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Monitoring circular biobased economy – Systematic review of circularity indicators at the micro level

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ABSTRACT

The systematic literature review of circular economy indicators at the micro level revealed that they are still at an early stage of development and so far, the specific considerations relevant for biobased systems is not sufficiently incorporated. Existing indicators provide good coverage of aspects related to the quantity of resource flows i.e., resource use efficiency and degree of recirculation. Yet, most indicators fail to include renewable resource share, cascading use, and organic recycling that are important characteristics of biobased systems. These characteristics were taken into consideration in a few recent papers focused on circularity measurement of biobased products. Still there are gaps especially related to assessing the functional use of resources and preservation of quality of recycled materials. This consideration is especially important to optimize cascading use of biomass. Besides quality, another aspect that deserves further attention is closing of the nutrient cycles. Further research is needed in the development of indicators addressing these gaps to extract the maximum potential of biological resources for circular economy. This will yield a monitoring framework based on a comprehensive set of circular economy indicators which can be used by businesses and policy makers to formulate targets for transition to a circular bioeconomy.

1. Introduction

Circular economy is already embraced in the EU policy and seen essential in decoupling of economic growth from the consumption of finite resources. The European Commission (EC) adopted the new Circular Economy Action Plan as one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth (EC, 2015). This circular economy was also linked with a transition to a bioeconomy (EUBA, 2016). It has been stressed that circular economy and bioeconomy should advance together in terms of facing global challenges and synergies between the two concepts should be exploited (Hetemäki et al., 2017). Accordingly, the term circular bioeconomy has been recently introduced to couple the two concepts (Carus and Dammer, 2018; Hetemäki et al., 2017; OECD, 2018; Stegmann et al., 2020).

As stated by the EC, "*to assess progress towards a more circular economy and the effectiveness of action at EU and national level, it is important to have a set of reliable indicators*" (EC, 2015). Indicators can be used to assess circular economy at different levels: macro (city, province, region, nation or beyond), meso (eco-industrial parks) and micro (single product, company or consumer). The focus of this paper is on micro level and specifically on biobased products which are products wholly or partly derived from biomass (CEN, 2014). Although there is a growing number of indicators developed at the micro level, the adoption of these indicators in industrial practice has been low as reported by Saidani et al. (2019), and further research into micro level CE indicators remains relevant. A specific gap is for the assessment of biobased products, where to the best of our knowledge, no comprehensive study exists analysing to what extent micro level CE indicators capture the role biobased products can play in the circular economy.

There is no commonly accepted way of measuring circular economy. This is considered to arise from the different interpretation of circular economy concept by different stakeholders (Corona et al., 2019). A recent literature review revealed 114 different circular economy definitions within peer-reviewed articles, policy papers and consultancy reports (Kirchherr et al., 2017). It was pointed out that because of this, the variety of circularity metrics developed so far present contradiction (Corona et al., 2019), and risk practitioners to reach conflicting conclusions about the same concept (Moraga et al., 2019; Saidani et al., 2019). Also owing to the absence of a clear and agreed definition of circular economy and its principles, quite a number of indicators have

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been developed in the recent years at the micro level.

The lack of structured information on circular economy (CE) indicators is a barrier for their further implementation (EEA, 2016). This has been recognised by several authors who have reviewed, inventoried and categorised these indicators (Kristensen and Mosgaard, 2020; Lindgreen et al., 2020; Saidani et al., 2019). A systemic review by Saidani et al. (2019) identified 55 different circular economy metrics, including 20 at the product level. Whereas, 30 micro-level metrics were reviewed by Kristensen and Mosgaard (2020) including indices, indicators, composite indicator sets and analytical tools, most of which have emerged in the past five years demonstrating a diverse approach to measuring CE. They reported that most indicators focused on recycling, while fewer indicators considered disassembly, lifetime extension, resource-efficiency or reuse. This was supported by De Pascale et al. (2021) where it was concluded that among the 3R (reduce, reuse, recycle) principles, recycling is the most explored. Here a review was made of 29 metrics at the micro level categorised into quantitative approaches, qualitative methods, analytical tools (collect, explain and visualise data) and value-based indicators. In their review of 63 metrics (not distinguished between system levels), Parchomenko et al. (2019) observed that only a few of the CE metrics assess the core objective of the CE which is to maintain the value of products, parts and materials over a maximum period of time. Additionally, Harris et al. (2021) reviewed 42 studies at micro level studying the correlation of circularity indicators to environmental performance. Along the same lines, the connection of circularity indicators with the three sustainability pillars (environmental, economic, social) was analysed by de Oliveira et al. (2021) where 58 micro level metrics were reviewed. Lindgreen et al. (2020) also looked at the relation of the circularity indicators to the environmental, economic, and social dimensions highlighting the underrepresentation of the social dimension.

It is seen that, so far, these review papers on circular economy indicators did not include a specific consideration for monitoring circularity of biobased products or the role biomass can play in the circular economy. This gap related to development of indicators for a systemic monitoring of the bioeconomy was also highlighted in literature (D'Adamo et al., 2020; Navare et al., 2021; O'Brien et al., 2017). Given the political support for the transition to a circular bioeconomy and recognition of its contribution towards achieving climate neutrality (EC, 2019, 2018), it is imperative that there are adequate indicators to monitor this transition and its impacts capturing the specific characteristics of biobased systems. These include replacement of virgin fossil resource input, valorization of biological wastes and residues, providing possibility of cascading use and regeneration of natural system (Bos and Broeze, 2020; Carus and Dammer, 2018; Stegmann et al., 2020).

Recently, Navare et al. (2021) assessed whether the existing CE metrics are apt to assess the circularity of biological cycles. They considered and focused on four CE monitoring criteria specific for biological cycles: renewability, potential for cascading use, closing of nutrient cycles and environmental impact specific to biological cycles. The study is similar to this research with respect to the method used i.e., analysing extent of coverage of specific characteristic of biobased systems and identifying of gaps. The difference lies in that Navare et al. (2021) focused solely on the biological cycles and only considered the biodegradation route for biobased products in the end of life. Whereas the focus of this paper on biobased products is much broader. Firstly, the circularity of biobased products in the technical cycles (through reuse, chemical and mechanical recycling and optimizing the time spent in each cycle) is also considered. Secondly, a more comprehensive list of 9 CE monitoring requirements is used in the analysis building upon our previous study where a systematic review of literature was conducted on CE principles and specific characteristics of biobased systems (Vural Gursel et al., 2022). Another difference is that this study focuses on the product level reviewing CE metrics at the micro level, whereas a mix of macro and micro metrics were reviewed by Navare et al. (2021). Until now, only very few papers developed or used indicators in relation to circularity of biobased products (Ladu and Morone, 2021; Lokesh et al., 2020; Razza et al., 2020). This is the first review paper capturing this niche of circularity metrics developed specifically for biobased products.

Against this background, this paper aims to answer the question: Are existing CE indicators adequate to capture the role biobased products can play in the circular economy? This calls for a systematic review of literature focusing on the extent of coverage of each CE requirement for biobased products by existing indicators. Such a concrete research on CE indicators against the specific characteristics of biobased systems is essential to identify gaps in the current state of the art of CE monitoring and derive recommendations for further development of indicators to fill the gaps. In this context, the objectives of this paper are threefold: (1) analyse to what extent the existing circularity metrics developed for products in general cover the defined CE requirements for biobased products, (2) present the status of circularity metrics development specific for biobased products, and (3) identify the gaps and point out the aspects that deserve specific attention for further development of metrics.

2. Materials and methods

The method applied in this study consists of three steps: (1) Definition of the requirements to measure circularity of biobased products (2) Literature search on circularity indicators at the micro/product level, and (3) Review and analysis of existing circularity indicators against the requirements.

The following Section 2.1 describes the method used for the definition of requirements for a circularity metric to measure circularity of biobased products. To identify the CE indicators, a systematic literature review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), aiming at both peer-reviewed articles and grey literature. Section 2.2 details the method used for the literature search.

The final step involved the review of the identified CE indicators against the defined requirements where it is analysed whether the principle is completely covered or only partially. Accordingly, the gaps were identified showing which CE aspects for biobased systems are insufficiently covered with the existing metrics. The results were used to derive recommendations for further development of indicators to fill these identified gaps.

2.1. *Definition of requirements to measure circularity of biobased products*

To be able to evaluate the existing CE metrics, we seek knowledge of what is required to be measured to adequately monitor progress towards CE. There is no defined list of CE strategies nor consensual definition of each strategy promoting CE (Reike et al., 2018). Different CE strategies and principles have been proposed in scientific and grey literature (EEA, 2016; EMF, 2019; Moraga et al., 2019; Potting et al., 2017; Reike et al., 2018).

The authors recently reviewed these existing CE principles in literature and defined CE principles for biobased products by complementing available CE principles for products in general with specific considerations relevant for biobased systems (e.g., renewable resource replacing virgin fossil input, biorefining, cascading use of biomass, regeneration of natural systems). This resulted in the identification of what needs to be measured for monitoring circularity of biobased products (Vural Gursel et al., 2022). The CE requirements for indicators were determined considering both intrinsic circularity, that measure the inherent circularity, and its effects, depicting the burdens or benefits of closing of loops.

Indicators are needed to assess intrinsic circularity providing a measure of success or progress in implementation of circular economy strategies as defined in our earlier paper: Reduce reliance on fossil resources, Use resources efficiently, Valorise waste and residues, Regenerate, Recirculate and Extend the high-quality use of biomass. This led to the definition of the CE requirements from 1 to 5 provided in Table 1. Additionally, indicators are needed to assess consequences of closing the loops i.e., impact of closing the loops on accumulation of hazardous substances and impact of circularity on sustainability considering all three dimensions (environmental, economic and social). Accordingly, 4 additional CE requirements were included resulting in the 9 CE requirements as listed in Table 1. For further information and background on the definition of the requirements presented in Table 1, readers can refer to Vural Gursel et al. (2022).

2.2. Literature search

The aim of the literature search was: 1) to identify the CE indicators applicable to products in general and 2) to identify the ones specifically developed for biobased systems.

In order to identify existing CE indicators at the micro level a literature search was conducted using the Scopus database for material collection. An advanced search was carried out using the search string: *TITLE-ABS-KEY (circularity OR "circular economy") AND TITLE-ABS-KEY (micro OR product) AND TITLE-ABS-KEY (indicator OR index OR metric) AND LANGUAGE (English) AND PUBYEAR > 2009* on 1 April 2022. Filters were applied to the Scopus database on document type and language to filter peer-reviewed papers (article and review) published in scientific journals (finalized publication stage) in English. This resulted in 520 publications. This was followed by a screening process performed by reading the title and abstract of every document and in some cases, the full content to filter against the inclusion and exclusion criteria presented in Table 2.

For review of the current status of circularity metrics development for biobased systems (in Section 3.2), an additional screening of the above search of the Scopus database was done to identify studies that looked specifically at measuring circularity of biomass use or of biobased products. This screening resulted in a short list of 7 journal papers that are considered in this study which are all from the last 5 years: (Ladu and Morone, 2021;Vamza et al., 2021;Rocchi et al., 2021;Karayılan et al., 2021;Razza et al., 2020;Lokesh et al., 2020;Hildebrandt et al., 2017). Additional search of literature for metrics for the quantification of cascading use of biomass, which is integral for circular economy, revealed the cascade factor (Mantau, 2015), and the Biomass Utilization Factor by nova-Institut (vom Berg et al., 2022). The latter builds on the Biomass Utilization Efficiency metric again by the same institute (Iffland et al., 2015). It should be noted that, although the cascade factor (Mantau, 2015) is more applicable for macro-level analysis, it was chosen to be reviewed due to the focus in this paper to provide an overview of the current state of the art on amongst others the cascading use of biomass. In this part of the study, also the 2019 update of the Material Circularity Indicator of Ellen McArthur Foundation was included where the methodology was specifically extended to include the use of biological materials. This yielded 11 CE indicators or sets of indicators specifically developed for the analysis of biobased systems in Section 3.2. The literature review process is summarized in Fig. 1.

The 7 papers identified specific for biobased systems from the Scopus database were accordingly excluded from the review in Section 3.1 of CE metrics for products in general. This screening process resulted in 14 CE metrics identified through the Scopus database search. To complement the literature search of the Scopus database, the snowballing method was used whereby additional relevant literature was identified from the recent 10 review papers on CE metrics (Corona et al., 2019; de Oliveira et al., 2021; De Pascale et al., 2021; Harris et al., 2021; Kristensen and Mosgaard, 2020; Lindgreen et al., 2021, 2020; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019). This was especially useful in capturing the grey literature from non-academic bodies such as private organisations and consulting agencies since many of the circularity assessment tools are developed as initiatives from non-academic institutions to support businesses (de Oliveira et al., 2021). This provided additional 11 CE metrics to include in the review (8 from academic, 3 from grey literature). Thus the final portfolio included 25 product-centric indicators or indicator sets from 22 journal papers, 1 technical report, and 2 websites with tools for review of CE indicators applicable to products in general (in Section 3.1).

Table 1
Requirements to be used for evaluation of existing CE metrics.

CE Requirements
1. Increase share of renewable resources (in primary resources used)
2. Use resources efficiently (including use of residues and wastes)
3. Ensure regeneration of natural systems
4. Increase recirculation of materials
5. Maximise the utility of products (include cascading use)
6. Minimise risk of accumulation of hazardous substances
7. Positive effect on environmental protection (e.g., pollutants, GHG emissions)
8. Positive effect on economic viability (e.g., value added)
9. Positive effect on social equity (e.g., jobs creation, social wellbeing)

Table 2
Inclusion and exclusion criteria used in literature search.

Inclusion criteria
Peer-reviewed scientific articles in English
Relevant grey literature derived from previous review papers on CE metrics
Micro level CE metrics
Studies that describe CE metrics measuring circularity in a quantitative way
Documents that explicitly describe the methodology of the metrics and specific to measure CE strategies
Exclusion criteria
Meso or macro level indicators
Metrics that do not perform quantification or measurement of circularity
Studies/metrics that focus solely on waste management or end-of-life
Metrics focused exclusively on disassembly and remanufacturing
Studies that only include conventional sustainability or life cycle assessments
Studies that only apply existing CE metrics on case studies
Studies focused on business models or supply chains
Studies focused solely to provide design guidelines

3. Results

3.1. Critical analysis of existing circularity metrics with respect to identified CE requirements

The 25 indicators (together with their abbreviation and source) and results from the evaluation of their coverage of the CE requirements are presented in Table 3. They are listed in chronological order.

The CE metrics mainly cover the main attribute of circular economy of recirculating materials (requirement #4) This concerns how much recycled input is used and/or to what extent a product gets recycled at the end of its life. Some indicators are focussed on recycling such as Recycling indicator set, RI, CEI and RPI, whereas in some others this requirement is covered among other CE aspects for example in CI, MCI, SCI, CM and CPI. CI considers mass of recovered material with respect to total material demand (Cullen, 2017). Van Schaik and Reuter (2016) defined two recycling indices: Product-RI refers to the total recycling and recovery rate of a product, while Material-RI expresses the recycling rate of the individual materials or elements of a specific product. Whereas in PLCM and CEI economic value was chosen instead of mass recycling rate to foster the separation and recycling of materials that can generate more revenues. PLCM is a metric calculated as the fraction of the economic value coming from recirculated parts (Linder et al., 2017), and CEI is a measure of the ratio of material value from recycled products to the material value needed for reproducing the product (Di Maio and Rem, 2015). RPI aims to assess the intrinsic value for reuse that a material has according to the current available technologies, showing technical feasibility of using waste as a resource (Park and Chertow,

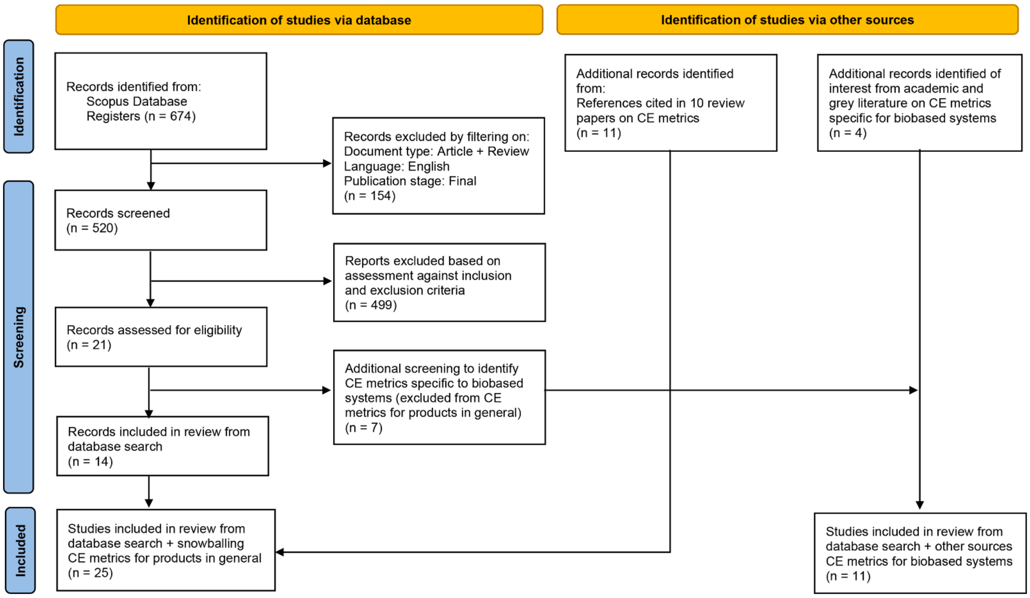

Fig. 1. The review process on CE metrics specific for biobased systems following the PRISMA guidelines.

2014). MCI considers both share of recycled material as input as well as the fraction going to recycling after use (EMF, 2015). MCI, PCI and SCI also include reuse, and CM and PLCM include remanufacturing as part of their recirculation strategies. Degree of recirculation covered in these metrics provide an easy way to communicate information, however it has a narrow scope and doesn't capture the many other aspects of circular economy (such as resource use efficiency and maintaining the value of products over a maximum period of time).

Resource use efficiency is another prominent strategy for CE (requirement #2) and concerns reducing material losses and wastes, improving utilization of resources and accordingly reducing input of primary/virgin resources. Indicators VRE and GRI were found to focus on resource efficiency, and it was included in indicators Circ(T), PCI, SCI and MCI. VRE calculation utilizes the monetary value of resources rather than the mass. Resource efficiency is calculated as the value added of a product divided by the weighted sum of the value of used resources (Di Maio et al., 2017). Circ(T) provides relative measure of the cumulative mass of a material, over a certain time interval, in terms of an ideal reference case where the material is kept functional throughout the entire period, Circ(T) assumes its maximal value 1 if no losses occur over the entire calculation period (Pauliuk et al., 2017). PCI includes efficiency of the production and recycling processes considering material losses during feedstock and product manufacturing (Bracquené et al., 2020). SCI (Azevedo et al., 2017) and MCI (EMF, 2015) measure how efficient the recycling processes is to produce recycled input and to recycle material after use.

Yet, most of the indicators fail to integrate scarcity and criticality of the resources used (requirement #2). This is explicitly included in the GRI by both geopolitical availability and recyclability of resources where the extraction rate and the available reserves of each resource are taken into consideration (Adibi et al., 2017). Applicability of this indicator for renewable resources was also attained by adapting the characterization factors with regeneration rates. Recycling indicator set includes recovery of critical materials considering economic importance and supply risk of the material as identified in the Ad-hoc Working group on critical raw materials (EC, 2014). RDI is a method to capture the desirability of product recycling considering material scarcity, integrating material security, recycling technology maturity and product simplicity (Mohamed Sultan et al., 2017). Additionally, VRE uses the market prices of resources as weights, considering as a proxy for the scarcity of resources (Di Maio et al., 2017) and PLCM considers economic value as a signal of the relative scarcity of goods (Linder et al., 2017). That is a reasonable approximation as the market price will mainly be determined by the balance between the supply and demand for that raw material and since the raw material shortage leads to a price increase of the respective raw material (Frenzel et al., 2017). Accordingly prices will to some degree reflect the scarcity of a raw material (Gleich et al., 2013). Thereby, market prices can give an indication of relative scarcity of material compared to other materials, albeit not being the most reliable indicator of scarcity as the price of a raw material can fall temporary despite ongoing exhaustion (Henckens et al., 2016).

Utility concerns maintaining the value of products as long as possible in as high a quality as possible and is a central strategy for CE (requirement #5). The utility consideration in the existing metrics is mostly limited to consideration of product lifetime and usage intensity. In MCI, a utility factor is used that includes these two components. Authors note that one would use one or the other for utility and it is important to make sure that any given effect is only considered once – either as an impact on lifetimes, or on intensity of use, but not both (EMF, 2015). Like MCI, in SCI and PCI a utility factor is calculated by the lifetime and intensity of usage of the product. SCI and MCI calculates in comparison to an industry average (Azevedo et al., 2017), whereas PCI calculates based on average product design specifications (Bracquené et al., 2020). LI concerns durability of a product and is measured as the length of time that a material is retained in a product system consisting of initial lifetime, earned refurbished lifetime and earned recycled lifetime (Franklin-Johnson et al., 2016). In the CM, this longevity indicator LI was adjusted and combined with a circularity metric which is expressed as the number of times a resource is used in a product system considering initial use, refurbishment and recycling (Figge et al., 2018). Thereby, the two concepts are merged and the contribution of circular practices to longevity or intensity or to both can be determined. In-use occupation indicator of Moraga et al. (2020) considers sequential products accounting for the losses occurring at each phase of each product as well as the strategies (e.g., repair, reuse, and refurbishment) used for each product to increase the lifetime. Except for PCI, decrease of quality in the recycled materials is not taken into consideration in these indicators (MCI, SCI, LI and CM).

Besides product lifetime and usage intensity that form integral part of utility assessment, quality is another aspect of utility (requirement #5) that deserves further attention of indicators in CE (Moraga et al., 2019; Panchal et al., 2021). This is important for CE as quality dictates

Table 3

Analysis of reviewed circularity metrics with respect to identified CE requirements in Table 1 (x = considered, p = partially or implicitly considered).

Indicator	Abbrev.	Source	CE requirements								
			1. Share of renew. resources	2. Resource use efficiency	3. Degree of regeneration	4. Degree of recirculation	5. Utility	6. Hazardous substances	7. Effect on environment	8. Effect on economy	9. Effect on society
Circular Economy Toolkit	CET	(Evans and Bocken, 2013)		*x*	*p*	*x*	*x*	*p*	*p*	*p*	
Recycling indicator set	–	(Nelen et al., 2014)		*p*		*x*	*p*		*x*	*x*	
Reuse Potential Indicator	RPI	(Park and Chertow, 2014)				*x*				*p*	
Circular Economy Index	CEI	(Di Maio and Rem, 2015)				*x*	*p*			*x*	
Material Circularity Indicator	MCI	(EMF, 2015)		*x*		*x*	*x*				
Longevity Indicator	LI	(Franklin-Johnson et al., 2016)				*x*	*x*				
Circularity calculator	–	(IDEALandCOExplore, 2016)		*x*		*x*				*x*	
Eco-efficient Value Ratio	EVR	(Scheepens et al., 2016)							*x*	*x*	
Recycling Indices	RI	(van Schaik and Reuter, 2016)				*x*					
Global Resource Indicator	GRI	(Adibi et al., 2017)		*x*							
Sustainable Circular Index	SCI	(Azevedo et al., 2017)		*p*		*x*	*x*		*x*	*x*	*x*
Circular Economy Indicator Prototype	CEIP	(Cayzer et al., 2017)		*x*		*x*	*x*				
Circularity Index	CI	(Cullen, 2017)				*x*			*p*		
Value-based Resource Efficiency	VRE	(Di Maio et al., 2017)		*x*						*x*	
Circular Economy Performance Indicator	CPI	(Huysman et al., 2017)				*x*	*x*		*x*		
Product-Level Circularity Metric	PLCM	(Linder et al., 2017)		*p*		*x*				*x*	
Recycling Desirability Index	RDI	(Mohamed Sultan et al., 2017)		*p*		*x*			*p*		
Circ(T)	–	(Pauliuk et al., 2017)		*x*		*x*	*x*				
Combination Matrix	CM	(Figge et al., 2018)				*x*	*x*				
Circularity Measurement Toolkit	CMT	(Garza-Reyes et al., 2019)	*p*	*x*		*x*	*x*		*p*	*p*	*p*
Circular economy benefit indicators	RBR, RCBR	(Huysveld et al., 2019)				*x*	*p*		*x*		
Circularity of material quality	QC	(Steinmann et al., 2019)				*x*	*x*		*p*		
Product Recovery Multi-Criteria Decision Tool	PR-MCDT	(Alamerew et al., 2020)							*x*	*x*	*x*
Product Circularity Indicator	PCI	(Bracquené et al., 2020)		*x*		*x*	*x*				
In-use occupation indicator	–	(Moraga et al., 2020)		*x*		*x*	*x*				

whether the secondary materials can be used to fulfil the same function as in the first cycle. QC indicator has a specific focus on quality where the energy required for processing and treating are considered and also possible mixing with primary material to obtain a secondary material of sufficient quality (Steinmann et al., 2019). It should be noted that, such quality consideration in terms of energy demand is applicable for abiotic resources, where steel is used in this study as demonstration, but may not be directly applicable for all biobased products. In CPI, the quality is explicitly considered for plastic waste looking at determination of optimal waste treatment and valorization options according to the quality of waste flow (Huysman et al., 2017). Circ(T) considers whether the product stays in high-quality application (closed-loop recycling) or is downcycled, specifically for metal products (Pauliuk et al., 2017). With RBR and RCBR, Huysveld et al. (2019) included a lifetime difference between the product made from recycled material and the one made from virgin material to capture potential loss in quality. In PCI the quality of the recycled material and potential quality losses preventing closed loop recycling is considered. Quality factors are included for both used and supplied recycled materials yet the authors noted potential data availability issues and proposed use of material value or price as a proxy (Bracquené et al., 2020). Quality aspect is implicitly included in CEI where market value is used as a proxy for material quality (Di Maio and Rem, 2015). Also, in the Recycling indicator set, quality is implicitly included in material cycle closure indicator where the market price of the recycled material is considered reflection of their quality (Nelen et al., 2014). However, such market value is considered to not adequately address the aspect of quality (accordingly noted as *p* in Table 3). The difference in the market price of the secondary and primary material can give an indication of to what extent it is considered that the recycled material can provide the same function as the primary material. Yet, the market price of recycled materials would be dependent on the market demand not necessarily reflecting its technical material quality (Tonini et al., 2022).

CEIP (Cayzer et al., 2017) and CET (Evans and Bocken, 2013) are multidimensional assessment tools evaluating product's circularity performance along life cycle stages (design, manufacturing, use, end of use) with a questionnaire. Similarly, CMT (Garza-Reyes et al., 2019) is composed of 8 questionnaires for manufacturing SMEs. These tools cover a range of CE principles including reuse, repair, remanufacture, recycle and resource use efficiency. In addition, CEIP considers potential circular business models like rental options and take-back schemes. In CET there is additional considerations for use of scarce materials and lifetime of products. Whereas in CMT, there are additional considerations for internal and external awareness, and development of green market, technology and legislation (Garza-Reyes et al., 2019). Additionally, Circularity calculator is an online tool for companies to discover the potential of different circular scenarios by visualizing material flows and the financial value of closing loops by reusing, refurbishing, remanufacturing, and/or recycling (IDEALandCOExplore, 2016).

All the CE metrics focus exclusively on the technical cycle and materials from non-renewable resources. They accordingly fail in providing measure of the share of renewable resources in materials (requirement #1) and degree of regeneration (requirement #3). For the utility aspect (requirement #5), the considerations of quality degradation, and most appropriate use of waste streams based on their quality in existing metrics is a key principle for cascading use. However, these metrics were not developed considering biological resources and so far the possibility of cascading use of biomass is not explicitly incorporated in these metrics assessing flow of biomass in consecutive products (see Section 3.2 for such metrics) and considering appropriate fit as it will be discussed in Section 4.

Furthermore, the risk of accumulation of hazardous substances in closing the loops is not taken into consideration in the developed indicators (requirement #6). Only in CET (Evans and Bocken, 2013) consideration is made for biodegradable materials which is linked to regeneration requirement (#3) and use of toxic materials in product which is linked to hazardous substances requirement (#6) and in CMT (Garza-Reyes et al., 2019) for renewable material input (requirement #1). Yet, they do not provide a measure of these requirements.

Looking at the coverage of impact of circularity performance on sustainability within existing metrics, it is seen that several metrics already considered the environmental and/or economic consequences whereas only 3 out of the 24 reviewed metrics covered social consequences. CPI and Recycling indicator set have an explicit coverage of environmental impact (requirement #7). CPI expresses environmental impact in terms of resource consumption taking into consideration resource footprint of recycling and avoided impact of the virgin production (Huysman et al., 2017). In Recycling indicator set, the indicator avoided environmental burden is calculated as the avoided environmental burden by recycling to the environmental impact of the production of virgin material. It equals 1 for closed loop recycling of all input materials (Nelen et al., 2014). RBR and RCBR advance the monitoring of environmental benefits of recycling (Huysveld et al., 2019). Environmental impact is implicitly considered in QC (Steinmann et al., 2019) and CI (Cullen, 2017) which calculate energy required to recover secondary material relative to the energy required to produce the material from virgin resource thereby taking into account possible trade-offs from circularity on energy use and accordingly on environmental impact. Also in RDI, for determining material security index, among others, global warming potential and climate change vulnerability is included (Mohamed Sultan et al., 2017).

The economic dimension (requirement #8) is mostly limited to the consideration of value or price of products or materials, monetary representation of resource flows. For example, in the PLCM, CEI and Recycling indicator set, market value (or price) of recycled material and the total product value or market value of all materials to produce the original product are considered. Also, RPI evaluates whether the material can be economically recycled so the associated costs of recycling technologies are considered (Park and Chertow, 2014). Additionally, in the economic dimension, the value gained from the CE activities are considered in VRE and Circularity calculator.

It is seen that some indicators consider the environmental dimension (requirement #7) in combination with the economic dimension (requirement #8). EVR is an life cycle analysis based metric calculated as the ratio of environmental burden (eco-costs) to the value of product. Eco-costs express the amount of environmental burden of a product on the basis of prevention of that burden in monetary units (Scheepens et al., 2016). EVR is focused on the impacts and does not provide a measure of the intrinsic circularity. Additionally, CET includes consideration of the use of materials with a high eco-efficiency (Evans and Bocken, 2013). SCI includes all three dimensions of sustainability using sustainability indicators in combination with circularity indicators. The social dimension (requirement #9) is focused on the workers well-being and equity (Azevedo et al., 2017). PR-MCDT focused on the evaluation of the impacts of circularity strategies considering all three dimensions of sustainability (Alamerew et al., 2020). The developed multi criteria decision making method uses life cycle analysis (LCA) and life cycle costing (LCC) for environmental and economic dimensions respectively and qualitative indicators for social dimension (job creation opportunity, exposure of employees to hazardous materials, level of customer satisfaction).

3.2. Status of circularity metrics development for biobased products

Table 4 provides an overview of the 11 studies identified and reviewed concerning circularity measurement of biomass or biobased products. The first version of MCI was published in 2015 and focussed exclusively on technical cycles and materials from non-renewable sources (provided in Table 3). It was updated in 2019 with the extension of the methodology to include the use of biological materials. Their share in the feedstock was included in calculation of virgin feedstock

Table 4
Overview of literature on circularity assessment of biobased products.

Study	Description of study	Indicator(s)	Description of indicator(s)	Linking to CE requirement #
EMF (2019)	Extension of the MCI (2015) methodology to include the treatment of biological materials	MCI (update 2019)	Update of the MCI (2015) to include share of biological materials as input and composting and energy recovery of biological materials in end of life.	1, 2, 4, 5
Razza et al. (2020)	Proposed modified MCI for calculating circularity of biobased and biodegradable products and applied it on mulch films	Modified MCI	Modification of the MCI (2015) to incorporate biobased content and organic recycling.	1, 2, 4
Rocchi et al. (2021)	Proposed modified MCI for calculating circularity of animal production systems and applied to the poultry sector.	Modified MCI	Modification of the MCI (2015) to specifically animal production systems where virgin feed is used for rearing animals and obtaining the final product meat and use of production residues as compost or biogas production.	1, 2, 4, 5
Karayilan et al. (2021)	Optimization model to investigate three circular economy strategies for European plastic packaging value chain	Modified MCI	Adaption of MCI (2019) for complete plastic packaging value chain evaluation including score of option analysis for products as a weight	1, 2, 4
Nova-paper #8 (Iffland et al., 2015)	Development of a metric to provide guidance on the best combination of biomass feedstock, process and bio-based product	Biomass Utilization Efficiency (BUE)	Percentage of initial biomass ending up in the end product. Four categories: BUE_S based on stoichiometry, BUE_L and BUE_H based on process yield (lowest and highest published), BUE_E based on energy content	2
Nova-paper #16 (vom Berg et al., 2022)	Development of a metric to investigate whether and to what extent biomass and materials are kept in use	Biomass Utilization Factor (BUF)	Quantifies to which extent (production efficiency) and how often (cascading use) the biomass is utilised in a biobased product value chain	2, 4, 5
Hildebrandt et al. (2017)	Indicator to assess the influence of design for recycling on cascading use of bio-based polymers	Cascade use indicators	Set of indicators for quantifying the material recycling and energy recovery (cumulative energy demand, material use efficiency, substitution of virgin materials, energy recovery)	2, 4, 5
Vamza et al. (2021)	Gives an insight into resource efficiency in a specific enterprise by quantifying the incoming raw material (biomass), the outgoing product, by-products, and waste.	Bioresource Utilization Index (Bu_{ind})	Summation of product and by-products divided by raw material on a dry weight basis. Assigning coefficients (0–1) to by-product utilization options based on the biobased value pyramid	2
Mantau (2015)	Wood flow analysis, resource assessment including all wood products in all process steps from forest to disposal	Cascading factor	A product cascade factor calculates single or multiple use of resource in a production system	2, 4, 5
Lokesh et al. (2020)	Proposes a set of hybridised indicators drawn from green chemistry and resource circularity principles. They are used in combination with LCA indicators.	Hybridised sustainability indicators	Set of indicators: Presence of hazardous chemicals, Feedstock intensity, Waste factor, Process material circularity, Renewability and Energy intensity	1, 2, 4, 6
Ladu and Morone (2021)	Proposes a new integrated assessment tool (IAT), representing a harmonised framework for the sustainability assessment of bio-based products including circularity aspects as part of STAR-ProBio project.	Circularity indicators	Set of circularity indicators: Presence of hazardous chemicals, Renewability, modified MCI, Waste factor, Energy intensity and Renewable energy use. In total 11 indicators, 5 quantitative, 1 semi-quantitative, 5 qualitative	1, 2, 4, 6

and the composting and energy recovery of biological materials were included in calculation of unrecoverable waste (EMF, 2019). It is considered that the biological resources should be sustainably sourced, however a method for validation of this is not provided. Besides the share of biological resources in materials, it is important to consider the sustainable sourcing of those resources. This aspect can be ensured through use of certified resources for example with sustainability certification schemes for wood FSC or PEFC, and for agricultural products e.g., RSPO for palm, Bonsucro for sugarcane and RTRS for soy.

Independently from the EMF update, Razza et al. (2020) carried out modifications to the first version of MCI to quantify the circularity of biobased and biodegradable products. This modified MCI was applied to biobased mulch films and the result was seen to be heavily linked with the biobased content. Although this modified MCI and EMF's 2019 update of MCI show similarities, they are not the same. They both include biobased content as non-virgin input and account composting as contributing to recycling. One difference observed is that biobased materials embodied in the biobased product that go to incineration are accounted as non-restorative in modified MCI (Razza et al., 2020). Whereas in EMF's 2019 update of MCI, biological materials that are used for energy recovery are not considered as unrecoverable waste if specific conditions are met. These conditions include: Recycling or composting is not possible; Energy recovery is optimised and usefully employed to displace non-renewable energy; and If by-products occur, they must be biologically beneficial e.g. can be used as a soil conditioner (EMF, 2019). Although, both methods consider organic recycling, and indicate the intent to usefully return the nutrients contained within biological material to the natural environment in a manner that is biologically accessible. No specific measure of the extent of regeneration of natural systems has been made.

Similarly, Rocchi et al. (2021) proposed modification of the first version of MCI for adapting to biological cycles, specifically to animal-based production. The unrecoverable waste is calculated subtracting the fractions used for composting and biogas recovery analogous to the EMF's 2019 update of MCI. Regarding utility, the authors considered use of a mortality rate of animals to determine the percentage of animals which stay for the whole cycle (Rocchi et al., 2021). The authors pointed out that although the MCI is a good indicator for understanding the degree of circularity of a product, it is not sufficient to oversee the whole context. They considered complementing the modified MCI with LCA, however noted that additional considerations are relevant which are not captured with neither of them such as the benefit of application of by-products from the food system as feed. With the modified MCI, the authors calculated the impact of returning manure on circularity but not did not consider the actual contribution of manure to close the nutrient loops.

Instead of modification of MCI, Karayilan et al. (2021) worked on the combination of LCA for environmental impact assessment with MCI for circularity assessment using the 2019 method update (EMF, 2019). They developed optimization models to assess how European plastic waste supply chains could be made more circular, where one option considered was introduction of biobased biodegradable products. The system considered is collection of plastic packaging wastes to their recycling to valorization in packaging, automotive, agriculture, fibers, construction and electronics industries. The authors did not modify the MCI calculation itself, instead they calculated an overall MCI of the whole value chain by calculating a weighted sum of MCI for each product. Scores were determined for each product through an option analysis based on a list of criteria which includes biodegradability of products. The ratio of product scoring to total scoring of all products was used as the weight. It is reported that introduction of biobased biodegradable plastics contributes to increase in circularity performance (Karayılan et al., 2021).

While the calculation of the production efficiency is straightforward for some sectors (e.g., forest), it can become more difficult to follow the biomass utilisation if chemical transformations occur. In cases of chemicals, polymers and fuels, the indicator Biomass Utilisation Efficiency (BUE) can be used (Iffland et al., 2015). BUE shows that it is important to combine the right molecule with the right process in the right application. Molecules that have low oxygen content are more suitable for energetic purposes whereas molecules with higher oxygen content (and additional functional groups) are more suitable to create material with specific chemical properties. The Biomass Utilization Factor (BUF) combines cascading use and production efficiency into one straightforward indicator that quantifies to what extent biomass and, in a wider sense, materials, are kept in use starting with the original biomass input into the first product stage, and from there tracing the biomass flow into potential further product stages (vom Berg et al., 2022). It provides a way to quantify impacts of increasing the recovery rate/recycling quota of specific products and political instruments, e.g., providing incentives towards higher biomass utilisation in products instead of bioenergy options. Hildebrandt et al. (2017) proposed a set of indicators considering the efficiency of raw material use, substitution of virgin materials along a series of materials and energy yields obtained at end of life for each fraction going through energy recovery. As with BUF, accounting of performance is done along multiple cascade use stages and differentiation is made for waste incineration with or without energy recovery (Hildebrandt et al., 2017).

The biobased value pyramid is commonly used to classify biomass applications according to their value and volume (Stegmann et al., 2020). In a recent study, a coefficient was attributed to the biobased value pyramid representing the value for bioresource utilization (coefficient of 1 was attributed to Pharmaceutical and Fine chemicals, coefficient of 0.75 to Food and Feed, 0.5 to Bioplastics and Polymers, 0.25 to Bulk chemicals and Materials, and 0 to Energy, Heat and Fuels) (Vamza et al., 2021). The coefficient is assigned to the raw material or the by-product when it is used for the corresponding application. Whereas in the BUF, all kinds of food, feed, biobased products, bioenergy and biofuels are counted in the same way for the production efficiency (no coefficient is used) (vom Berg et al., 2022), but only biobased products deliver biomass to the next cascading stage.

A cascade factor for the wood flows in the EU was calculated in the Mantau et al. (2015) paper. If only wood resources from trees are used in industry the cascade factor is 1.0. The more the residues from the sawmill and the more recycled products get used for example in panel and pulp industries the higher the cascading factor gets (Mantau, 2015). The cascade factors have been calculated based on overall wood resource balance, rather than tracing a specific amount of biomass input in cascading stages as done in BUF. Another difference is that in BUF, the efficiency of biomass utilization is considered so BUF could be below 1 if some part of biomass is unused (i.e., losses occur) and the rest is used in production of energy or food/feed, so biomass does not reach a next cascading stage. Yet, the focus here is on the quantity of biomass that is kept in use. As it will be discussed in Section 4, it is also important to consider whether high or low quality products are produced in the subsequent stages and the extent to which the functionality of biomass is preserved.

Recently, a set of hybridised indicators was proposed including hazardous chemical use, waste generated, resource circularity, renewability and energy intensity (Lokesh et al., 2020). These are used in combination with LCA indicators to compare biobased products with their fossil-based counterparts accordingly also covering the 7th CE requirement (see Table 1). They accordingly provide a very good coverage of the CE requirements identified especially with the inclusion of indicators concerning share of renewable resources and presence of hazardous chemicals. Although not included as a separate indicator, also in Hildebrandt et al. (2017), consideration is made for the legislative restriction and thresholds for hazardous substances for the ingredients used in production.

As a result of a transdisciplinary process involving contributions from both industry and academia, an integrated assessment tool (IAT) was proposed consisting of 48 sustainability indicators covering three pillars of sustainability (environmental, economic and social) as well as circularity aspects (Ladu and Morone, 2021; STAR-ProBio, 2020). The circularity indicators show many similarities with the indicator set of Lokesh et al. (2020). There is inclusion of a renewable energy share indicator and for process material circularity the modified MCI of Razza et al. (2020) is used.

4. Discussion

The review reveals a good coverage of aspects related to the quantity of resource flows i.e., resource use efficiency and degree of recirculation by existing indicators. Yet, quality is an aspect that deserves further attention of indicators in CE (Moraga et al., 2019; Panchal et al., 2021). If an increased circularity is aimed for, it is essential to monitor quality and to incorporate quality aspects in decision making. Quality refers to the potential resource utility or functionality based on the inherent and intrinsic material properties such as structure and chemical composition (Sirkin and Houten, 1994). This is especially true for biomass, as it consists of multiple components that together have higher functionality than the sum of parts.

There are two considerations to be made related to quality i.e., the loss in quality when making products out of biomass and the loss in quality when recycling the products. The first consideration is what happens to the biomass when a product is made from it. We can take the biomass apart (e.g., for wood sawing, milling, pulping), but we cannot put it together in its original form. In general, it is better to use the functional qualities first, as the components will usually be preserved in the product and may be used later (cascading use of biomass). The second consideration is about what happens to the biobased products after use. Can the recycled product fulfil the same function as in the first cycle (closed-loop recycling e.g., PET bottle into a new PET bottle) or is there loss in quality that causes downcycling (open-loop recycling, e.g., PET bottle to fibre recycling for textiles)? Here it is also important if the product follows the cascading steps. For example, if a recycled sawn wood is burned instead of used for particle board production, this results in shortening of the cascade and a lost opportunity in terms of resource use and quality. Therefore, there is a strong need to consider these aspects in the circularity assessment.

There can be trade-offs between the two strategies of circular economy of keeping as much material in the economy and keeping products in high quality applications. Pauliuk et al. (2017) observed that keeping steel in high quality applications, resulted in higher losses. This shows the importance of considering the quality together with the quantity (recycling efficiency) in evaluations.

Related to quality, appropriate fit is an important aspect of cascading use where the resources should be applied to highest quality products possible (Sirkin and Houten, 1994). For example this refers to not using sawn wood for low-quality applications (such as energetic purposes) or not using a primary plastic in an application that can be performed with recycled plastic such as shampoo bottles. The assessment of this value or quality of a resource, which determines its optimal application and continued allocated use in economy, is generally lacking in CE monitoring and is essential to achieve the maximum potential of the biobased systems. This will provide prioritization of the highest-value application based on the inherent resource properties to provide the highest utility.

As presented in Section 3.2, a few metrics have been developed already for the quantification of cascading use of biomass most notably BUF. While BUF provides quantification of extent biomass kept in use, no explicit consideration is made about the quality of the biobased products in the different stages. Although it can be seen that exploiting biomass for higher quality applications and promoting higher quality recycled materials would extend the use and yield a higher BUF.

Besides quality, another aspect that deserves further attention, is closing of the nutrient cycles. It is often seen that supply and uptake of nutrients are not balanced where both the surplus and deficit of nutrients cause problems. The nutrients not returned to the field or returned at a rate at higher than the ecosystems can absorb the nutrients may disrupt the nutrient cycles (Navare et al., 2021). It is therefore required to monitor both to where, and in what amount, nutrients should be distributed to avoid damaging the ecosystems (EEA, 2018). It is further required to examine whether the minerals returned result in closing of nutrient cycles and actually contribute to regeneration of natural systems. For biobased products, this concerns assessment of whether the nutrients in the products can be returned to the soil. Depending on the product and production process, the nutrients may stay in the product (e.g., straw into boards), or go into the side streams (e.g., in production of ethanol nutrients are in the side stream distillers grains and solubles). Nutrient can be reclaimed from a side stream (e.g., biochar applied to soil) or lost in a side stream (e.g., in wastewater). If nutrients stay in the product, then only the end fate will determine whether the nutrient is lost or can be reclaimed. If organic recycling of the product is possible (i.e., with in-situ biodegradation, composting, or anaerobic digestion) then the nutrients can be reclaimed by the soil. Other considerations include whether the biological material returned to the natural environment is bio-compatible (non-hazardous) and do not accumulate in nature negatively affecting the ecosystem functioning.

Additionally, a gap is seen in taking into account both intrinsic circularity and the effects of this circularity i.e., on the three pillars of sustainability that can potentially lead to undesirable burden shifting from reduced material consumption to increased environmental, economic and/or social impacts (Corona et al., 2019). Assessment of the positive contribution of renewable and circular products to SDGs in comparison to non-renewable and circular ones was found to be a driver for circular bioeconomy (Salvador et al., 2022). A recent study highlights how circular bioeconomy strategies can help in climate action, yet the sustainability of advancements in biobased products need to be assured (Sharma and Malaviya, 2023). This review revealed that only few of the metrics made an attempt to provide a more holistic approach. These included mostly assessment of economic or environmental impacts whereas social consequences were largely not addressed. To address this gap, existing circularity assessment approaches can be combined with conventional sustainability methodologies of life cycle analysis (LCC), life cycle costing (LCC) and social LCA (S-LCA) for a holistic assessment. This has also been considered by Lindgreen et al. (2020) and Niero and Kalbar (2019) to provide a more comprehensive assessment. Such initiatives are already appearing in literature. The combination of circularity indicators with LCA has been the focus of some recent research (e.g. (Niero and Kalbar, 2019;Rigamonti and Mancini, 2021) and (Schulte et al., 2021)). Niero and Kalbar (2019) combined LCA with the Material Reutilization Score and the MCI, whilst (Lonca et al., 2020) combined material flow analysis (MFA), MCI, and LCA to assess plastic (PET) bottles. Also, the EMF report indicated that MCI can be complemented with environmental impact indicators (energy use, GHG emissions, water use, toxicity) (EMF, 2019). Yet, the link with socio-economic impacts is still lacking. At macro level, a socio-economic indicator for the bioeconomy has been proposed and applied for the measurement of performance of different biobased sectors in Europe (D'Adamo et al., 2020; Morone et al., 2022). Learning from such an indicator can be adapted for micro-level indicator development.

The presented research centered around the core CE strategies for biobased products that were identified (Vural Gursel et al., 2022) and presented in Table 1. CE strategies concerning refuse, rethink, and dematerialization are not specifically incorporated. These are related to the design of the products as well as on consumer behaviour which are not analysed in this study, yet are very significant for realizing circular economy. The analysis in this study of the existing metrics against the defined CE requirements, showed results of not only if the requirement was assessed but also whether it was being completely assessed. Yet, a limitation is that some metrics aim to combine multiple aspects of CE and it is challenging to assess whether each aspect is captured at an appropriate level of detail. Also, the direct applicability of the existing indicators to biobased products needs to be further evaluated (e.g., whether indicators developed to assess quality loss in recycling are also applicable to all biobased products or whether additional considerations would be needed).

5. Conclusions

This paper provided a literature review on the existing circularity metrics at product level and analysed their coverage of the defined CE monitoring requirements for biobased products. It was seen that existing metrics took into consideration just some of the aspects of circularity and that they do not capture all the requirements to measure the circularity of biobased products. Gaps were revealed especially concerning measurement of renewable resource use in products, cascading use, preservation of quality of the recycled materials, nutrient recycling and presence of hazardous substances.

It was highlighted that in circularity assessment there is a strong need to take into account functional use of biomass and preservation of quality. The authors therefore, encourage the reader to create metrics to be able to address these quality aspects (i.e. exploiting biomass for higher quality applications), as well as metrics related to closing of nutrient cycles and their contribution to regeneration of natural systems.

To make a comprehensive comparative assessment among the different application possibilities, it is required to complement the circularity assessment with the sustainability assessment (encompassing environmental, economic and social dimensions). This is explained to be possible by using in combination the existing sustainability assessment frameworks i.e., LCA for environmental and LCC for economic and S-LCA for social aspects.

The increase in biomass as a renewable resource in the economy should also go together with a more sustainable and circular use of biomass. A suitable monitoring framework based on a comprehensive set of CE indicators is essential to be able to measure this. The science-based knowledge generated this way, will yield a deeper understanding, and help industry and the policy makers in setting suitable circular economy targets (i.e., quantifiable objectives linked to the circular economy strategies) and monitor progress.

CRediT authorship contribution statement

I. Vural Gursel: Conceptualization, Methodology, Writing – original draft. **Berien Elbersen:** Conceptualization, Writing – review & editing, Project administration. **Koen P.H. Meesters:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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