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# Circular economy and life cycle thinking applied to the biomass supply chain: A review

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## A B S T R A C T

The adoption of circular economy and life cycle thinking (LCT) tools plays an important role in implementing and evaluating sustainable development strategies of companies. However, until now there is no review paper on the application of these concepts in the biomass supply chain (BSC). This paper aims to review the application of circular economy and LCT in BSC. PRISMA method was used for the review. The analysis was conducted to examine case studies focusing on (1) approaches and practices of applying circularity economy concepts such as circular economy principles, strategies, indicators, business models, (2) application of LCT tools and sustainable concepts. Besides, benefits, limitations, and discussion of applying these concepts and tools were conducted. The review results show that four circular economy principles are applied (reuse, recycle, reduction and recovery), in forms of three strategies: use innovative technologies, improving operational activities and extending the BSC. Regarding LCT, most of the studies focus on environmental assessment, with some extension to economic and social impacts. Most of the exiting literature studied circular economy and LCT separately; therefore, it is recommended that comprehensive, life cycle-based tools should be developed for businesses and decision-makers to thoroughly assess and improve circularity and sustainability of bioenergy.

## 1. Introduction

Circular economy (CE) is the key to sustainability. The adoption of CE and circular business models (CBMs) is widely recognized as a significant approach in driving sustainable development of companies and organizations within the supply chains [1]. In the biomass supply chain (BSC), the adoption of biochemical extraction technologies and utilization of biomass waste for energy purposes are identified to contribute to the transition from linear economy into CE [2]. At the same time, the application of multiple bioenergy technologies contributes to reducing greenhouse gases (GHGs) in various energy consumption sectors, plays the role of carbon sinks for other economic sectors and helps to fully decarbonize the socio-economy [3], which is one important goal of sustainable development. Due to the importance of biomass materials and their potential contribution in transition to CE and aiming at sustainable development, the practical application of these concepts in the BSC recently attracts more attentions [4–8].

CE is developed on the principle that "everything is input to something else“ [9]. The European Commission (2015) stated that "in a CE, the product value and raw materials are maintained for as long as possible; waste and resource use are minimized, and resources are kept in the economy when a product has reached the end of its life cycle, to be used to continue to create even more value" [10]. Currently, the concept of CE identified by the Ellen MacArthur Foundation is widely accepted, which defines CE as a restorative or regenerative industrial system [2]. CE operates on the philosophy of recreating natural systems and maximizing the useful lifetime of products, supplies, and materials, while minimizing waste and pollution. It replaces the "end of life" of materials with the concept of recovery, switching to renewable energy, no use of harmful chemicals, and minimizing waste through the design of materials, products, engineering systems, and business models [2].

The adoption of CE has several advantages in both short and long terms. Firstly, it minimizes the resource consumption and waste generation, which ultimately reduce the businesses’ cost for resource purchase and waste management. These extra economic benefits might be used for other investment, for example innovating equipment and

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factory, improving working environment, creating employees' social benefits, etc. In the short-term, CE brings direct economic and social benefits for enterprises, employees and consumers. Secondly, the reduction of resource consumption, in the long term, will save the earth's limited resources, reduce relevant environmental impacts, and ensure the clean and green environment for the next generations.

The application of CE is acknowledged on three different levels, namely macro-level (cities, nations and global), meso-level (industrial parks), and micro-level (products, enterprises, consumers). In general, it is presented in 10 principles, including reduce, reuse, recycle, recover, repair, refuse, rethink, refurbish, remanufacture, and repurpose [1,11].

The CE application at the micro level encourages enterprises to redesign their business strategies and aim at circular business models (CBMs) [1,12]. According to the Organisation for Economic Co-operation and Development (OECD), CBMs are different ways of producing and consuming goods and services [13]. The CBM focuses on extending the product's life cycle to maintain the product's value for as long as possible, reducing environmental impacts and bringing economic benefits for customers [12]. There are different types of CBMs according to various classifications. OECD reclassifies CBMs into five categories, including, circular supply models, resource recovery models, product life extension models, sharing models, and product service systems models [13]. Moreover, Ludeke-Freund et al. proposed six main CBMs, following the CE principles, including repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading and repurposing, and organic feedstock [14].

According to Sherwood, biomass plays an important role in promoting CE and creating CBMs, as it can be exploited as an alternative organic feedstock to replace crude oil and natural gas [15]. BSC comprises different processes, such as harvesting, collection, transportation, pre-treatment, storage, and end-use [16]. A BSC with waste-free biorefineries utilises all the available biomass components to make products and energy consistent with the fundamental objective of a CE [15,17,18]. While the role of biomass in the CE has been confirmed [2], the gap still exists in evaluating the application of CE to the BSC. Furthermore, the differences in CE concepts and CBM classifications make it difficult to apply them to the BSC. Because of the disparate concepts, there is also a lack of a standardised set of indicators to evaluate the degree of circularity for the BSC. As a result, the issue of applying CE principles and implementing CBMs to BSCs, as well as using CE indicators for assessing these chains needs to be fully clarified.

The production of bioenergy has been expected to contribute to sustainable development by reducing fossil fuel consumption and GHG emissions, for example, energy production from biowaste can help to decrease 60 % of GHG emissions [19]. Because biomass has many different origins, the benefits and drawbacks of energy production from biomass sources must be thoroughly evaluated. Regarding the environmental aspect, energy production from waste is believed to contribute to pollution reduction; however, the process also generates emissions and waste. In addition, the economic and social impacts of the bioenergy production process must also be assessed. The life cycle thinking (LCT) tools, including life cycle assessment (LCA), life cycle costing (LCC), social life cycle assessment (SLCA), and life cycle sustainability assessment (LCSA) are expected to provide the most reliable scientific evidence for evaluating the performance of BSC [20,21]. The variety of biomass materials, differences in biomass processing technology and multiple end-products lead to challenges in the application of LCT tools such as identifying sustainable hotspots, methodological aspects and impact indicators. This can also cause a trade-off in sustainable aspects leading to difficulty in the final result of assessment for sustainable alternatives. Therefore, applying LCT tools to BSC is necessary to be completely evaluated.

To the best of the author's knowledge, there is no previous review covering all topics of LCT, CE and biomass, and the existing reviews covered only on aspect (CE or LCT) in the biomass sector. For example [22], reviewed the innovations and optimizations in biogas production, covering upstream, mainstream and downstream biological technologies such as those for pre-treatment of biomass materials, biogas production and removal of impurities. The fundamentals and the technology for biogas production from lipids and lipid-rich wastes has been studied in Ref. [23], focused on the application of anaerobic technologies as potential technologies for facilitating CE. Huang et al. studied the performance of industrial sludge and waste biochar for facilitating a circular bio-economy [24]. Hussin et al. reviewed the life cycle environmental impacts of hydrothermal technology applied for biomass conversion [25].

Other review paper concerns the CE and LCT topics in general, without putting it in the BCS context. For example, Sassanelli et al. have reviewed the existing CE performance assessment methods for companies and concluded that there is a lack of methodologies regarding the overall evaluation of CE benefits [26]. The authors pointed out that life cycle assessment, material flow analysis, discrete event simulation, input-output, and multi-criteria approaches are aimed at considering and evaluating all the possible variables involved in the system, along its entire life cycle, while the design for X and some guidelines are specifically used for the product design and development. The strong tendency of these methodologies is to focus on the environmental level [26]. There are some gaps in these review papers. These review papers mainly focused on either life cycle environmental impacts of biomass based technologies or their benefits to CE. In addition, CBMs were not mentioned in the existing review. Finally, most of the existing review focused on one production technology.

This article aims to review the application of CE principles, CBMs, and LCT to the BSCs, covering multiple biomasses, production technologies, and products. Specifically, the research papers on the BSC, CE and LCT were searched and selected by following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline. In order to differentiate the application of CE at different levels, the searching term "CE principles" refers to as the application of CE in general, while the term "CBMs" denotes the application of CE principles at micro level. By reviewing the existing literature related to BSC, CE and LCT, this paper will provide information on which and how CE principles, CBMs and CE indicators have been applied in the BSC. Furthermore, the application of LCT tools, sustainability hotspots and life cycle impact indicators in the BSC will be pointed out. From this review, benefits and limitations of applying CE principles, LCT tools and CBMs in the BSC will be identified, the issues that need to be studied in the future will be proposed. The findings of this article can be a good reference to scholars, businesses and policymakers in applying CE principles, CBMs and LCT tools in BSCs.

The following sections present the research context, methodology and obtained results of the review. Section 2 describes the method for selecting papers and extracting information to be reviewed. Section 3 analyzes the research context of BSCs relevant to CE and LCT in reviewed papers, with the main focus on end-products, biomass inputs, regions and applicable technologies. Section 4 includes the obtained results on the application of CE principles in general, the adoption of CBMs at enterprises and CE indicators used for circularity assessment. The application of LCT approach, identified sustainability hotspots during BSCs, and sustainability indicators used to convey life cycle impacts are presented in Section 5. The advantages and barriers of applying CE principles and LCT tools in the BSC are pointed out in Section 6, followed by a discussion in Section 7. Finally, the conclusion and future work are included in Section 8.

## 2. Materials and methods

The review is conducted in five steps of (1) defining the research problem, (2) identifying strategy for searching and selecting literatures for review, (3) searching and selecting literatures, (4) extracting data and analysing the information and (5) reporting the obtained results [27]. In step (3), the process of selecting literatures for review is based on [28–30] and follows the PRISMA diagram [31], as shown in Fig. 1.

The keywords relevant to CE, LCT and BSC were separated into two groups. The first group is composed of BSC keywords such as "biomass," "biofuel," and "bioenergy". The second group comprises keywords such as "circular economy," "circular business model," "life cycle thinking", "life cycle assessment", "life cycle costing", and "social life cycle assessment". The string chain ("biomass" OR "biofuel" OR "bioenergy") AND ("circular economy" OR "circular business model" OR "life cycle thinking" OR "life cycle assessment" OR "life cycle costing" OR "social life cycle assessment") was used to search the literature.

The literature search was conducted in the titles, abstracts and keywords of the articles in two scientific databases such as ScienceDirect and Scopus, which are well-known academic search engines [26]. These databases offer extensive coverage, reliable sources, recent research, and advanced search tools. This search gave out 3262 documents being published by the end of 2022. Book chapters, and articles in conference proceedings were excluded, because their full texts are inaccessible or provide inadequate information for the analysis [32]. Only one conference paper is included in the review because it provides incomplete and interesting information on the circularity strategies in the BSC. After excluding book chapters, articles in conference proceedings and duplicated articles, there were 640 papers which were collected for further analysis.

The screening examination was conducted through two steps. The first step was checking for titles, keywords, and abstracts to exclude articles which are not focused on BSC, CE or LCT. After this step, 112 articles were retained. Secondly, the full-text article check was conducted, with the same criteria (the articles must concern the application of either CE or LCT, in the BSC). During these screening examination, inclusion and exclusion criterias for literature selection are employed.

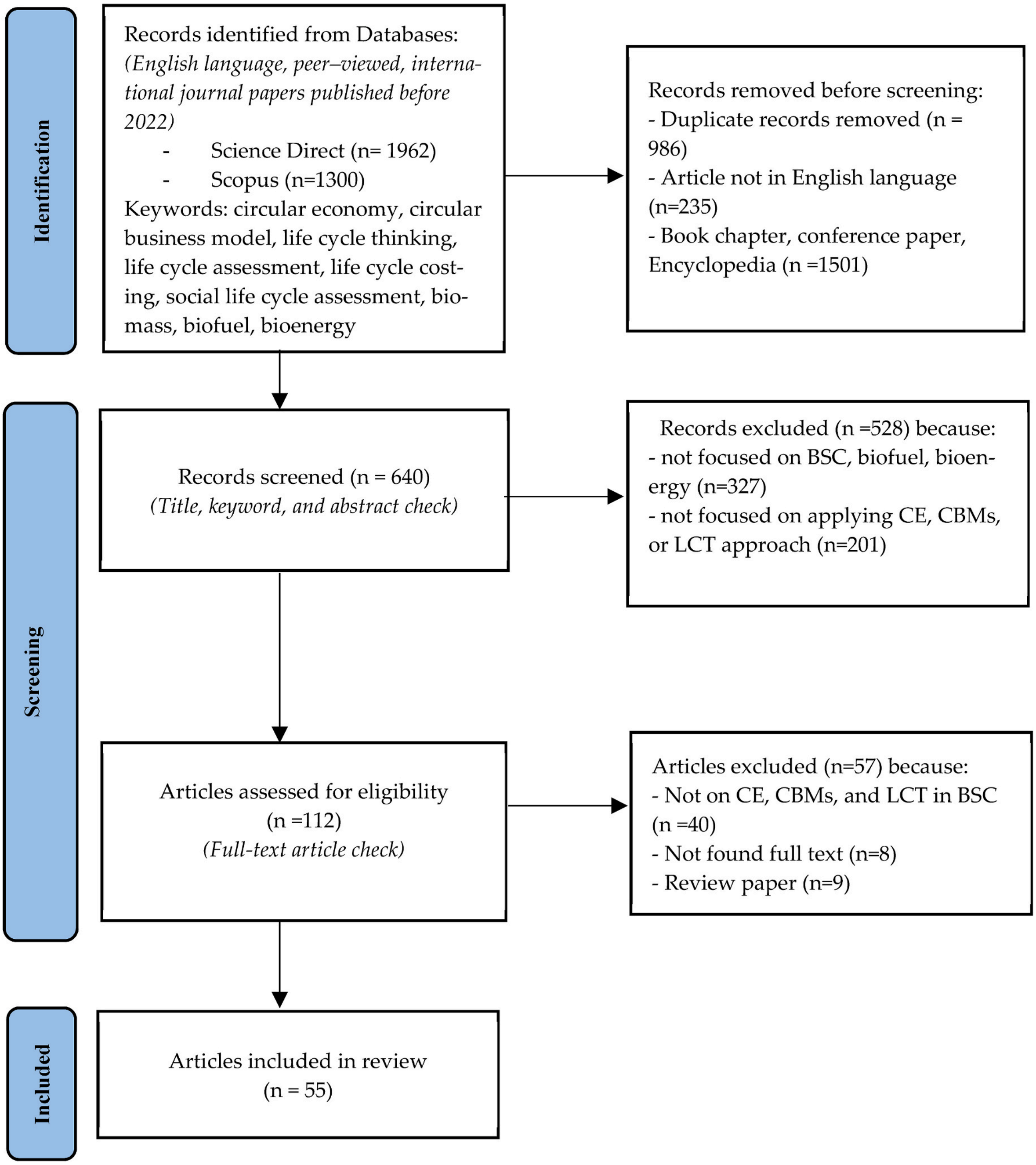

**Fig. 1.** PRISMA diagram of papers collected.

Inclusion criteria comprise a comprehensive biofuel production process, integration of CE principles and CBMs within the BSCs, and the application of LCT approach. The exclusion criteria ensure that three types of articles are excluded from consideration: (1) articles focused on narrow aspects such as biomass properties, policy evaluation, technical specifications, CE and LCT in general, (2) review articles, and (3) articles with inaccessible full texts. As a result, the number of articles was narrowed down to 55, which were considered as case studies for this systematic review, including 13 articles relevant to CE, 38 LCT articles and 4 articles simultaneously applying CE and LCT in BSC.

## 3. Biomass supply chain - BSC

Starting from the analysis of the selected papers, it was possible to identify different aspects of the BSC in terms of end-products, biomass inputs, regions and applicable technologies.

The end-products of BSC in 55 case studies include biofuel, bioelectricity, and heat. Biofuel is the most popular end-product, which is studied in 34 papers. Bioelectricity is mentioned in 18 papers and 10 papers are about heat. It should be noted that bioelectricity and heat are frequently studied simultaneously, and there are several papers studying all types of bioenergy and agriculture/forestry products such as wood, gas, electricity and fuels.

The types of biomass inputs being studied are remarkably diverse. 34 case studies refer to biomass from agricultural origin, 12 studies about forestry biomass, seven studies about waste, and five studies about algae. There are several studies mention a mixture of biomass from different origins, for example both agricultural and forestry biomasses, or both agricultural and algal biomasses. The majority of studies focus on the ‘second generation’ bioenergy, except the case of palm oil and algae.

The agricultural biomasses are either grain (rice, wheat, etc.) farming by-products in Asian countries [33–36], and bagasse and sugarcane by-products in Brazil and India [37], or palm oil in South East Asian countries [38,39]. Studies of forest biomass are mainly wood by-products and wood burning in the USA, EU and African countries [40–48]. The research on industrial and municipal waste, mainly from organic waste and food, beverage industrial waste, has received much attention from European countries [35–39]. Algae studies are mostly conducted at laboratory scale [49–51]. It can, thus, be seen that producing bioenergy and biofuel from agriculture has received much research attention in countries with large-scale agricultural production such as South American and Asian countries. Meanwhile European countries and the USA mainly referred to production from industrial and municipal waste, and forestry biomass.

The applicable technologies are different according to the various types of biomass inputs and end-products. Anaerobic digestion (AD) and combined heat and power (CHP) are frequently used for agricultural biomass and organic waste for either bioelectricity [48,52] or biofuel [33,35,39,53–55]. Meanwhile forestry biomass is directly combusted or gasified for bioelectricity and heat generation [43,45,48].

Fig. 2 illustrates the end-products and biomass inputs, by regions in reviewed case studies. Half of the case studies were conducted in EU. The input and outputs of these case studies were diverse and extended to all types of biomass inputs including agricultural, forestry and waste origins; as well as end-products of biofuel, bioelectricity and heat. A third of case studies was in Asia. Though the end-products composed of all types of bioenergy, these case studies mostly focused on agricultural biomass inputs. The number of case studies in Africa and American was small. While the inputs of American case studies were similar to those in EU, the inputs of Africa case studies were similar to those in Asia. These African and American case studies did not concern all types of bioenergy end-products.

## 4. CE application in BSC

### 4.1. CE principles, strategies and CBMs applied to BSCs

Among 10 CE principles, only four principles were employed for BSC, including reduce, reuse, recycle and recovery. Nine out of 17 case studies considered the recycle principle. The reduce principle was covered in seven studies, whilst reuse and recovery were considered in four studies. The recycle principle was frequently applied to waste management, while the reduce principle was applied in resource consumption, which consequentially decreases the production cost and mitigates environmental impacts. In some studies, different CE principles such as recycle and recovery, are simultaneously applied. For example, Gonçalves et al. assessed the circularity and resource efficiency

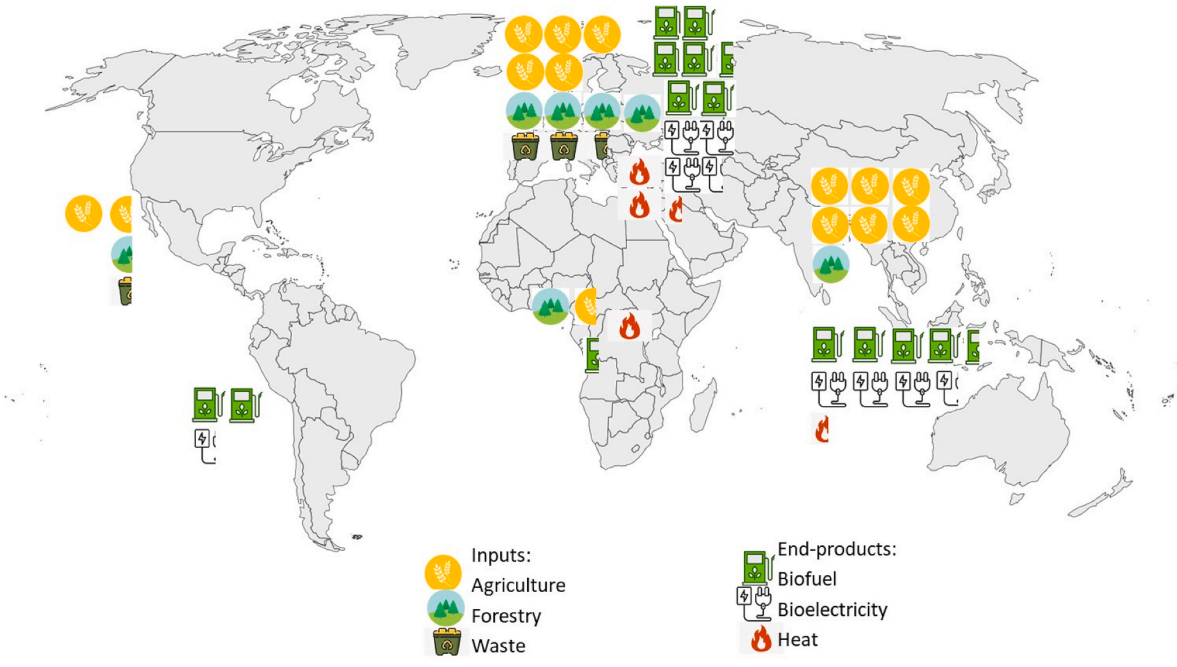

**Fig. 2.** End-products and biomass inputs by regions.

of the forest biomass in Portugal, with the inclusion of recycle, recovery and other CE principles [8]. In 2015, Portugal used 49 % of its forest biomass for energy and 51 % for materials. The national wood industry's circularity was diverse, in which 27 % of wood-based goods were recycled or recovered. On the input scale, the recycling rate was much lower, in which only 7 % of the fiber input to various industries was collected and recycled [8]. The applications of different CE principles in the case studies will be further described in the following section.

These CE principles are applied by changing the applicable technologies during the life cycle of the product system and improving the operational practice within the BSC; or even extending the BSC to cover multi products or multi sectors. The applicable technologies includes biomass waste treatment technologies for example AD, and supportive technologies of the biomass feedstock plantation such as sprinkler or drip irrigation technologies. By changing the waste management technologies, the waste will be recycled, hence the amount of generated waste and the amount of required virgin material/energy can be reduced. An example is the combination of AD for organic waste management and CHP or pyrolysis for energy generation. These combined technologies are applied to culture algae [6,51,56], to produce fertilizer [57,58], biogas [59] and power [56,57,59–61].

In other cases, CE principles were applied by changing operational activities during the BSC management. For example, in Mirkouei et al.'s study, by locating biorefineries near the harvest and collection sites, the number of truck trips and fuel use for feedstock transportation can be reduced, hence, minimizing processing costs and environmental consequences. The mixture of circularity strategies, such as improved technologies (heat recovery) and operational practice (optimized transportation operations) reduced GHG emissions by 2–5% [41].

Similarly, Bai et al. proposed to change the quantity and location of woody input purchase stations to optimize the cost, energy consumption and GHG emissions of a Mongolian and Chinese power plant [62]. In this case, the economic cost and GHG emissions are lowest, at 1.6 million Yuan and 4.1 thousand $tCO_2e$, respectively when the number of purchase stations significantly reduces [62]. Moreover, energy consumption could be reduced by choosing an optimal distance between raw material collection sites and processing plants, and appropriate plants' capacities [53].

In other case, Zeller et al. investigated the shift of the conventional biowaste flow management systems into the circular ones, which helps to increase the recycling rate from 0.4 to 1 [60]. The specific circular actions include changing the existing waste collection and treatment modes, and by-products management into the decentralized waste collection system, industrial co-composting, combination of local system and green waste (organic waste) and food waste management [60].

It can be observed that the operational circular strategies mostly concentrates on logistic activities such as transportation, waste collection and treatment and optimization of site location, in order to reduce the transportation distance and fuel consumption for transportation. Besides, strategies relevant to feedstock, for example diversified biomass feedstock and appropriate selection of feedstock have been identified as circular strategies.

While the circular strategies applicable within the same BSC are quite common, there are not many studies extending the existing BSC to include other products. The extension of the existing BSC can only be found in Zabaniotou et al.'s studies, which extend the olive and winery supply chain into biomass - energy - fertilizer supply chain, by integrating the production of olive/wine product, bioelectricity, fertilizers, and other valuable products from olive/winery waste [10,63].

It should be noted that various circular strategies are frequently combined in the same studies. The majority of studies simultaneously applied both technological improvement and efficient operational activities to obtain the highest circularity benefits. The benefit of applying these strategies do not limit in reducing input consumption, for example consumption of energy, water, raw materials, but also extend to mitigate emissions and environmental consequences. Eventually, these strategies would help to reduce production cost, enhance the economic profile of the BSC and enterprises, and bring socio-economic benefits.

At micro scale, CE principles were applied through CBMs. Several CBMs have been applied in the existing literatures such as reuse, recycle and recovery; cascading and repurposing; circular supply model and organic feedstock models. A framework of CBM application is presented in Fig. 3. The reuse, recycle and recovery models are frequently applied on the main products or by-product of the agriculture and forestry sectors. The residues and waste during plantation and husbandry activities are further processed with the application of innovative technologies. Through applying these technologies, the cascading and repurposing model is recognized. At this time, the waste becomes useful products, which are utilized in energy and other economic sectors; and/or returned back to the agriculture and forestry sectors. If these useful products are used in energy or other economic sectors, they may be reused, recycled and recovered in other supply chain. In some cases, these useful products are used in the same biomass supply chain, meaning that the circular supply model and resource recovery model have been applied.

The reuse, recycle and recovery CBMs could be found in several case studies [6,10,56–59,63,64]. Table SI1 of the Supporting Information summarized CE principles and strategies, and CBMs applied in the case studies.

It is common that one study applies several CBMs, specifically the combination of reuse, recycle and recovery; and resource recovery or cascading and repurposing. For example, Zabaniotou et al. (2015) applied pyrolyzing technology on the solid wastes of olive plantation, e. g pomace and pruning, to produce biogas and biochar. Biochar is returned back to the olive plantation and being used as a fertilizer. Meanwhile, biogas is condensed into bio-oil and combusted to generate electricity. Before the pomace and pruning are pyrolyzed, they are dried by using electricity from bio-oil combustion. The electricity is also used in olive oil production. Besides, any waste heat from the waste drying process is used for olive oil production [10]. In this study, firstly waste is recycled; secondly waste heat is recovered. At the same time, waste is transformed into two useful products such as biochar and electricity, e. g cascading and repurposing.

Similar, these CBMs are applied in Zabaniotou et al.'s study. In this study, the winery wastes (including pomace, stalks and lees) are gone through the primary refining process, becoming solid waste, hydrocolloids and grapeseed oil. While hydrocolloids can be used in health and medicine sectors, grapeseed oil is a common product for cosmetics and food purposes. The winery solid wastes are then gone through a similar procedure as the olive solid waste [63]. By applying the cascading and repurposing CBM, at the end of the winery supply chain, apart from wine as the main product, several useful products have been obtained such as biogas, bio-oil, biochar, hydrocolloids and grapeseed oil, which can be used in the food and beverage sector, and extended to energy, fertiliser and healthcare sectors.

The studies of Vega-Quezada et al. [56] and Fuentes-Grünewald et al. [6] simultaneously applied reuse, recycle, recovery; and resource recovery CBMs. Vega-Quezada et al. studied the third generation of bioenergy from algae [56]. Biodiesel and glycerine are produced by applying the transesterification process on algae biomass. The main product of the transesterification process, e.g. biodiesel is used for energy purpose; and the by-product, e.g. glycerine is commonly utilized by cosmetic and health care sectors. Waste of this process, e.g. algal residues are combined with municipal waste and livestock manure to produce biogas. Biogas is then used in combined heat and power plant to generate electricity and heat. The $CO_2$ emission from the electricity and heat production process is neutralized by the algae plantation process [56]. From energy production perspective, the algal residues are recycled, while from the waste management perspective, the applicable CBMs includes resource recovery model and organic feedstock. In this CBM, algal residues are diverting from disposal to recover the organic materials, being utilized as resources for other processes.

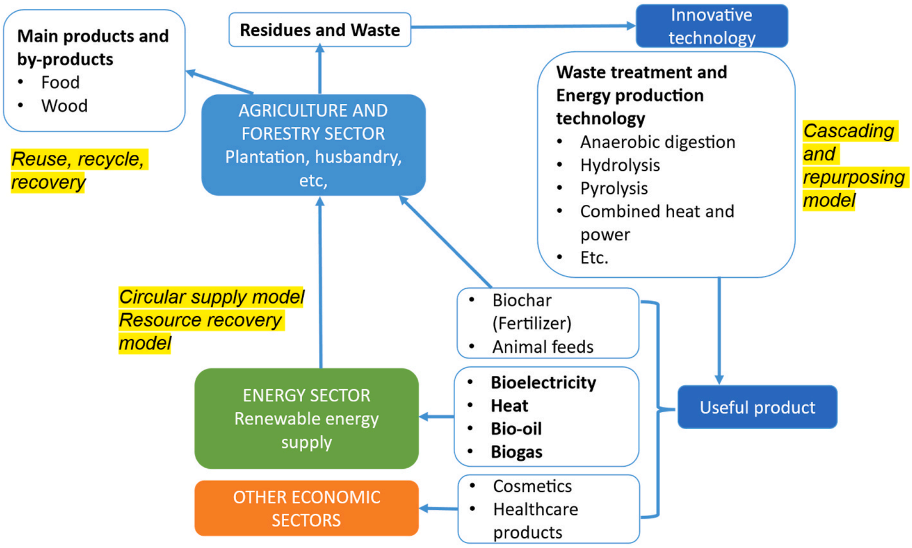

**Fig. 3.** Framework of CBM application in BSC.

The CBMs in Fuentes-Grünewald et al.'s study was also applied in microalgae supply chain. The microalgae is utilized to make animal feed, which is used in husbandry. Animal waste from husbandry are put through anaerobic digestion to make N&P-rich digestate, which is consequently the input for microalgae plantation. In this study, the recycle CBM is applied on animal waste; and the resource recovery model indicates the recovery of biomass resources in microalgae and digestate. The CBMs reduced the doubling time of algae (the time for algae duplicated themselves) by 35 %, from 2.1 days to 1.4 days; and the growth rate increased from 0.3 to 0.5 per day [6].

### 4.2. *Circularity indicators*

Circularity indicators are used to measure the circularity of the economy of a nation, a region or a business [65]. These indicators focus on measuring the circularity of material flows [66–68], the achievement of circular economy strategies on resource consumption [66–68], energy and environment, and benefits and potential impacts of the transformation from linear economy into circular economy [67–69]. Sánchez-Ortiz et al. categorized circularity indicators into nine groups of:

1. infrastructure for waste collection, reparation, reuse and recycle;
2. regulatory and policy framework on product standard; reuse, recycle of raw material or product; waste management and resource management;
3. participation of business into the material flow management according to circularity principles;
4. application of circular business model;
5. availability of the system for resource efficiency, for example the availability of the recyclable, reusable material;
6. information, education and social awareness on circular economy;
7. voluntary program on encouraging the value chain, interdisciplinary initiative and information sharing;
8. integration of circular economy into public purchase;
9. product standards relevant to circular economy strategies [70].

While the circularity indicators proposed by Sánchez-Ortiz et al. refer to CE in general, there are several indicators which are specific for energy production and consumption. Some examples of energy related indicators includes: energy recovery potential (ratio of energy generated per waste inputs consumed) [68] and energy self-sufficiency (percentage ratio of energy production and consumption) [70]. However, in reviewed case studies, energy related indicators are rarely used as circularity indicators, which may be explained by the fact that energy is an important input/output, and it is frequently studied on its own in energy analysis, rather than being integrated into CE studies.

In the examined studies the circularity indicators are divided into three levels of macro, meso and micro. At the macro level, the indicators are used for supporting the decision makers in integrating economic, financial and environmental policies, strategies and action plans on sustainable development, waste management and resource conservation. These macro indicators are relevant to material exchange between the economy and environment, international commerce and deposition in the national economy [69]. The indicators at the meso level allow the detailed monitor and analysis of the material flows in the production and consumption sectors. These meso indicators help to identify any material inefficiency, pollution and opportunities to improve the efficiency in a specific sector [60]. The micro indicators provide detailed information for the decision making process at enterprises or local government, being relevant to a material, or specific product, in order to support the policy and decision on product development [63,64]. Several examples of micro indicators are environmental performance indicators, circular economy performance indicator, and key performance indicators [26].

An example of meso indicators can be found in the Italian standard on methods and indicators for measuring the circularity of an organization[1] (UNI/TS 11820:2022). There are 71 indicators at total, being classified into seven categories of material resources; energy resources; waste and emissions; logistics; product and service; human resources, asset, policy and sustainability.

In the reviewed case studies, the most common circularity indicator is recycling rate. For example, Zeller et al. used the recycling rates to assess the benefits of shifting biowaste flows from conventional to circular management systems [60]. When circular management systems were applied, the recycling rates increased, meaning that resource consumption reduced. The impact on natural resource decreased from 0.46 million USD per year to −0.08 million USD per year. However, circular management systems did not always bring environmental and social benefits. In this case, the human health impact of the conventional system was lowest, at less than 6 disability-adjusted life year (DALY) per

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[1] https://www.certifico.com/normazione/358-news-normazione/18270-uni-ts-11820-2022.

year; and highest when local and decentralized composting systems are implemented, at 12 DALY per year. Besides, the ecosystem impacts of local and decentralized composting systems were highest, impacting 0.031 species-year per year [60].

In the Gonçalves et al.'s study, some indicators related to recycling are applied, being called the recycled input rate and recovery rate [8]. The recycled input rate denotes the ratio between the input of recycled products and the total fiber inputs [8,71], thus focusing on recycling at material level. Meanwhile the recovery rate is the ratio between the amount of recycled products and the amount of produced products [8], which conveys the recovery concept at product level. Besides, the study reported some other circularity indicators of the Portuguese forestry biomass such as cascade factor, material circularity indicator and recovery rate. The cascade factor present the use of virgin material. If all materials are virgin, the cascade factor equals 1. If a part of inputs is virgin, the other parts are recycled inputs, the cascade factor is larger than 1 [8]. The material circularity indicator was developed by the Ellen Macarthur Foundation and ANSYS Granta to measure the circularity of material flows of a product taking into account the life span of the product, when compared to the industry average [72].

Another case study on CE did not report circularity indicators; however, it provided relevant indicators, for example the increase of resource efficiency. Zabaniotou et al. created a closed loop of winery supply chain, in which winery waste is used for producing biofuel. The circularity of the supply chain was indicated in the Effective Mass Yield (EMY) to present the efficiency of resource consumption based on mass (the efficiency of using fresh grapes for different desired products). In this study the EMY of the supply chain from winery to biofuel is up to 81.5 %, and that of the supply chain from winery waste to biofuel is 29 % [63]. Apart from red wine, hydrocolloids and grade seed oil, the winery supply chain (with 15 tonne of fresh graph) produced 0.52 tonne of biochar, 0.80 tonne of bio-oil, and 0.630 MWh of electricity. Other advantages of the circular winery supply chain are increasing the number of useful products (from 3 to 6), creating an economic value of 4.47 thousand EUR per ha, and eliminating 355 kgCO$_2$e per tonne of dry grape pomace [63]. Table 1 reported the circularity indicators in reviewed case studies.

There are some difficulties in using circularity indicators. Firstly, it is the shortage of data, limitation on time and capacity to link the macro and micro data. Secondly, most of the available indicators focus on physical aspects of the technology, and pay little attention to institutional and social aspects. This occurs in most of existing circularity indicator sets. There is a small number of indicators being relevant to the production and consumption of smart product and extended lifetime of the product. The transformation into CE should not only be considered from the physical point of views, but also environmental and socio-economic impacts, for example, climate change, human health, welfare, etc.

## 5. LCT application in BSC

### 5.1. Some methodological aspects applying LCT approach in BSC

The economic, environmental, and social impact assessments, considering the LCT approach are conducted with applications of LCC, LCA and SLCA method, respectively. Among 42 case studies applying LCT approach, 32 studied used LCA method, 17 cases considered LCC method, while there are three studies considered SLCA method. Besides, eight studies used several LCT tools simultaneously, either combining LCA and LCC, or all three LCT tools for LCSA. The summarization of

**Table 1**
Circular indicators in the review case studies.

| Paper | Indicators | Products/scenarios | Value | Formulas | Notes | Ref. |
|---|---|---|---|---|---|---|
| Gonçalves et al., 2021 | Cascade factor | Total forest biomass system | 1.59 ± 10 % | $\mathrm{CF} = (B^i + R^i_{p,p,m} + R^i_{f,p,m} + R^i_{p,p,e} + R^i_{f,v,e})/B^i$ | • CF: Cascade factor (dimensionless)<br>• $B^i$: Virgin forest biomass inputs per sector i (cubic meter of wood fiber equivalent ($\mathrm{m}^3\mathrm{f}$)<br>• $R^i_{p,p,m}$: Industrial residues used in industrial processes for material ($\mathrm{m}^3\mathrm{f}$)<br>• $R^i_{f,p,m}$: post-consumer residues used in industrial processes for material ($\mathrm{m}^3\mathrm{f}$)<br>• $R^i_{p,p,e}$: Industrial residues used in industrial processes for energy ($\mathrm{m}^3\mathrm{f}$)<br>• $R^i_{f,v,e}$: post-consumer residues used for energy ($\mathrm{m}^3\mathrm{f}$) | [8] |
| | | Industrial waste | 1.15 ± 16 % | $(B^i + R^i_{p,p,m})/B^i$ | | |
| | | Recycled products | 1.09 ± 8 % | $(B^i + R^i_{f,p,m})/B^i$ | | |
| | | Industrial waste and recycled products | 1.24 ± 13 % | $\mathrm{CF} = (B^i + R^i_{p,p,m} + R^i_{f,p,m})/B^i$ | | |
| | Material circularity indicator | Paper | 0.49 ± 4 % | $MCI = 1 - LFI \times F(X)$ | • MFI: Material circularity indicator<br>• LFI: Linear flow index<br>• $F(X)$ Utility factor of a product<br>Detailed approach to calculate MCI, LFI and F(X) can be found in [72] | |
| | | Wood panels | 0.17 ± 14 % | | | |
| | | Furniture | 0.34 ± 55 % | | | |
| | | Packaging | 0.28 ± 21 % | | | |
| | Recycled input rate | Wood-based products | 7 % | RIR = Input of recycled products/Total input of fiber | • RIR: Recycled input rate | |
| | | Paper | 6 % | | | |
| | | Wood panels | 8 % | | | |
| | | Furniture | 7.70 % | | | |
| | | Packing | 7.70 % | | | |
| | Recovery rate | Wood-based products | 27 % | RR = Recycled products/ production | • RR: Recovery rate | |
| | | Paper | 39 % | | | |
| | | Wood panels | 4 % | | | |
| | | Furniture | 16 % | | | |
| | | Packing | 54 % | | | |
| Zeller et al., 2020 | Recycling rate | Baseline | 0.5 | | The current biowaste management system (in 2018), applied to the quantities managed in 2025 | [60] |
| | | Scenario 0 | 0.74 | | Export of food waste in 2025 | |
| | | Scenario 1 | 1 | | Installation of a local co-composting facility in 2025 | |
| | | Scenario 2 | 1 | | Installation of a local AD facility in 2025 | |
| | | Scenario 3 | 1 | | Local, decentralized initiatives (home & neighbourhood composting, a small scale composting) in 2025 | |

applicable tools, system boundaries, functional units (FU), and data acquisition of reviewed case studies is presented in the Supporting Information, Table SI2.

Regarding system boundary, 31 out of 42 LCT case studies considered the whole BSC from cradle to grave [34,36,38,39,41–43,45–47,49,51,53–56,73–82]. In these case studies, sometimes the terms such as “from well to tank”, “from well to wheel”, or “from cradle to wheel” were used, with the same meaning of “from cradle to grave”. These case studies quantify the impacts from the stage of biomass feedstock plantation to the consumption of biofuels for transportation (e.g. tank or wheel) or the end of life of bioenergy. There are seven case studies considering the impacts from cradle to gate [35,37,40,48,50,60,83], and two studies from gate to gate [44,84]. Interestingly, two studies considered the BSC from cradle-to-cradle [85,86].

There were multiple FUs in 42 case studies. FUs for energy products such as 1 MJ, 1 GJ, 1 kWh, 1 MWh were the most common FU, occurred in 21/39 case studies [36,37,42,43,45,48,53,55,61,75–83,85,86]. Mass based FUs such as 1 ton, or volume based FUs such 1 L, 10 million gallons are also frequently applied, for example 1 kg of biofuel [54], 1 tonne of biodiesel/bioethanol [33,74], 20 kt of bioethanol [87], 1 L of algal biodiesel [88], 1 gallon of bio-oil [41], 10 million gallons of biofuel [51]. It is quite interesting that FUs for energy products such as biofuel and electricity are frequently applied, being used in 70 % of LCT case studies. This can be explained by the fact that final product of the BSC which attracts a lot of attention is the energy product. Meanwhile, FUs of biomass feedstock or bio-waste is less common, e.g. 1 tonne of dry (or wet) matter of biomass [47,84], 1 cubic meter of biomass [40], 1 ha of forest [43], 40 thousand ha of food crop [56], the total amount of agricultural by-products available for fuel production [34,35,53], a milling site capacity of 1000 tonne of fresh fruits bunches per day [39], the biorefinery with a capacity of 4.10 million tonnes of glycerine per year [73], 1 tonne of processed bio-waste [77], 50 thousand tonne of green and food waste [60], treatment of waste produced by 100 cows per year [50]. The least common FUs are the ones neither used for energy product, nor biomass feedstock/bio-waste, such as 1 year of operation of a large scale CHP plant in Finland [44], a meal cooked [38], 20, 000 vehicle kilometre travelled/year [49].

The case studies collected data from a variety of sources, such as directly obtained from fieldwork and indirectly extracted from inventory databases, modelling, and literatures. In these cases, the primary data are used for foreground processes, while the secondary and proxy data from inventory databases, modelling, and literatures are used for background processes. The most popular source for secondary data is Ecoinvent.

### 5.2. Environmental, economic and social hotspots

The LCA results indicated that most of environmental impacts of the BSC lie in the harvesting and collection of biomasses [38]. Most of fossil material and mineral (fertilizer and pesticides) consumption is for resource production and transportation stages [19,38]. Besides, resource production is the stage causing most of ecosystem impacts such as land use, eutrophication potential. The consumption of chemical resources such as energy and water during this stage accounts for the largest share of total life cycle resource consumption. At the same time, LCC studies used the initial cost (capital cost) and operation cost for calculating life cycle cost, and revealed that the cost for resource production and transportation activities are the most significant cost categories [39,82,84]. Therefore, the resource production and transportation stages are identified as the environmental and economic hot-spots of the BSC.

The SLCA case studies showed that several social concerns during the general BSC are employees, suppliers, product users, local communities, and host governments [79]. At the same time, the social concerns being identified during the life cycle of biorefinery systems include occupational health and safety, local community, and compliance [73]. In spite of the limited number of studies relevant to social aspects, it is agreed that local community need to be taken into account when evaluating and assessing social impacts of the BSC.

### 5.3. Sustainability indicators

To assess environmental sustainability, two case studies used endpoint environmental indicators [36,78], remaining cases considered midpoint indicators.

With regards on environmental sustainability indicators, the number of indicators was different among case studies. There are several indicators being studied in the case studied, including Global Warming Potential (GWP), Ozone Depletion Potential, Human Toxicity, Particulate Matter Formation, Ionizing Radiation, Photochemical Ozone Formation, Acidification, Eutrophication, Ecotoxicity, Resource depletion, Land use and Water consumption. Among these indicators, the most common ones are GWP and energy consumption. The environmental indicators are frequently studied in combination. It is rare that only one indicator is applied, for example water usage [89], and GHG indicator [40].

The GHG emissions, and other similar indicators such as $CO_2$ emissions, climate change, GWP are the most frequently assessed indicators, which were used in 29 studies. The GHG indicator was used in five case studies using LCA and LCC to assess economic and environmental impacts [45,49,50,83,85]. In 24 remaining cases, GHG was used to determine the ecological effects of BSC globally whilst for evaluating local environmental impacts, eutrophication potential, water consumption, and land use were used. Results of GHG emissions in the case studies is reported in Table 2.

To evaluate the economic sustainability, some indicators such as the life cycle cost, revenue, net present value (NPV), interest rate of return (IRR), return on investment (ROI), and payback period were used. 13 studies used life cycle cost, NPV was considered in five studies, and there were two cases considering IRR [81,85]. Besides that, there were two cases considering the payback period for financial analysis [81,85]. Results of economic sustainability in the case studies is reported in Table 3.

Some social indicators, which were employed to examine the social sustainability, include knowledge-intensive jobs, total employment, child labour, forced labour, regional income, and global inequalities [73,79]. These indicators are quantitative, while some qualitative are less common. Results of social sustainability in the case studies is reported in Table 4.

## 6. Advantages and barriers of applying LCT tools and CE principles to BSC

Results of CE and LCT studies are useful for developing a resource/material efficiency business strategy. Three studies have outlined the plan on efficient use of biomass, energy, fossil fuels, and water [33,62,86]. For example, Bai et al. aim at reducing resource inputs for a Mongolian and Chinese biomass-based power plant. By optimizing the quantity and the location of raw material purchasing stations, as well as improving existing technologies, the consumption of biomass and fossil fuels reduces, which consequently maximizes the environmental, economic and social benefits [62]. Similarly, Ren et al. considered the amount of feedstock, transportation activities, technology and market demand under uncertain conditions. The authors identified that the mixture of feedstock and technology selection, and improved transportation efficiency help to reduce the life cycle energy consumption, $CO_2$ emissions of the BSC, and bring economic profit [33]. Besides, Zhu et al. examined life cycle water consumption of the biomass-based power generation in Hubei, China. The system’s life cycle water intensity was 11,708 L/MJ, in which biomass plantation consumed 84 % of the life cycle water use. As biomass plantation is a water intensive stage, it is suggested that the choice of biomass feedstock and planting

**Table 2**
GHG emissions in review case studies.

| Paper | Indicators | Units | Value | Ref |
|---|---|---|---|---|
| Chen et al., 2020 | GHG | kg per kWh of electricity | 1.05 to 0.79 | [85] |
| Mirkouei et al., 2016 | GHG | kgCO$_2$e per litre of bio-oil | 1.82-1.86 | [41] |
| Murphy et al., 2016 | GHG | kgCO$_2$e per MWh of electricity | 619.9–839.6 | [43] |
| Valente et al., 2011 | GHG | kgCO$_2$e per m$^3$ of woody biomass | 17.60 | [40] |
| Kc et al., 2020 | GHG | kgCO$_2$e per MWh of electricity | 2.72 - 3.46 | [44] |
| Resurreccion et al., 2012 | GHG | kgCO$_2$e per 20,000 VKT per year | 260–730 | [49] |
| Zhang, White and Colosi, 2013 | GWP | tCO$_2$e per year | 196 | [50] |
| Wang et al., 2014 | CO$_2$ emissions | kg per MWh of electricity | 59.60 | [53] |
| Ren et al., 2015 | CO$_2$ emissions | kg per tonne of bioethanol | $2.97*10^8$ to $3.42*10^8$ | [33] |
| Liu et al., 2020 | GHG | kg per GJ | 144.1–218 | [76] |
| Ren et al., 2016 | total CO$_2$ emissions | kg per total amount of biomass available | $2.97*10^8$ - $3.25*10^8$, $3.13*10^8$- $3.42*10^8$ | [35] |
| Quispe et al., 2019 | GWP | gCO$_2$e per MJ of biofuel | 4.29 | [75] |
| Parajuli et al., 2017 | GWP | kgCO$_2$e per tonne dry matter | 84–246 | [47] |
| Contreras-Lisperguer et al., 2018 | Climate change | kgCO$_2$e per 2.2 MW installed capacity of biofuel plant | −3,574,623 | [79] |
| Foteinis et al., 2020 | Climate change | kgCO$_2$e per tonne of biofuel | 553 | [74] |
| Ramos et al., 2020 | GWP | kgCO$_2$e per MWh of electricity | 121.8 | [83] |
| Cusenza et al., 2021. | GWP | kgCO$_2$e per kWh of electricity | 1123 | [19] |
| Hosseinzadeh-Bandbafha et al., 2021 | Climate change | kgCO$_2$e per MJ of bioethanol | 0.363 | [78] |
| Cusenza et al., 2021 | GWP | kgCO$_2$e per MJ of heat | 2.34 | [77] |

area is particularly essential for water-saving [86].

Moreover, the results of CE and LCT case studies are the scientific basis to support decision-makers in selecting raw materials. Three LCA studies compared different types of biomass feedstocks for choosing the most environmental friendly feedstock profile [43,47,54]. Specifically, Murphy et al. predicted environmental impacts of biomass-to-energy systems in Ireland by 2020. Various feedstocks such as pulpwood, forest wastes and sawmill residues were compared. The study found that the combustion of one feedstock in CHP plants has lower GWP, acidification and eutrophication potentials than co-firing, e.g. mixing several types of feedstocks [43]. Besides, Sanz Requena et al. compared land use, fossil fuel consumption, carcinogen effect, inorganic respiration and climate change impacts of biofuels from sunflower, rapeseed, and soybeans. The paper showed that rapeseed oil extraction consumed the greatest amount of fossil fuels, while sunflower seed production required the largest land area, and caused the most critical soil effect [54]. Finally, Parajuli et al. examined the environmental footprint of willow, alfalfa, and spring barley straw, and identified that straw requires less agricultural land than the other two counterparts, but causes the largest negative impact on soil quality [47].

The results of CE and LCT case studies informed that the application of LCT and CE also identified environmental and economic hotspots during the BSC [16,19,34,37,40,42,77,79,84]. Biomass plantation and transportation accounted for the largest shares of environmental impacts [37,40,42,77] and consequently implying the greatest impact on

**Table 3**
Economic sustainability indicators in the case studies.

| Paper | Indicators | Units | Value | Ref. |
|---|---|---|---|---|
| Chen et al., 2020 | Payback period | year per kWh of electricity | 7.71 - 12.03 | [85] |
| | IRR | % | 19.16 - 13.49 | |
| Odavić et al., 201 | NPV | Million EUR per 1 MW biomass plant | 4.10 | [81] |
| | IRR | % | 11.32 | |
| | ROI | % | 18.24 | |
| | Profitability | % | 15.48 | |
| Valente et al., 2011 | Cost | Norwegian Krone per m$^3$ of woody biomass | 463 | [40] |
| Silalertruksa et al., 2011 | Total cost | Thai Baht per litre of diesel equivalent | 32.29–38.13 | [39] |
| Afrane et al., 2012 | Annual environmental damage cost | USD per household | 36.497 | [45] |
| Okoko et al., 2018 | Life Cycle Cost | USD per meal | 0.03-0.04 | [46] |
| Zhang et al., 2013 | NPV | Million USD per year | −0.06 to 0.85 | [50] |
| Sawaengsak et al., 2014 | Cost | Thai Baht per litre of biodiesel | 68–450 | [88] |
| Lahiri et al., 2013 | Life Cycle Cost | Indian Rupee per kWh of electricity | 7.86-10.43 | [74] |
| Wang et al., 2014 | Life Cycle Cost | USD per MWh of electricity | 41.9 | [53] |
| Yang et al., 2021 | Carbon capture cost | USD per tCO2 | 37.76–89.21 | [82] |
| | Avoided cost | USD per tCO2 | 68.22–158.85 | |
| Zabaniotou et al., 2015 | Extra income | Thousand EUR | 4 | [10] |
| Vega-Quezada et al., 2016 | NPV | Billion USD | 1.4-1.8 | [56] |
| | Benefit-Cost Ratio | | 5.48-5.70 | |
| Luu and Halog, 2016 | Total cost | USD per MWh of electricity | 57.91 | [36] |
| Contreras-Lisperguer et al., 2018 | Life Cycle Cost | Jamaican Dollar per 2.2 MW installed capacity of biofuel plant | 106,192,327 | [79] |
| Bosona et al., 2019 | Life Cycle Cost | EUR per tonne of biomass (wet basis) | 50.06–108.90 | [84] |
| Ramos et al., 2020 | NPV | Million EUR per MWh of electricity | 0.11 | [83] |
| | Life Cycle Cost | Million EUR per MWh of electricity | 0.06 | |
| | Payback period | year | 10 | |
| | IRR | % | 9.12 | |

**Table 4**
Social sustainability indicators in the case studies.

| Paper | Indicators | Unit | Value | Ref. |
|---|---|---|---|---|
| Luu and Halog, 2016 | Total employment per MWh of electricity | Hour | 0.21 | [36] |
| | Child labour per MWh of electricity | Hour | 0.0321 | |
| | Forced labour per MWh of electricity | Hour | 0.00215 | |
| Contreras-Lisperguer et al., 2018 | Change of seasonal jobs to the same number of full-time jobs per 2.2 MW installed capacity of biofuel plant | | >200 | [79] |

the total biomass/bioenergy cost [53]. These information on environmental and economic impacts would help authorities adjust renewable energy development policies toward sustainable development goals. The result of nine case studies have provided comprehensive and scientific-based evidence of environmental, economic, and social benefits (or disadvantages) of biomass feedstocks and bioenergy generation technologies, so that the decision-maker can select the most effective option [35,38,46,51,73,75,78,81].

However, no literature comprehensively assesses circularity and sustainability impacts. In 55 case studies, four papers considered the application of both CE principles and LCT tools to BSC [41,51,56,60]. Among different LCT tools, only the LCA was used to assess environmental impacts, while LCC and SLCA, were not considered. Therefore, the CE measures are only evaluated in their environmental aspects, disregarding the economic aspects, while economic indicators are important components of CE. CE principles and LCT tools involved in these studies are shown in Table 5.

In addition, there were very few studies evaluating the sustainability of the BSC on all three pillars. Only two studies simultaneously applied three LCT tools, including LCA, LCC and SLCA for assessing the sustainability of BSC [36,79]. Five studies combined LCA and LCC for evaluating project's environmental impacts and economic feasibility [49,50,83,85].

Table 5
Case studies on CE and LCT application.

| Author | Ref. | CE principles | LCT tool |
|---|---|---|---|
| Mirkouei et al. | [41] | Reduction, Reuse, Replacement | LCA |
| Vega-Quezada et al. | [56] | Reuse, Recycling, Reduction | LCA, LCC |
| Zeller et al. | [60] | Recycling | LCA |
| Kern et al. | [51] | Recycling, recovery | LCA |

## 7. Discussion

This review provides a comprehensive assessment of the application of CE and LCT to the BSC. It encompasses multiple biomasses, production technologies and bio-products. Results of the CE review reveal which CE principles (such as reuse, recycle, reduction and recovery) were priority used and activities to create closed loops as well as which CBMs (for example, recycle and recovery; resource recovery; cascading and repurposing; and circular supply) were implemented. Furthermore, it identifies the circularity assessment indicators that have been employed in bioenergy contexts. The review also highlights specific processing technologies (anaerobic digestion, microalgae cultivation, gasification, pyrolysis) that are being leveraged to enhance circularity are also indicated. Therefore, this article provides information for the academic community, industries and policymakers on CE principles and how to deploy the circular strategies and CBMs in their work.

Additionally, this review has fully evaluated significant methodology aspects of LCT tools in the biomass production context. Furthermore, the results of this review provide insights into sustainable hotspots and sustainable indicators values of BSCs, offering a holistic view of sustainability across different stages of BSCs ranging from cradle to grave. Thus, the findings about the LCT and BSCs of this study can be a good reference to measure sustainability and a benchmark for comparison. They are also valuable notes for researchers when they perform assessment with LCT approach. Moreover, this review article addresses the relevance of its findings to the broader field of bioenergy technology relevant to hot topics such as CE, LCT, biofuels, and renewable energy. Therefore, it provides a valuable reference view for researchers and scientists, aiding them in identifying future research directions within the dynamic and ever-evolving realm of bioenergy technology.

However, this review paper has some limitations in the results obtained. The social assessment for BSCs is carried out with a limited number of studies (three case studies) for certain production processes and biomass, so the assessment results make it difficult to cover all remaining cases of biomass. In addition, there is a lack of methods for identifying social indicators. There are some indicators to be practised in calculation values, remaining qualitative indicators are mostly theoretically discussed. The application of CE also only takes place for certain processing processes, which are heavily related to biogas production and only 4/10 CE principles are applied. Furthermore, there are several recommended CBMs (theoretically) which have not mentioned or analysed in the reviewed case studies; therefore, the role of CE applications for BSCs has not been fully evaluated. The CE indicators used to measure the level of circularity were limited, so they do not completely reflect the circularity of BSCs.

## 8. Conclusions and suggestions for future studies

This review studied the application of CE and LCT tools in BSC. The CE applied to the BSC covers both CE principles and practices of the CBMs at enterprises, whilst the application of LCT focuses on using LCT tools to assess environmental, economic, and social sustainability. By applying CE, it is expected to reduce fossil energy use, increase energy efficiency, improve recycling efficiency, and mitigate environmental negative impacts of bioenergy. In that context, the LCT tools measure the sustainability indicators and provide evidence for effective decision-making.

The present work shows that applications of CE principles for BCS focus on four principles such as reuse, recycle, reduction and recovery, and the application of CE principles are conducted in three forms of strategies, including applying innovative technologies, improving operational activities and extending the BSC to cover a larger supply chain. At enterprise scale, specific CBMs includes reuse, recycle, recovery; cascading and repurposing; and circular supply and organic feedstock models. In most of the cases, the application of these CE principles, strategies and CBMs contribute to a more environmental-friendly, resource-efficient and cost-effective BSC.

There are not many studies on circularity indicators in BSC. Several circularity indicators have been proposed, such as recycling (input) rate, recovery rate, material circularity indicator, and cascade factor. This is a good start for quantifying the circularity indices of product system or sector; and they are so novel that there are not many case studies reviewing the appropriateness and accuracy of these indicators. The quantified circularity indicators in one case study pointed out that the application of CE does not always bring environmental positive impacts.

Besides, this review indicates the usefulness of LCT tools in thoroughly assessing the performance of the BSC in sustainability aspects. Though environmental and economic sustainability are frequently assessed, the social aspect of bioenergy is sometimes neglected. The environmental, economic and social impacts of bioenergy are various depending on the types of biomass inputs, end-products, goals and scopes of the LCT-based studies. In contrast with circularity indicators, sustainability indicators are well-developed and comprehensive, covering all three aspects of sustainable development.

Unfortunately, there are no existing list of indicators for assessing both circularity and sustainability of the BSC at national and business scales, except the above cited Italian standard UNI/TS 11820:2022. It is suggested that a comprehensive list of circularity and sustainability indicators for BSC should be developed in the near future. This list of indicators will serve as a basis for comparing technological as well as operational options, aiming at a more sustainable and circular supply chain.

Moreover, the review indicates the lack of holistic tools which can fully assess all aspects of both circularity and sustainability of the BSC, which suggests the need to develop such a decision-supporting tool for businesses. First, this tool should be user-friendly so that the enterprises can easily and quickly utilize it to evaluate their circularity and sustainability. Second, it is necessary to incorporate both quantitative and qualitative data in the tool, because the circularity and sustainability indicators frequently goes beyond quantitative and monetized results to include qualitative social benefits. Finally, this tool will identify any sustainable hotspots during the BSC, for initiating circular and sustainability measures applicable to the enterprises, taking into account their needs and budget. This feature is crucial as, in case of limited budget, the enterprises will have various needs and they need to know the sustainable and circular hotspots which should be prioritized to invest.

Other future researches that may be useful for developing a more sustainable BSC with higher level of circularity, include: (1) technological research and (2) multi-disciplinary research. The technological research should focus on innovative processes and technologies to reduce, reuse and recycle of biomass materials and energy. Some examples of these innovative technologies are advanced anaerobic digestion methods with biological treatment for upstream and downstream processes [22,90], gasification of biomass waste with consideration of energy, environment and economic benefits [91] and microwave pyrolysis techniques and integration of catalytic upgradation of bio-oil to improve the product quality [92]. Besides, the multi-disciplinary research is recommended as BSCs are connected to various sectors in the economy. Therefore, it is an opportunity to obtain the potential synergies from implementing CE principles in BSCs across economic sectors such as agriculture, forestry, energy, and waste management.

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## Institutional review board statement

Not applicable.

## Informed consent statement

Informed consent was obtained from all subjects involved in the study.

## CRediT authorship contribution statement

**Sonia Longo:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. **Maurizio Cellura:** Conceptualization, Resources, Writing – review & editing, Supervision. **Le Quyen Luu:** Conceptualization, Resources, Data curation, Writing – original draft, Writing – review & editing. **Thanh Quang Nguyen:** Conceptualization, Methodology, Resources, Data curation, Writing – original draft, Writing – review & editing. **Roberta Rincione:** Methodology, Resources, Writing – review & editing. **Francesco Guarino:** Resources, 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

Data will be made available on request.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.119598.

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## NOMENCLATURE

*AD:* Anaerobic digestion
*BSC:* Biomass supply chain
*CBM:* Circular business model
*CE:* Circular economy
*CHP:* Combined heat and power
*DALY:* Disability-adjusted life year
*EMY:* Effective mass yield
*GHG:* Greenhouse gas
*IRR:* Interest rate of return
*LCA:* Life cycle assessment
*LCC:* Life cycle costing
*LCSA:* Life cycle sustainability assessment
*LCT:* Life cycle thinking
*NPV:* Net present value
*OECD:* Organization for Economic Co-Operation
*PRISMA:* Preferred Reporting Items for Systematic Reviews and Meta-Analyses
*SLCA:* Social life cycle assessment
$tCO_2e$: tonne of carbon dioxide equivalent