)" in the following). ISO 14040 and 14044, ISO 14067, the PAS 2050 and the GHG Protocol propose the allocation hierarchy (1)–(3), but do not specifically address biogenic C. The ILCD Handbook adds the approach

(4) allocation due to quality. The PEF supplements it with (4) allocation based on some other relationship that *shall* be used, but specifies that biogenic C *shall* be allocated by mass. EN 15804 and prEN 16485 align with the allocation hierarchy (1)–(3) but state that for wood-based multiple output product systems and the biogenic C content, physical allocation *shall* be used. EN 16760 determines rudimentary that for bio-based products, it can be viable to use the content of biogenic C as a basis for the allocation method. The draft standard prEN 18027 only notes that allocating biogenic C introduces problems, as the modelled biogenic C flows might not reflect the actual physical content and flows. ISO 22526–3 does not refer to allocation. Thus, it is assumed to be in line with ISO 14067. In contrast, EN 16214–4 exclusively refers to the calorific value as an allocation approach. Thereby, for (co-) products with negative calorific values, no allocation is to be applied. This may occur when (co-) products have high water content and the amount of heat for drying is greater than that released during incineration. As a negative allocation is not permitted, the negative calorific values are set to zero. This means that the associated GHG impacts are assigned to the other (co-) product.

3.2.9 Substitution effects or the DF (criterion 9)

Regarding substitution effects or the DF, EN 15804, the related draft PCR prEN 16485, EN 16214–4, the Guide to PAS 2050 and the GHG Protocol refer to it (criterion 9). However, the guide to PAS 2050 only notes that the energy produced by on-site CHP can be subtracted from the footprint of the product under study, as it can displace grid electricity/heat, and the GHG Protocol prescribes not to consider substitution effects. Thus, EN 16214–4, EN 15804 and the related draft PCR prEN 16485 are the only standards dealing with substitution effects. The latter determine that the potential benefits and loads beyond the system boundary *shall* be calculated in the SI beyond the building life cycle (EN 2022). This includes the potential benefits of avoiding the use of primary materials and fuels, as well as the burdens associated with recycling and recovery processes. Due to its marginal presence in the standards, criterion 9 is not listed in Table 4.

3.2.10 Reporting of biogenic C (criterion 10)

With regard to the reporting requirements, ISO 14067, ISO 22526–3, ISO 22526–4, EN 16760 and prEN 18027 mandate separate reporting of biogenic and non-biogenic C emissions and uptakes (Table 4, criterion 10). Thereby, ISO 22526–4 specifies that non-CO_2 emissions/uptakes *shall* be recorded in the LCI but are *not mandated* to be reported separately. Furthermore, the GHG emissions/uptakes occurring in the cradle-to-grave phase *shall* be calculated and reported even for the partial CFP. EN 16214–4 *mandates* a separate inventory of non-biogenic and biogenic C, while in the LCIA biogenic C is to be set to zero. Thus, the impact arising from biogenic C is not to report. EN 15804 and the related draft PCR prEN 16485 *prescribe* reporting GHG emissions/uptakes separately for *each* life cycle phase within the three defined GWP sub-categories $GWP_{biogenic}$, GWP_{fossil} and GWP_{LULUC}. Separate reporting of GWP_{LULUC} may be omitted if its contribution is less than 5 % of the total GWP of the declared modules except module D. The ILCD Handbook and the GHG Protocol state that the biogenic and non-biogenic emissions and uptakes *shall* be reported separately *when applicable*. The ILCD Handbook adds that the LCIA results of short-term (> 100 years) and long-term (< 100 years) emissions *shall* be calculated and reported separately in the three defined GWP sub-categories since one accounts for more than 5 % of the total. The PAS 2050 *mandates* a separate inventory, but does not explicitly prescribe separate reporting. The fundamental standards ISO 14040 and 14044 do not provide reporting requirements. Due to these numerous differences in the reporting requirements, the comparability of LCA studies based on the various standards is lacking.

4 Discussion

The number of standards developed in recent decades shows that there is a need in research and above all in practice to define methodological aspects within LCA in the BE. Most of these standards are intended to serve as guidelines for carrying out LCA or, in particular, EPD, as the fundamental standards ISO 14040 and 14044 consciously leave aspects open. This is due to the flexibility and the necessity of taking specific conditions into account in the LCA. It is the favoured method to support BE stakeholders in improving their products and value chain. However, specific aspects related to biogenic C that are relevant to BE have not yet been comprehensively considered either in LCA standards or in scientific discussions.

4.1 Assessment of GHG emissions and biogenic C storage

Referring to the bio-based value pyramid and its change in the future (Fig. 1), bulk chemicals and materials as well as bioplastics and polymers that store biogenic C will increase in terms of product diversity and market volume (Mitchell et al. 2024; Shah et al. 2020). In the BE, the delayed emissions and the duration of biogenic C storage in these products could play an important role in climate protection in the future. In particular, the temporal duration of biogenic C storage in these products significantly exceeds that of energy, heat and fuels from biomass. As a parameter for climate change mitigation, the quantity and duration of biogenic C storage is becoming a decisive factor. This is because it temporarily reduces the climate-relevant concentration of CO_2 in the atmosphere (Bergman et al. 2014). These characteristics are taken up by the European Commission in a "Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution" (European Commission 2023e). A common method for quantifying and assessing the storage of biogenic C is necessary, at the latest when political decisions and steering effects take effect on this basis. Rinke Dias de Souza et al. (2021) already raised the need for harmonisation in the context of C credits for biofuels. However, more harmonisation is not only required within the assessment of C credits for biofuels. In addition to energy products, the transformation to a BE requires harmonisation across all bio-based product groups. There are currently major differences between the standards. For example, the fact that EN 16214–4 only assesses three GHG (CO_2, CH_4 and N_2O) compared to others is far-reaching, as this is also stated in the RED II (European Commission 2018a). In contrast, other standards require a more comprehensive assessment. Thus, products, or more precisely their product-relevant processes or raw materials, are assessed differently depending on sector-specific standards. This means that even if products within one sector are assessed in the same way, the same raw material or process may be assessed differently in other sectors due to different standard requirements. For example, wood can be used as fuel or processed into particleboard. While the fuel is assessed according to EN 16214–4, the energy recovery of the particleboard is assessed at the EoL according to EN 16485. Consequently, the wood-related environmental impacts may vary due to the different GHG emissions taken into account.

In C accounting at a macro level, the product-specific content of biogenic C is precisely quantified. This determines the half-life of products in order to assess the temporal duration of biogenic C storage and its contribution to climate change mitigation. This applies in particular to harvested wood products and quantifies the stock of biogenic C (IPCC 2019). LCA approaches, such as the GWP or GTP, do not necessarily take into account the temporal duration of C storage and delayed emissions. Thus, various DLCA approaches are being discussed in research to consider the temporal effects (Arehart et al. 2021; Brandão et al. 2019; Breton et al. 2018; Cherubini et al. 2011; Daystar et al. 2017; Garcia et al. 2020; Kendall 2012; Levasseur et al. 2010; Resch et al. 2021). To the best of the authors' knowledge, it is noticeable that the GWP is increasingly interpreted and applied dynamically in science and LCA studies (Albers et al. 2020; Arehart et al. 2021; Daystar et al. 2017; Garcia et al. 2020; Garcia and Freire 2014; Head et al. 2021; Levasseur et al. 2010, 2012, 2013; Resch et al. 2021), while the GTP is rarely applied in this way (Brandão et al. 2019; Breton et al. 2018; Cherubini et al. 2012). Most of these approaches discussed in research are very complex and not easy to apply; however, they may be most accurate from a scientific point of view. Except for prEN 18027, none of the analysed LCA standards refers to DLCA approaches. Nevertheless, some standards consider calculating the benefit of storing biogenic C depending on the storage period. The ILCD Handbook suggest a separate assessment if required (European Commission 2010b). With its approach, the biogenic C storage is credited linearly up to 100 years and subtracted from the CFP. The need for such an approach is emphasised by the references in EN 16760 and prEN 18027, and are carried out as an additional assessment. Similar approaches can be found in the PAS 2050 and are referred to in prEN 16485. All approaches are easy to apply and transparent, but above all they incentivise the use of biomass in long-life products by granting benefits in the assessment. Brandão et al. (2013) have already stated that there is no overall consensus in this regard. However, due to its importance for the BE, further research is required to develop a standardised method for the assessment of biogenic C storage. A coherent approach that balances the trade-off between accuracy and simplicity while also bringing together the micro and macro levels would be desirable. This is because in product development (micro level), decisions are made that influence the national C accounting at the macro level. Coherent approaches increase effectiveness, especially if future legal regulations refer to them. The duration of C storage is crucial, as it can have a significant impact on the assessment depending on the methodology, and thus gaining importance in product development. The latter is an enabler to the transformation to a BE. Upcoming technologies according CCS and CCR could support climate change mitigation. Concerning the standards analysed within the present review, solely EN 16214–4 explicitly addresses their assessment describing credits out of the duration of C storage and its subtraction from the total amount of GHG emissions. As CCS and CCR are quite new in the context of LCA, and to enhance comparability, they should be conducted according to specific standards or guidelines, such as the "Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization" (Global CO_2 Initiative 2022).

4.2 Substitution effects or the DF

Furthermore, the substitution effect or DF is discussed as added value for the BE (European Commission 2023e). In the LCA, only EN 15804, the related draft PCR prEN 16485, the Guide to PAS 2050 and the GHG Protocol refer to substitution effects as additional information. From a bio-based product perspective, it is certainly appealing to show the savings resulting from substitution across all impact categories. In the BE, the substitution effects of using biomass in terms of climate change mitigation and resource conservation are particularly important. However, the DF is frequently overestimated and should be applied carefully, only with accurate C accounting that allows judgement to be made on a case-by-case basis, taking into account technical, economic, social or societal needs (Leturcq 2020). In most cases, a 1:1 substitution cannot be assumed. This means that there is great uncertainty when estimating the substitution potential on the market, for example the extent to which market share has been replaced by the bio-based product versus the proportion attributable to additional sales volume. A comparative assessment applying the attributional and consequential LCA approach could prevent the overestimation of substitution effects. Since the attributional approach considers the production systems and their direct environmental impacts, the consequential approach focuses the environmental impacts caused by changes. For example, a change in the demand for a product can be taken into account. In this way, the reactions of the market can be estimated and the effects of substitution can be depicted more realistically (Vadenbo et al. 2017). In addition, a direct comparison of the bio-based product with its fossil alternative is also not expedient, as the product systems may, for example, require different structures or construction methods. These uncertainties raise the question whether a substitution effect or the DF is already robust enough to be included in LCA standards. If used, it should be ensured that the DF uses an appropriate functional unit that reflects the equivalence of the product systems being compared. However, it is strongly recommended that the substitution effects are only presented as additional information, as is the case in the standards mentioned.

4.3 Biogenic C in the context of recycling and cascade use

With regard to CE in BE (CBE), the standards must also provide guidance for recycling and cascade use. The PEF offers the CFF for this purpose. It is used to model the EoL of products including product recovery and recycling and is a combination of formulas calculating *material*, *energy* and *disposal* (European Commission 2021b). It is a comprehensive LCA allocation method, but it is quite complex as it involves multiple parameters regarding material quality, marketing behaviour, etc. (Farrapo et al. 2023). However, no specifications are given for biogenic C, which reduces the value of its application for the BE. Farrapo et al. (2023) suggest developing an updated CFF that includes relevant ecosystem services, such as C sequestration. No less relevant is the biogenic C content of bio-based products, which must be correctly calculated and made transparent if bio-based products are part of a cascade use. Some standards, such as ISO 22526–4, EN 16760 and EN 15804, already provide guidance on estimating or quantifying biogenic C content. However, a standardised approach should be chosen to ensure consistency.

4.4 Assessing the upscaling of processes in the BE

In addition, the BE is confronted with the scaling of processes like no other industry. Some bio-based products and their processes are available on a laboratory or pilot plant scale. The next step is scaling up to pilot or industrial plant scale. LCA guidance is needed to support the different levels of technology maturity and to ensure an assessment of the environmental performance. Recently, the European Commission published a technical report addressing this need. This report offers guidance on conducting prospective LCA for bio-based products, providing background knowledge, tools and suggestions for addressing challenges in this context (European Commission 2022). Sander-Titgemeyer et al. (2023) presented a more specified step-by-step approach for prospective LCA to assess emerging technologies related to the wood value chain. However, further research is needed to accompany the requirements for scaling up bio-based products across various value chains of the BE with an LCA and to analyse uncertainties and risks concerning environmental aspects.

4.5 The integration of LCA into legislation

Over the last 30 years, LCA has been increasingly integrated into legislation, and its influence on policy is expected to continue to grow (Sala et al. 2021). In relation to the BE, LCA approaches have been implemented in several key policies, such as the RED II (European Commission 2018a), the European Green Deal (European Commission 2019b) and the new Circular Economy Action Plan (European Commission 2020). Notably, both the Circular Economy Action Plan and the EU Ecolabel (European Commission 2010c) refer to the PEF. Given the growing importance of LCA in legislation, it is crucial to achieve harmonised specifications not only among standards, but also between standards and directives. Currently, discrepancies exist, as can be illustrated for example by a comparison between EN 16214–4 and RED II. Both the standard and RED II mandate the assessment of three GHG. However, these assessments are conducted under different conditions. EN 16214–4 specifies the assessment of GHG from the extraction and cultivation of raw materials to final transport and distribution, excluding the use phase. In contrast, RED II include the use phase in the assessments. Furthermore, both EN 16214–4 and RED II prescribe that biogenic CO_2 should generally be set to zero, while biogenic CH_4 and N_2O should be assessed from extraction through to distribution (EN 16214–4) or from extraction through to the use phase (RED II). This comparison highlights different assessment approaches in standards and directives within the same sector or even for the same product. In addition, new BE-relevant legislations, such as the Carbon Border Adjustment Mechanism (CBAM) (European Commission 2023b) or new Ecodesign for Sustainable Products Regulation (ESPR) (European Commission 2024), also refer to LCA, CFP or PEF as assessment methods. Therefore, it is essential that organisations responsible for developing standards and regulatory authorities collaborate closely.

The overall aim should be to consistently further develop the powerful and recognised instrument of LCA with regard to the aspects of environmental assessment relevant to the BE. However, the systematic review emphasises that existing LCA standards can already provide valuable approaches for this purpose.

4.6 Potentials and limitations

Even if the standard identified may not reflect the totality of standards that assess or discuss biogenic C in LCA research, the review provides a comprehensive overview. The identified standards have been extracted out of the hits received within a systematic review within the database Nautos. Standards not covered can thus result from the implemented term “Life Cycle Assessment”, as well as the search engine itself. Furthermore, it cannot be entirely precluded that the analysis of the records received with regard to their eligibility has been subjectively influenced and important standards have been excluded. Nevertheless, this should not affect the main conclusions drawn. In addition, the standard draft prEN 18027 also provides a brief overview of standards relevant to the assessment of biogenic C in its Annex. Developed simultaneously with the present review, the draft standard provides a supplement in the description of the impact categories and sub-categories relevant for biogenic C as well as an overview of versions of the IPCC reports referred to in the different relevant standards and guidelines (status April 2022). However, this does not detract from the importance and uniqueness of this review, as it discusses additional standards and criteria in more detail and places them in the context of the BE.

5 Conclusions

This review presents a comprehensive overview of existing standards that guide the assessment of (intermediate) products in BE. It reveals the state of the art of the standards and whether they are valid to support the transition to a BE. In this regard, criteria relevant to the assessment of bio-based products have been determined and differences between the standards have been worked out. Thus, the present review highlights important aspects in terms of biogenic C that should be considered when assessing bio-based products in a BE.

Referring to the BE, the transparency of biogenic C flows over the life cycle phases plays a major role. Neglecting this, in LCA practice the 0/0 approach is commonly used. For instance, following the PEF methodology, this approach is based on the assumption of C neutrality and thus excludes biogenic C flows. Thus, for the highest transparency, the −1/+1 approach should be mandatory, which is already specified in most standards. In this context, prEN 18027 mandates the −1/+1 approach specifically for bio-based outside the bioenergy sector. In the case of the destruction of C reservoirs, such as the deforestation of primary forests, the 0/+1 approach can be implemented, as described in prEN 16485. Additionally, the assessment of biogenic C in the LCA at the product level should also be discussed in the context of biogenic C accounting at a national level. It is to analyse to what extent the assessment approaches for national accounting can also provide valuable information for decision-making in the BE. In this context, it is important to implement harmonised assessment approaches, as legal regulations increasingly take up the LCA method to assess the environmental impact.

The quantity and duration of biogenic C storage is a decisive factor for climate change mitigation, as the climate-relevant concentration of CO_2 in the atmosphere is temporarily reduced. Dynamic and thus complex approaches are being discussed in research and more streamlined approaches are provided in the standards. Even though the standard approaches are simplified, they incentivise the use of biomass in long-life products by granting benefits in the assessment. However, a coherent approach that balances the trade-off between accuracy and simplicity is needed. The duration of C storage is essential, as it can have a significant impact on the assessment depending on the methodology.

In the BE, the substitution effects of using biomass in terms of climate change mitigation and resource conservation are particularly important. However, the DF is frequently overestimated and is to be applied carefully only with accurate C accounting, as a direct comparison of the bio-based product with its fossil alternative is often not expedient. If used, it should be ensured that the DF uses an appropriate functional unit that reflects the equivalence of the product systems being compared. However, it is strongly recommended that the substitution effects are only presented as additional information.

With regard to CBE, the PEF offers the CFF to guide recycling and cascade use. However, no specifications are given for biogenic C. To be valuable for the BE, an updated CFF including aspects such as C sequestration is recommended.

The systematic review shows that existing LCA standards can already provide valuable approaches to support the transformation to a BE. However, further research, consistency and harmonisation work is required in terms of biogenic C in the LCI and LCIA. The overall aim should be to consistently further develop the powerful instrument of LCA concerning the different aspects of biogenic C in LCA.

Appendix

The ILCD Handbook advocates separate reporting of delayed emissions *only if* biogenic C is specifically focused. Therefore, it is describing a method for the *linear discounting of emissions over a 100-year time period*. This method is translated into an equation in EN 16760 and taken up in prEN 18027:

$$CFP_{temporal\ storage} = \frac{-\sum m_i \cdot t_S \cdot GWP_{IPCC,i}}{100} \tag{1}$$

with $CFP_{temporal\ storage}$, the CO_2 footprint of the temporarily stored GHG of type i; m_i, the mass of the GHG i emitted; t_S, the time of temporal removal/storage in years and $GWP_{IPCC,i}$, the GWP of IPCC for GHG i over a period of 100 years. *The realised additional benefit due to the temporal storage of bio-based C, $CFP_{temporal\ storage}$, is finally subtracted from the* CO_2*-equivalents* (CO_2*e) of the total CFP of the product*.

The PAS 2050 supports the separate accounting and reporting of delayed emissions by providing methods to calculate WF for the case (a), where emissions occur as a *single release* within the first 25 years of the TH and the case (b), where *single releases* occur in the subsequent years or *gradual releases* occur over a 100-year TH. In case (a), the $WF_{single\ release\ (<25\ years)}$ is applied to the GHG emissions released at the specific point of time and shall reflect the number of years the release of the emissions has been delayed. In case (b), the $WF_{single\ (>25\ years)\ or\ gradual\ release}$ is multiplied on the total amount of emissions in CO_2e over the TH to reflect the weighted average time these emissions have been present in the atmosphere during the 100 years. The corresponding formulas are:

$$a)\ WF_{single\ release\ (<25\ years)} = \frac{100 - (0.76 \cdot t_0)}{100} \tag{2}$$

$$b)\ WF_{single\ (>25\ years)\ or\ gradual\ release} = \frac{\sum_{i=1}^{100} x_i \cdot (100 - i)}{100} \tag{3}$$

with t_0, the number of years between the beginning of the TH and the single release of the emissions; i, each year in which emissions occur; and x, the proportion of total emissions occurring in any year i. Unlike the method provided by the ILCD Handbook, EN 16760 and prEN 18027, *the realised additional benefit in* CO_2*e due to the temporal storage of bio-based C is not finally subtracted from the total CFP of the product, but its benefit is reported separately*.

Abbreviations BE: Bioeconomy; BES: Bioeconomy strategy; C: Carbon; CF: Characterisation factor; CFF: Circular Footprint Formula; CFP: Carbon Footprint of Products; CO_2: Carbon dioxide; DF: Displacement factor or substitution factor; DLCA: Dynamic life cycle assessment; EoL: End-of-life; EPD: Environmental product declaration; GHG: Greenhouse gas; GTP: Global temperature change potential; GWP: Global warming potential; ILCD Handbook: International Reference Life Cycle Data System Handbook; IPCC: Intergovernmental Panel on Climate Change; LCA: Life cycle assessment; LCI: Life Cycle Inventory; LCIA: Life Cycle Impact Assessment; LUC: Land use change; LULUC: Land use and land use change; PAS 2050: Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services; PCR: Product category rule; PEF: Environmental Footprint for Products; PEFCR: Product Environmental Footprint Category Rule; RED: Renewable Energy Directive; RQ: Research question; SI: Supplementary information; TH: Time horizon

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Declarations

Consent for publication For the use of pictures, the permission of the respective authors was obtained and referred to at the appropriate place. To the authors’ knowledge, there are no further copyright issues.

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