

## Review Article

## Barriers to transitioning to a circular bio-based economy: Findings from an industrial perspective

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## ABSTRACT

The transition from a linear fossil-based to a circular bio-based economy represents an opportunity and a suitable pathway for achieving several sustainable development goals. However, the transition is a complex process since it requires transformative policies, purposeful innovation, access to finance, risk-taking capacity as well as new and sustainable business models and markets. Accordingly, the first step in this transition process is the identification of barriers that are hampering the transition to a sustainable circular bio-based economy. With this motivation in mind, this study reviews grey literature to identify barriers focusing on four critical sectors facing major challenges within the current linear economy and requiring a sustainable transition most urgently: construction, chemicals, plastics, and textile sectors. Employing an adapted STEEP methodology (Social, Technological, Economical, Environmental, Political), a total of 193 different barriers have been identified and clustered under six categories: cultural, technical, economic, environmental, governance, and structural. Regardless of the sector, cultural and structural barriers are identified as the most prominent; the lack of incentives for consumer behaviour change and lack of stakeholder collaboration were the most cited barriers among the literature records. From a value chain perspective, most of the barriers are related to the material processing and product manufacturing stage. Finally, potential solutions, extracted from the grey literature, are proposed to fill the gaps and overcome the identified barriers. Many of the identified barriers are common across the four investigated sectors, indicating the solutions or measures can be applicable in a wider perspective to promote the transition in the right direction.

## 1. Introduction

A shift from a linear fossil-based economy to a circular bio-based economy is needed. This offers a novel approach to decoupling economic growth from the use of natural resources, while promoting the establishment of sustainable economic systems for a liveable planet (UNEP, 2011; Bianchi and Cordella, 2023). To this aim, the integration of the bioeconomy and circular economy has become increasingly significant (EC, 2019). In 2014 and 2015, the European Commission introduced a circular economy strategy and action plan aimed at “closing the loop”, sparking extensive discussion and establishing

connections between the circular economy and the bioeconomy (Carus and Dammer, 2018). This synergy is now considered paramount. As a result, a growing number of studies place attention on the bioeconomy that is expected to use renewable biological resources (including organic residues and wastes) in a sustainable manner to produce food, energy, and industrial goods (Francocci et al., 2020). The basic idea is that the bioeconomy offers a potential substitute for fossil resources, while the circular economy enhances resource efficiency. Consequently, the intersection of the bioeconomy and circular economy has been coined as the circular bioeconomy, characterised as the sustainable, cascading transformation of biological residues into products that can be shared,

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reused, remanufactured, recycled, or safely reintroduced into natural cycles (Carus and Dammer, 2018). Recently, a more specific concept has emerged known as the Circular Bio-Based Economy (CBBE) (Lange, 2022). Diverging from the traditional focus on agricultural products, the bio-based economy aims to fully exploit various forms of sustainably sourced biomass, including residual biomasses (Olofsson and Börjesson, 2018) and degradable wastes from diverse sectors (Gontard et al., 2018). However, there is no universal agreement on the definition of terms such as 'bioeconomy' and 'bio-based economy.' Commonly, especially in the European context (including EU-funded projects) following the EN16751 standard, bio-based products typically exclude food, feed, and energy, while encompassing bio-based chemicals, materials and bioactive substances. Conversely, according to Lange (2021), the bio-based economy not only uses agriculture-derived products (cereals, vegetables, and meat), and conventional products from fishery and forestry, but also emphasises the production of bio-based chemicals, health products (e.g., medications, skincare items, wound care solutions, gut-health promoting ingredients for food and feed) and bio-based fuels. In this view, considering the differences in the definition of the bio-based economy, CBBE underlines the common scope of the circular economy and bio-based economy of creating value from biological waste and residues.

The focus of the current study lies in the analysis of the CBBE considering its potential for the wise use of renewable resources along with its potential to bring together the objectives of sustainable long-term economic growth and environmental protection. The transition to CBBE can bring multiple positive impacts, including economic, environmental, and social benefits. Innovative circular models could induce gross domestic product growth (CEPS, 2018; Lehmann et al., 2022), increasing savings and creating a significant shift in the labour demand (Laubinger et al., 2020). Circular economy strategies in key sectors such as cement, aluminium, steel, plastics, and food could eliminate almost half of the current emissions from the production of goods in these areas (Ramakrishna and Ramasubramanian, 2024; Ventosa, 2022). Some examples of the significant gains of this transition could be related to the construction sector, in which this transition can lead to resource-efficient construction, reducing material and waste costs, and resulting in a 50 % decrease in virgin material use, a 40 % reduction in energy consumption, and a 35 % decrease in CO<sub>2</sub> emissions, as well as in the chemical sector, where a renewed production system is expected to create 29 million jobs by 2050 (CBCI, 2020; SYSTEMIQ, 2022a).

This transition is strongly needed, but highly complex at the same time. It depends on societal transformations as well as cutting-edge supply-side technologies, and these transformations must be determined through processes in which all interested parties are active participants. To gain a better understanding of the economic agents behind CBBE strategies, it is crucial to identify the limitations and barriers that hinder their implementation or slow down their progress. However, the literature on the concept of CBBE is still in its infancy, and relatively few studies have addressed the theme, especially to the best of our knowledge, regarding the identification of drivers and barriers. On the other hand, some studies have been developed on the drivers and barriers of the circular bioeconomy, for instance, Gottinger et al. (2020) performed a systematic literature review to identify the most relevant barriers that could hamper the adoption of circular bioeconomy practices, highlighting that policies and regulations, social acceptance, investment, funding conditions, material and traceability of the value chain, knowledge and networks could play a decisive role in the future of the circular bioeconomy. The same arguments were also raised in a paper by Salvador et al. (2022) in which they acknowledged by exploiting a multi-method approach that there are regional differences that may facilitate or hinder circular bioeconomy solutions. They argue that to advance these solutions, strategies need to be devised to overcome the lack of financial/capital resources, develop and/or make available locally the appropriate technology, and enable price competitiveness

with traditional (linear and non-renewable) options.

This article aims to conduct a comprehensive review of grey literature sourced mainly from industry associations and sectoral networks, with a focus on understanding the dynamics underlying the transition from a linear fossil-based economy to a CBBE. Specifically, the article seeks to explore industry perspectives on this transition, including barriers inhibiting progress, and to identify potential solutions necessary to facilitate the successful adoption of CBBE principles within various sectors.

This article presents the first attempt to combine the topic of circularity with the bioeconomy by examining the literature that does not come from official peer-reviewed scientific journals or white literature. This represents the first element of novelty compared to the existing literature. Secondly, the study identifies the main barriers to transition to a circular, low-carbon and bio-based economy. The work also adds a new level of analysis by focusing on four carbon-intensive sectors. We investigated the relevance of identified barriers across different industrial sectors, specifically for the chemicals, construction, plastics, and textile sectors that are facing challenges with the current linear economy and requiring a sustainable transition most urgently (Charef et al., 2022; Siltaloppi and Jähi, 2021; Tickner et al., 2022).

## 2. Methodology

The results presented in this study are derived from extensive desk research, which included a thorough analysis of grey literature, followed by codification of barriers and the identification of possible measures that could effectively enable overcoming the barriers. The research questions (RQ) addressed were formulated as:

- RQ1. What are the barriers hindering the transition from a carbon-intensive linear economy to a circular biobased economy in selected sectors?
- RQ2. How are these barriers distributed across different value chain stages and selected sectors?
- RQ3. Which barriers are most prominent and are most in need to be addressed?

### 2.1. Grey literature search and selection criteria

To ensure a comprehensive and systematic identification of the barriers to transition to a CBBE, a robust search strategy was designed to capture relevant grey literature on the topic. As a general definition, grey literature is composed of knowledge artefacts that are not the product of peer-review processes characterizing publication in scientific journals (Lawrence et al., 2014). The relevance of grey literature has been affirmed in various fields, from health and wellness to the environment (Chakraborty et al., 2021; Favin et al., 2012; Galafassi et al., 2019). The benefits of a grey literature analysis are manifold. Firstly, as Conn et al. (2003) suggest a meta-analysis that excludes grey literature could lead to overstated outcomes since a literature review from official and peer-reviewed journals might tend to select only significant studies, i.e., studies that actually provide evidence of phenomena excluding those that lead to unambiguous or not significant solutions, but which can still increase knowledge of a certain situation. Secondly, systematic reviews that include grey literature can provide an important source of information for research and practical projects, especially those concerning new fields of inquiry where knowledge from early experience is needed (Adams et al., 2017). In particular, the latter point is related to the objective of this paper. It is evident that CBBE is an emerging topic, and official knowledge in this field is significantly lacking. Therefore, the significance of grey literature as an essential source of knowledge cannot be overstated.

The methodological approach of this article aimed to provide an unbiased and extensive review of non-peer-reviewed sources that offer

valuable insights not covered in the conventional literature. Various types of grey literature were considered in this study to ensure the comprehensiveness of the review. The selected types of grey literature included: technical and research reports; working papers; policy briefs and white papers; industry publications; EU project deliverables; action plans, roadmaps, and guidance documents; discussion papers; and position papers. This diverse range was selected to encapsulate both academic and practical perspectives from different stakeholders including researchers, industry representatives, and policymakers. To identify the relevant grey literature, several databases and platforms were consulted, such as the Directory of European Circular Economy Networks / Platforms (ECENP, n.d.) and the Projects & Results Database of the Community Research and Development Information Service (CORDIS, n.d.). Additional sources included websites of relevant organisations, networks of professionals, and other relevant non-academic sources focusing primarily on the selected four sectors. A combination of keywords and search terms were used to retrieve relevant documents from the selected grey literature sources. The main terms were clustered around four central themes:

- (1) Economy, e.g., “linear economy”, “carbon-intensive economy”, “fossil-based economy”, “carbon economy”, “circular economy”, “bio-based economy”, “bioeconomy”, etc.
- (2) Transition, e.g., “sustainability transition”, “transformation”, “SDG”, “green deal”, “circularity”, etc.
- (3) Barriers, e.g., “challenge”, “hindrance”, “obstacle”, “limitation”, “limit”, “gap”, etc.
- (4) Industry sectors, e.g., “construction sector”, “construction industry”, “building material industry”, “building industry”, “cement industry”, “textile sector”, “textile industry”, “fashion industry”, “clothing sector”, “clothing industry”, “apparel sector”, “apparel industry”, “chemical sector”, “chemical industry”, “plastic sector”, “plastic industry”, “plastic economy”, etc.

These terms were used singularly and in various combinations to ensure a wide coverage. This approach led to the identification of 198 potentially relevant grey literature records, with a publication time frame spanning from 2013 until early 2023 (Fig. 1 and Supplementary material). During the search, we did not limit our selection to a specific year of publication, though we considered works published primarily in recent years to account for the dynamic development of the CBBE concept.

Once the grey literature was identified, a systematic review process was established. All documents were first screened based on their title and abstract or summary. The inclusion criteria were documents that focus on the transition towards CBBE, and that address, discuss, list, or mention barriers or challenges related to such transition. Documents that did not have their full text available in English, and repetitive publications or multiple versions of the same document were excluded

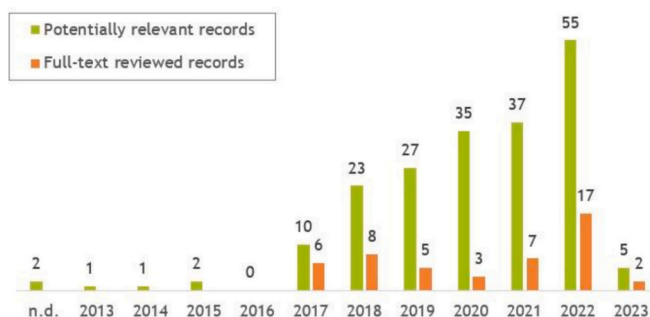


Fig. 1. Distribution of the number of grey literature records according to their year of publication.

from further analysis. 48 documents that met the inclusion criteria, dated between 2017 and 2023 (Fig. 1), underwent a full-text review, wherein the specific barriers to the transition to a CBBE were extracted and catalogued.

The fully reviewed documents represent equally the four selected sectors, i.e., 10, 9, 9, and 12 documents represent the chemical, construction, plastics and textile sectors, respectively. The remaining 8 documents are not attributed to any of the four selected sectors, but address the circular economy in broader terms. Type of the fully reviewed documents mostly falls under technical and research reports ( $n = 30$ ), 4 documents fall under position paper type, another 4 documents fall under policy brief type, 2 documents are white papers, while the remaining 8 documents are of a different document type each.

## 2.2. Codification of barriers

We adopted the definition of *barrier* from the *Oxford Learner's Dictionary* (2023) stating that “a barrier is a problem, rule or situation that prevents somebody from doing something, or that makes something impossible”. We screened the 48 selected documents with this definition in mind to extract specific quotes referring to all potential barriers that hinder the transition. In total, 530 quotes were extracted. Each extracted excerpt (quote) was coded by defining a specific barrier, i.e., providing a name to a barrier (Fig. 2).

Subsequently, we used an adapted version of the STEEP (Social, Technological, Economic, Environmental, and Political) methodology (Fisher et al., 2020), a widely used tool which helps assess contextual factors influencing strategic decision-making processes in both academic and industrial fields. This methodology is a comprehensive framework used to analyse and predict macro trends in society, technology, economy, environment, and politics (see, for instance, Grima et al., 2020; Akinyele et al., 2018; Schmidt et al., 2015). An adapted STEEP method is used in this study to categorise the identified barriers into five “base” barrier clusters: (i) Cultural, (ii) Technical, (iii) Economic, (iv) Environmental, and (v) Governance, and an additional cluster, namely, (vi) Structural to categorise barriers of a more systemic and cross-factorial nature. We also categorised the clusters into sub-clusters wherever possible or needed. However, it should also be kept in mind that the defined clusters are not mutually exclusive, some barriers might fit under more than one cluster. Barriers were attributed to different clusters based on the following understanding:

- (1) Cultural barriers are related to consumer behaviour, perception, attitude, awareness, consumption trends and traditions, workers' skills, qualifications, education, age and gender, as well as barriers related to internal culture, processes, attitudes, actions, and governance of companies.
- (2) Technical barriers are related to technology development, innovation and adoption, infrastructure capacity, quality and quantity of feedstock, composition of materials, as well as digitalisation and automation.
- (3) Economic barriers are related to costs incurred on a company, a company's profitability, competitiveness, access to funding and investment, as well as barriers related to a product's market share, demand, and price.
- (4) Environmental barriers are related to the environmental performance of products and processes, as well as to environmental impact assessment.
- (5) Governance barriers are related to policy, regulation, policy targets, and incentives, as well as to standards, certification schemes, and standardisation and certification procedures.
- (6) Structural barriers are systemic institutional barriers, practices and norms, as well as barriers related to overall persisting systemic issues and regimes, and the complexity of systems.

Further, we allocated each barrier to the part of a value chain these

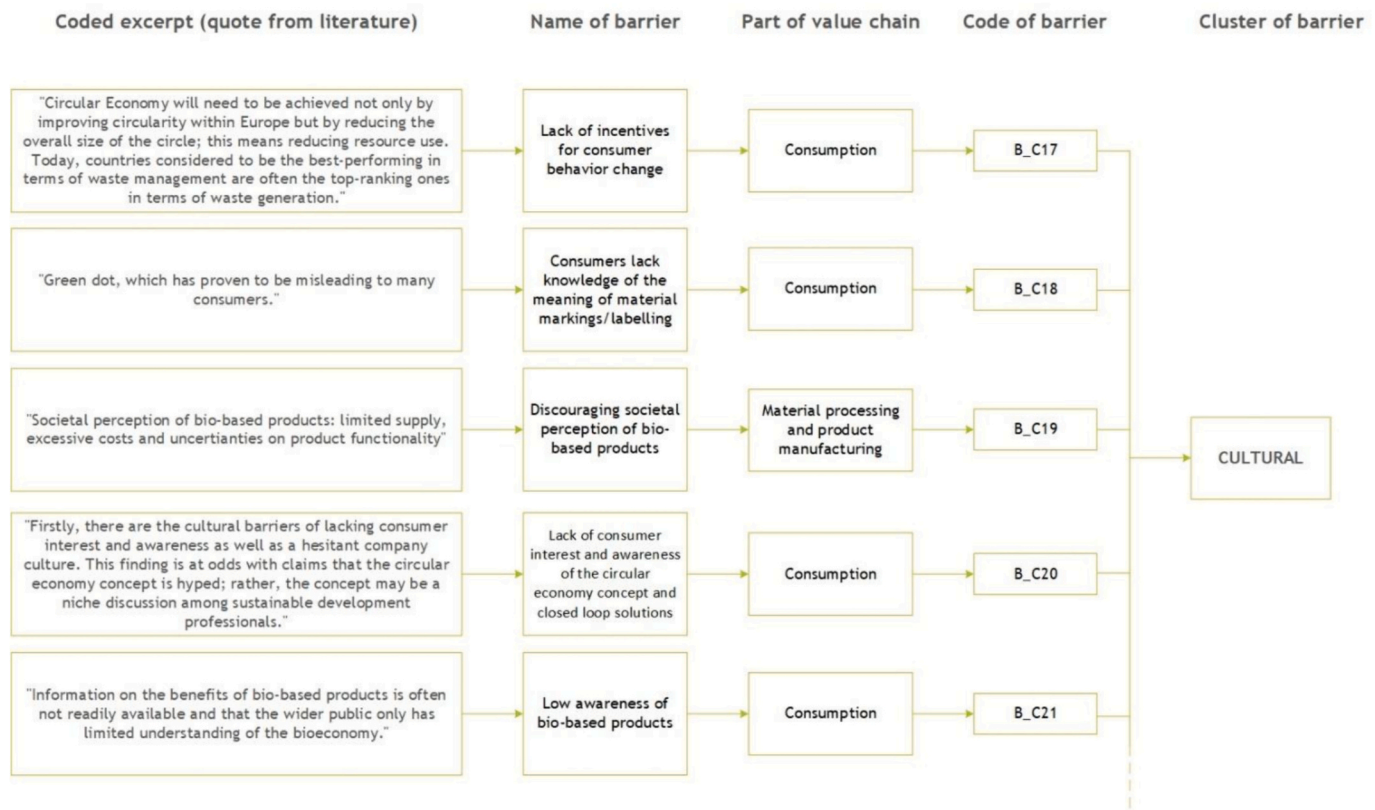


Fig. 2. The coding scheme of the barriers identified in the literature (an example).

barriers relate to (Fig. 2). Six different parts of the value chain were selected for allocating the barriers, i.e., raw material cultivation/extraction; material processing and product manufacturing; market and distribution; consumption; end-of-life management; and use of secondary bio-based materials. Some of the barriers were allocated to the whole system.

### 2.3. Determination of barrier prominence

The identified barriers have been mentioned at different frequencies in the reviewed literature. Regarding the prominence of the identified barriers, we used a cut-off criterion to select the most cited barriers in the covered literature. To define this criterion, we analysed the distribution of the citations in the reviewed literature. Based on the related literature, several empirical papers use the cumulative distribution function as a reference to evaluate the prominence of different items, such as the relative citation indicator for scientific papers (See, for instance, Lin et al., 2023; Wuchty et al., 2007). Accordingly, we provide an analysis of the cumulative distribution function of the citations, based on Eq. (1).

$$F_x(x) = P(X \leq x) \tag{1}$$

where  $X$  is a random variable identifying the number of citations, and  $P(X \leq x)$  refers to the probability that it assumes values lower than or equal to a given citation value “ $x$ ”. Therefore,  $F_x(x)$  indicates the cumulative distribution function. The analysis of the cumulative distribution function is provided in Section 3.4.

## 3. Results

In this section, the grey literature results are presented comprehensively. First, we provide an overview of the identified barriers across thematic clusters (Section 3.1). Then, the allocation of identified

barriers is shown throughout the value chain stages (Section 3.2) along with the allocation across industrial sectors (Section 3.3). Finally, the most prominent barriers are discussed in comparison with the existing literature (Section 3.4).

### 3.1. Overview of Barriers to Transition Categorised According to Thematic Clusters

The grey literature review led to the identification of 193 different barriers that limit the transition towards a CBBE (see Supplementary material). Table 1 presents these barriers categorised into six clusters, along with an overview highlighting the most frequently mentioned barriers. The highest number of barriers was identified for the Technical (43), Structural (40), and Governance (40) clusters; a relatively lower number of barriers was identified for the Economic (33) and Cultural (32) clusters, while for the Environmental cluster, only 5 barriers were identified.

The predominance of governance, structural and technical barriers may reflect the systemic complexity that structural change such as the transition to a CBBE requires. In this area, the lack of value chain stakeholder collaboration (including information exchange) (FIEC, 2022; GIZ, 2019) is not only one of the (structural) barriers most often cited in the reviewed literature, but it is also a cross-cutting barrier in the sense that it was encountered across several sectors, including chemical, construction, plastic, and textile. The lack of collaboration is also strictly linked to another relevant structural barrier identified, i.e., the lack of transparency and traceability (GIZ, 2019; EEB, 2020). Other key structural barriers identified include the difficulty of entering a well-established fossil-based market (EEA, 2014) and the lack of systematic circular initiatives (SUSCHEM, 2018). The first refers to the challenge for new circular bio-based businesses and innovations to penetrate and compete in a market dominated by incumbent fossil-based industries (Bos and Broeze, 2020; STAR4BBI, 2018). The second refers to the



**Table 1**  
Overview of the identified barriers most mentioned in the thematic barrier clusters\*

Barrier Cluster	Sub-category	Number of barriers	Top three barriers by sub-category with at least three mentions
Technical		43	Increasing complexity of materials and their combinations Lack of adequate feedstock: recycling Lack of infrastructure capacity: material recycling
Structural		40	Lack of value chain stakeholder collaboration (including information exchange) Difficulty to enter a well-established fossil-based market Lack of systematic circular initiatives
Governance	Policy	29	Inconsistent and/or partial data collection and reporting Lack of government and public support for transition Lack of clarity around policy targets
	Standards	11	Lack of product standardisation Lack of standardised waste collection systems and harmonised infrastructure Complicated certification and labelling procedures and requirements for new materials
Economic	Business	14	Lack of profitability for firms in areas that deliver high public benefits High operating costs: bio-based vs. fossil-based production Weak cost competitiveness: bio-based vs. fossil-based ingredients, materials or products
	Investment	12	Lack of investment in new systems for transition High investment cost for bio-based industry High investment risk for bio-based industry
	Market	7	Structural price differences: virgin vs. secondary materials Lack of consistent and reliable consumer demand for green products
Cultural	Business	16	Lack of systematic business model analysis Inconsistent or partial application of industry targets Lack of company's internal resources for initiating and maintaining transition
	Consumer	9	Lack of incentives for consumer behaviour change Low awareness of bio-based products
	Education	7	Lack of specialised knowledge, skills and expertise in bio-based production Lack of specialised knowledge, skills and expertise in closed loop systems
Environmental		5	Lack of data on impacts

\* Due to space limitations, we only presented the first three barriers cited at least three times in the analysed literature. The full list of barriers remains available in the Supplementary Material.\*

inconsistency of how circular economy principles and practices are implemented across industries, sectors and policy domains, hindering the widespread adoption of circular solutions (Guldmann and Huulgaard, 2020).

Concerning governance barriers, we differentiated between those of policy and standard nature. The first relates to policy, regulation, policy targets, and incentives; while the latter specifically refers to standards, certification schemes, and standardisation and certification procedures. The most cited policy barrier refers to inconsistent and/or partial data collection and reporting (Philp and Winickoff, 2018), including in some

cases, the absence of such a collection and reporting scheme. As an example, the lack of information on waste management worldwide, especially regarding individual waste streams (Hartmann and Metternich, 2020) such as plastics, results in differing definitions, data, methodologies, and framework conditions across countries, which inhibits sounding policies and roadmaps that drive the transition to the CBBE. This barrier is also strongly connected to the above-mentioned structural barriers addressing the lack of collaboration and traceability along the value chains. Other key policy barriers identified include the lack of government and public support for the transition (KBBPSS, 2015), and the lack of clarity around policy targets (SYSTEMIQ, 2022a). On the other hand, standards-related barriers mainly refer to the lack of product standardisation (STAR4BBI, 2019b).

Within the technical barrier cluster, the top cited barrier is the increasing complexity of materials and their combinations. A good example would be plastic colourings such as commonly used carbon black since plastics containing black carbon pigments are not amenable to mechanical recycling leading to reduced recyclability of plastic products. Another significant technical barrier to bio-based materials circularity is the insufficient amount of feedstock available for recycling processes. This challenge is compounded by the high variability of materials and the wide dispersal of bio-based plastic waste across millions of households, making it difficult to collect and consolidate enough feedstock to support economically viable recycling operations. Additionally, the diverse range of polymers and additives used in materials, optimised for specific applications, further complicates recycling efforts, as different materials require different recycling processes, and mixing them can result in lower-quality recycled products. The loss of material quality and value during recycling and the lack of infrastructure capacity for end-of-life product collection, transportation, recycling and storage are also among the most relevant technical barriers identified.

Within the economic barrier cluster, barriers were classified according to market, business, or investment sub-clusters. In this context, the lack of profitability for firms in areas that deliver high public benefits represents the most relevant business barrier. As the transition from a linear fossil-based economy towards a CBBE requires significant changes in the way businesses operate, it may not always align with short-term profitability goals. In particular, developing innovative solutions that deliver high public benefits may require substantial investment in research and development, which can be financially challenging for credit-constrained firms. In this line, the structural price differences between virgin and secondary materials, a relevant market barrier, certainly do not help to introduce secondary bio-based material in the market. Among other relevant economic barriers encountered, we highlight the high implementation costs of reuse (circular) systems vs. established single-use systems, the high investments, both in terms of capital and operating expenditures, required for the bio-based industry deployment and the high risk associated.

Cultural barriers were classified into educational, business and consumer sub-clusters. Among these, the lack of incentives for consumer behaviour change is not only the most relevant consumer's barrier but it is also the most cited barrier across all clusters (it was reported across 11 reports). This reflects how consumer behaviour, perception, attitude, and awareness, along with consumption trends and traditions, play a crucial role in shaping the transition process. In the current linear economy, throw-away convenience and the preference for new products often outweigh considerations of resource conservation and waste reduction. On the other hand, from a business point of view, the lack of understanding of the potential economic advantages of implementing circular value chains was identified as another important cultural barrier. Finally, we also identified two relevant cultural barriers related to education as prevalent obstacles to the transition to a CBBE. These barriers are the lack of specialised knowledge, skills and expertise in bio-based production and the lack of specialised knowledge, skills and expertise in closed-loop systems.

Finally, the lack of data on environmental impacts represents by far

the most important environmental barrier in both linear fossil-based and circular bio-based industries, hampering the overall transition process. In the CBBE, there is a lack of data on the environmental impacts of circular bio-based products and processes, including biodiversity, biodegradability, and other aspects. Insufficient information and uncertainty of environmental performance of such products and processes together with high costs and lower competitiveness of bio-based products is perceived as a significant risk for linear fossil-based businesses to transition.

### 3.2. Barriers to transition categorised according to the value chain stages

The identified barriers along with their codes allocated across the different value chain stages are shown in Fig. 3. The barriers are allocated for (i) Raw material cultivation/extraction, (ii) Material processing and product manufacturing; (iii) Market and distribution; (iv) Consumption; (v) End-of-life management; and (vi) Use of secondary bio-based materials. In addition, we present a further category “whole system”, comprising the barriers that are not related to a specific value chain stage, but rather to the entire value chain. Most of the barriers (i.e., 72 out of 193) are allocated to the material processing and product manufacturing stage, which might be explained by the sources of the reviewed literature, i.e., primarily industry associations and sectoral networks. This corresponds to a share of 37 % of the total identified barriers. The second highest share of barriers (28 %) comprises barriers

related to the whole system. Barriers associated with end-of-life (EoL) management of products and materials represent 17 % of the total identified barriers ( $n = 33$ ). Barriers related to the Consumption phase ( $n = 15$ ) represent 8 % of the overall identified barriers. Surprisingly, only 10 of the identified barriers relate to raw material cultivation and extraction, representing 5 % of the overall identified barriers. Lower shares were allocated to the categories “Market and Distribution” (3 %) and “use of the secondary bio-based materials” for producing new products (1 %).

### 3.3. Barriers to transition present in industrial sectors

We further investigated the relevance of identified barriers across different industrial sectors, specifically for the chemicals, construction, plastics, and textile sectors.

In the chemicals sector, 63 different barriers were identified for transitioning to a CBBE (see Supplementary material). Cultural barriers include a lack of prioritisation for circular solutions, a linear mindset, inconsistent definitions of ‘natural’ or ‘bio’, and limited innovation in design-for-recycling. Consumers demonstrate low awareness of bio-based products, and education faces challenges in specialised knowledge and engagement with circular economy concepts. Economic barriers range from high costs in product formulation and operation to weak cost competitiveness compared to fossil-based alternatives, limited access to finance for start-ups and Small and medium-sized enterprises

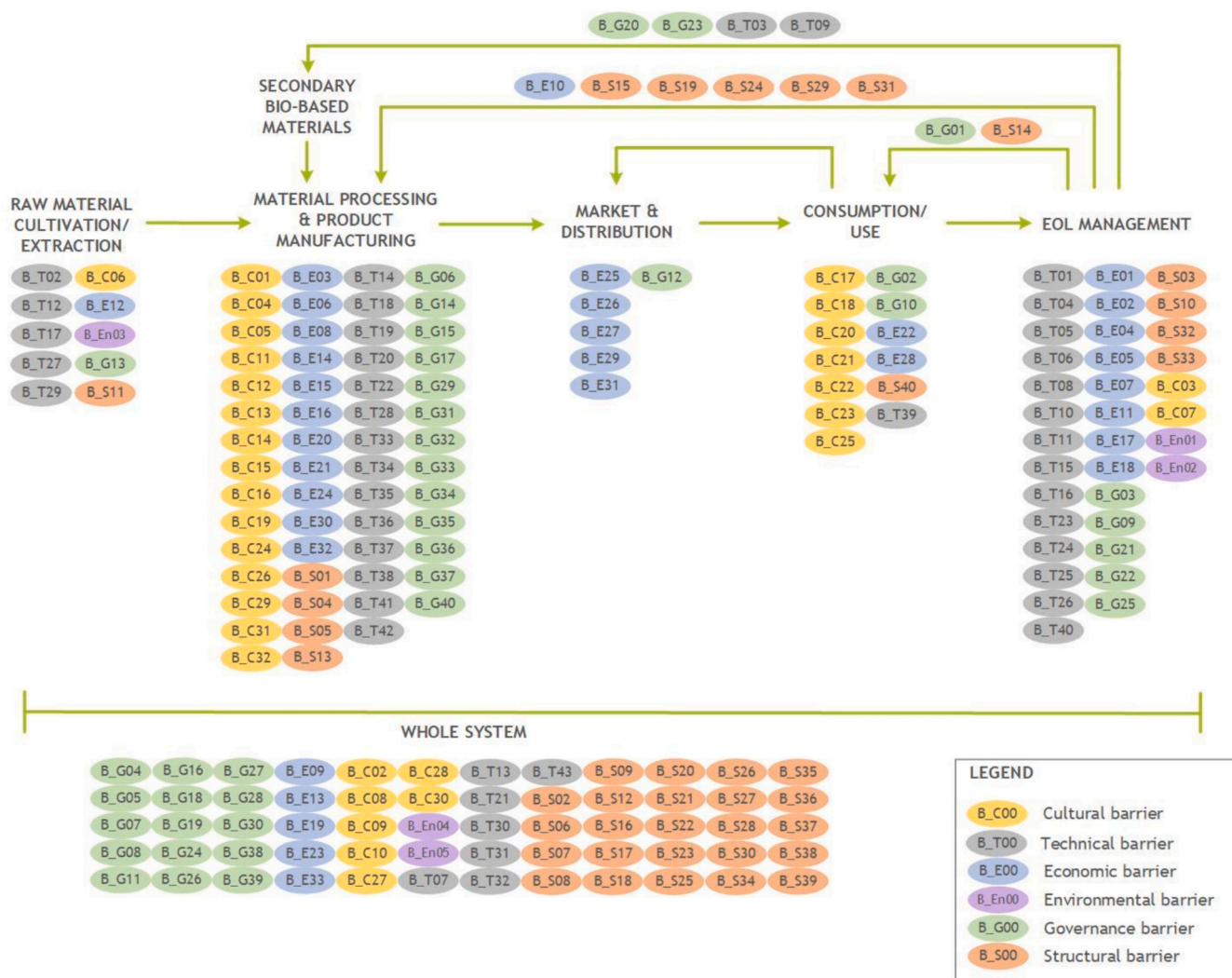


Fig. 3. Distribution of identified barriers across the value chain (see Supplementary material for barrier name according to code).

(SMEs), and higher prices for green products. Environmental barriers involve higher land use for bio-based products compared to fossil-based products. Governance barriers feature a lack of comprehensive bio-based material identification systems, fragmented regulatory environments, misaligned policies, and complex regulatory and certification procedures. Structural barriers include high uncertainty in new chemical processes, low data accessibility, difficulties in entering fossil-based markets, and lack of value chain collaboration. Technical barriers encompass the need to develop new biomass feedstock sources, challenges in molecule recycling, high complexity in chemical product formulations, immature technology, and insufficient purity of recyclable bio-waste streams.

In the construction sector, 62 different barriers were identified (see Supplementary material). Cultural barriers include a lack of prioritisation for circular solutions, resistance to change, deeply entrenched norms, inconsistent industry targets, and a limited understanding of the circular economy concept. There is a skills gap in education and a lack of specialised knowledge, skills, and expertise in closed-loop systems. Economic barriers encompass higher upfront costs for green solutions, high investment risks, insufficient investment in energy-efficient buildings, and structural price differences between virgin and secondary materials. Environmental barriers involve a lack of data on impacts. Governance barriers include unclear policy targets, limited government and public support, policy support for linear production processes, and a lack of standardisation for sustainable or net-zero buildings. Structural barriers feature industry preference for cheap fossil-based virgin materials, limited opportunity for substitution of fossil-based materials, and misalignment between business planning cycles and built environment asset life cycles. Technical barriers comprise increasing complexity of materials, loss of material quality during recycling, technological inefficiencies, and challenges in implementing renewable electricity-based solutions.

In the plastics sector, 116 different barriers were identified (see Supplementary material). Cultural barriers include a lack of explicit prioritisation for circular solutions, resistance to change, deeply entrenched norms, and a linear mindset. There is also a lack of specialised knowledge and consumer awareness about the circular economy concept and closed-loop solutions. Economic barriers involve high costs in various aspects of the circular economy, including the collection and sorting of end-of-life products, recycling processes, and bio-based production. There is also insufficient investment in infrastructure and waste management practices and a lack of market demand for bio-based and biodegradable plastics. Governance barriers include fragmented regulations across countries, inadequate policy frameworks, and a lack of standardised waste collection systems. Additionally, there is a lack of material-specific design-for-recycling standards and alignment between different policies. Structural barriers encompass low data accessibility, high reliance on virgin materials, and a lack of transparency and traceability. There is also a weak reconciliation between the need for economic growth and sustainable development. Technical barriers include immature recycling technology, increasing complexity of materials, and lack of infrastructure capacity for recycling and end-of-life product collection. Furthermore, there is a loss of material quality and value during recycling, hindering the circular economy's progress.

In the textile sector, 54 different barriers were identified (see Supplementary material). Cultural barriers include a lack of prioritisation for circular solutions, linear mindsets and company cultures, and a persistent cultural habit of fashion shopping. A lack of specialised knowledge and expertise in bio-based production and closed-loop systems within the education system also poses a challenge. Economic barriers include high collection and sorting costs for end-of-life products, lack of profitability in areas that deliver high public benefits, and higher prices for green products, which hinder consumer demand. Environmental barriers include higher land use for bio-based products and uncertainty over potential environmental gains. Governance barriers encompass insufficiently ambitious target levels, lack of clarity

around policy targets, policy support for linear production processes, and lack of product standardisation. Structural barriers include difficulty entering well-established fossil-based markets, externalisation of environmental and social costs, lack of value chain stakeholder (researchers, industry representatives, and policymakers) collaboration, and logistical challenges associated with closed-loop recycling of end-of-life products. Lastly, technical barriers consist of the increasing complexity of materials and their combinations, lack of adequate feedstock for recycling, technology inefficiencies, and lack of advanced technological innovation to maintain the quality of materials in a circular economy.

### 3.4. Prominence of barriers

According to the methodology proposed in Section 2.2, we ended up with the aggregate number of citations as 442, with an average of 2.29 and a standard deviation of 1.95 citations. Since the distribution of citations was both asymmetric (Skewness: 1.94) and leptokurtic (Kurtosis: 3.73), we need to evaluate the cumulative distribution function of the set of citations to decide a cut-off criterion. As discussed in Section 2.3, several papers select a citation threshold on the base of the cumulative distribution function. For instance, a citation-based metric known as “hit papers” is often employed in the literature, denoting papers that are within the top 5 % of citations within their specific field and year (Wuchty et al., 2007).

Therefore, we provide an analysis of the citations' cumulative distribution function, based on Eq. (1). Accordingly, we selected as the cut-off criterion the number of at least three mentions in the grey literature since it is the first integer number larger than the average citation, and it ensures a representation of more than half of the total number of identified barriers (Fig. 4). The final list of 51 barriers represents around 58 % of the total number of barriers identified in the grey literature.

It was found that the cultural barrier “Lack of incentives for consumer behaviour change” has been mentioned in 11 different reports, followed by the structural barrier “Lack of value chain stakeholder collaboration (including information exchange)” (10 reports) and the technical barrier “Increasing complexity of materials and their combinations” (9 reports). These three are the top-mentioned barriers to transitioning to a circular bio-based economy (see Fig. 5). Among other frequently mentioned barriers (three or more reports) are mostly governance barriers (14 different barriers), economic barriers (11), structural barriers (9), and technical barriers (9). Only one barrier is related to environmental impacts.

Our results are consistent with and complement previous studies. Firstly, the high costs associated with developing and utilising newly created bio-based products are also highlighted in Salvador et al. (2022) and Gottinger et al. (2020). These studies emphasise the challenge of competing against well-established businesses, citing elevated expenses, including infrastructure and operational costs, compared to conventional synthetic options, along with the pricing competition posed by

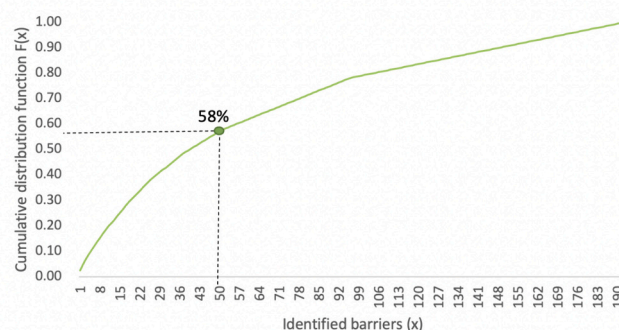


Fig. 4. Cumulative distribution function of barrier citation frequency.





Fig. 5. Number of grey literature records where a specific barrier is mentioned (only barriers mentioned in at least three different reports are presented in the chart).

fossil-based alternatives. Secondly, the linear mindset within both industries and consumer behaviours emerges as a significant hurdle, as noted in prior research by Salvador et al. (2022) and Gomes et al. (2022). The authors advocate for a shift in industry and consumer mentalities towards embracing circular consumption systems to foster greater acceptance. Lastly, Senaratne et al. (2023) confirm that despite the advancements in digital technologies, which have undoubtedly improved communication and transparency, collaboration among stakeholders remains a significant bottleneck hindering the development of circular bio-based systems.

The number of unique reports that mention each barrier provides an indication of the most pressing or most common barriers for the industry. However, it cannot be concluded based on the methodology used that the barriers with the highest number of unique mentions are the most important. Identifying the most or least important barriers to transition to CBBE requires further research.

#### 4. Discussion

The literature sources reviewed provide potential solutions and opportunities to overcome the barriers identified. This section summarizes these solutions. Many of the barriers identified are common to more than one industrial sector, so the solutions or measures are relevant to several or all of the four selected sectors. This section summarizes the different proposed solutions based on the cluster of barriers. However, some solutions to the barrier of a particular cluster may be related to another thematic cluster, e.g. cultural barriers cannot be addressed by cultural solutions alone and may require solutions for overcoming governance barriers first.

##### 4.1. Potential solutions for cultural barriers

Overcoming the identified cultural barriers requires addressing several gaps. A significant cultural barrier is the lack of incentives for consumer behaviour change, as well as the lack of awareness and education on the environmental impact of consumption choices (EEA, 2017;



Ekins et al., 2019; EMF, 2018a, 2018b; EEB, 2021; JRC, 2021; Melati et al., 2021; NIST, 2022; Policy Hub, 2022; SYSTEMIQ, 2022b; ZWE, 2020). To tackle these challenges, a multifaceted approach involving strategies such as leveraging digital technology, improving functional benefits of circular products, and providing consumer guidance and incentivization mechanisms is essential. Furthermore, shifting societal mindsets, raising awareness, and promoting education on the implications of consumption choices are imperative to foster responsible behaviour (EMF, 2018a; SYSTEMIQ, 2022a).

Another gap in overcoming cultural barriers is the low awareness of bio-based products, stemming from the limited availability of information on their benefits (RoadToBio, 2017). Clear communication by the European Commission, national governments, NGOs, and other stakeholders regarding the real environmental effects of bio-based products is necessary. Harmonised sustainability schemes can help address the proliferation of labels and certification schemes that may have green-washing effects (STAR4BBI, 2019a). Additionally, educational activities conducted by various stakeholders can raise awareness about the advantages and potential issues associated with bio-based products, thus promoting their adoption in a CBBE.

The current education system is not adequately structured to train individuals in these multidisciplinary skills needed for circular bio-based processes, resulting in a shortage of skilled professionals (Ekins et al., 2019; FESI, 2022; Philp and Winickoff, 2018; SusChem, 2017). To overcome this, investing in education and training programs that focus on the specialised knowledge and skills needed for bio-based production and closed-loop systems is crucial (OECD, 2022a).

To address the lack of technical expertise among small and medium-sized enterprises, it is necessary to develop clear guidelines, best practices, and standardised methodologies for companies to follow, support the development of new technologies and innovations, and promote collaboration between stakeholders (Melati et al., 2021). Additionally, creating an enabling environment for innovation and entrepreneurship in the CBBE is essential. Governments and policymakers should create favourable conditions for startups and SMEs by offering financial incentives, tax breaks, or funding for research and development. This will help attract investment and talent to the field, promoting the growth of businesses focused on bio-based production and closed-loop systems.

#### 4.2. Potential solutions for technical barriers

To overcome the technical barriers to achieving circularity, several gaps need to be addressed. Firstly, research and development should focus on phasing out problematic colourants in plastics and harmonising design approaches and regulations of chemical substances internationally (ZWE, 2021). This will facilitate the global circularity of materials used in packaging. Improving waste management infrastructure, particularly in developing countries, is essential (OECD, 2022b). Investments in waste collection, sorting, and recycling infrastructure should be made, and effective legal frameworks should be implemented. Collaboration among designers, manufacturers, and recyclers is crucial for developing more recyclable products (SYSTEMIQ, 2022a).

Secondly, addressing the limitations of existing material design and recycling technologies is necessary. Alternative recycling methods or materials that can better withstand degradation should be developed. Research and development efforts should be directed towards enhancing recyclability and material quality. Collaboration between academia, industry, and regulatory bodies can facilitate the development of advanced technologies and processes that maintain the material quality during recycling, supporting the transition towards a circular bio-based economy.

Lastly, addressing the lack of adequate local biomass feedstock requires efforts to improve biomass supply, enhance sustainability assessments, and explore new sources of feedstock (Accenture, 2017; Philp and Winickoff, 2018; RoadToBio, 2019b; STAR-ProBio, 2018; Stasiškienė et al., 2022). Research and development should focus on

improving biomass supply, such as enabling Europe to produce highly productive crops rather than relying on imports (RoadToBio, 2019b). The oceans also offer significant opportunities for cascading use in the bioeconomy, including utilising fisheries discards and exploring the potential of algal biorefineries and seaweed farming (RoadToBio, 2019a).

#### 4.3. Potential solutions for economic barriers

To overcome identified economic barriers, new policy instruments are needed to make unsustainable practices less profitable. This includes enhancing landfill tax incentives, implementing tax measures, and reinforcing extended producer responsibility schemes. Green public procurement criteria, research and development subsidies, and investments in innovative formulations and application methods can further support the shift (OECD, 2022a).

Collaboration among value chain stakeholders is essential to improve cost competitiveness between bio-based and fossil-based products. Demand-side “pull” measures should be implemented to create lead markets for carbon-neutral products and support innovation. Establishing a reliable secondary materials economy, stimulating high-value resource loops, and expanding the scope of the Ecodesign Directive can contribute to the transition (ZWE, 2019; OECD, 2022b).

Significant investment is needed in mature closed-loop recycling systems, post-shredder technologies, and automated sorting facilities for textiles. Developing waste sorting and collection infrastructure is crucial, as well as exploring additional funding sources and enabling policy frameworks. Policymakers can apply taxes to landfills and incineration to make recycling more cost-competitive, while the textile industry should invest in high-quality mechanical and chemical recycling technologies (OECD, 2022b).

The transition to bio-based materials and circular practices requires overcoming resistance to change and accessing finance for sustainable solutions (Ekins et al., 2019; RoadToBio, 2018, 2019a). Start-ups and SMEs should be supported with easier access to finance and open-access pilot plants. Multi-actor approaches, such as innovation funds, ecotaxation, and bio-based criteria in public procurement, can help address the challenges faced by bio-based value chains.

#### 4.4. Potential solutions for environmental barriers

To overcome environmental barriers, enhancing access to information, such as carbon footprints, is crucial for improved monitoring and transparency (EEB, 2020). Uniform data collection methods and reporting standards across industries would enable the evaluation and comparison of environmental impacts. Developing consistent measurement systems and reporting frameworks would ensure data accuracy and reliability.

Centralised databases or platforms could be established to share relevant information across industries. Investment in innovative digital technologies and training programs is needed to bridge the digitalization gap in manufacturing sectors. Material traceability is critical for enhanced recycling and reuse, which can be achieved by implementing digital technologies that tag materials or construction parts and store data in open-source databases.

Innovations for regional, resource-efficient material cycles in the construction sector are necessary. In the CBBE, addressing the lack of data on environmental impacts is essential to encourage businesses to transition from linear fossil-based models (EEB, 2020; TE, 2022a, 2022b).

#### 4.5. Potential solutions for governance barriers

To overcome governance barriers in advancing circularity and bio-based production, a comprehensive and integrated policy framework aligned with the goals of a CBBE is essential. This framework should

involve collaboration and coordination between stakeholders, clear communication, and educational activities to raise awareness about the advantages and potential issues of bio-based products. Setting clear, measurable, and enforceable objectives for policies is crucial, as is establishing bolder and more ambitious targets to drive systemic change and accelerate the adoption of circular practices.

Addressing governance barriers requires developing common standards and guidelines for waste collection and management, investing in the necessary infrastructure to support circular bio-based value chains, and establishing partnerships with industry and civil society organisations. Streamlining certification and labelling procedures for new circular bio-based materials, providing support to businesses in meeting these standards, and implementing supportive market and tax incentives will further encourage the adoption of circular bio-based products and services (BIOVOICES, 2018).

Building awareness and understanding of the benefits of a CBBE among both policymakers and the public is vital, which can be achieved through education, outreach efforts, and targeted communication campaigns.

#### 4.6. Potential solutions for structural barriers

Addressing the structural barriers requires fostering cross-stakeholder efforts, legislative reform, co-funding of research programs, and improved collaboration between academia and industrial biotechnology companies (Philp and Winickoff, 2018). Strong alliances among stakeholders and a legislative framework that facilitates collaboration are essential, as well as introducing measures like a CO<sub>2</sub> tax and fossil carbon tax to overcome the preference for cheap fossil-based virgin materials. Shifting the industry's reliance on unsustainable materials and promoting bio-based alternatives requires adjustments to procurement processes and supply chain management. Addressing the externalisation of environmental and social costs is crucial for transitioning to a CBBE, which involves implementing polluter-pays principles, market-based mechanisms, and strengthening regulations (CGC and SYSTEMIQ, 2022; Eunomia, 2022; JRC, 2021; Melati et al., 2021; Spekrijse et al., 2019; SYSTEMIQ, 2022b).

Policymakers and businesses should prioritise long-term sustainability alongside economic growth, improving data collection and impact assessment tools. Overcoming the lack of mid- and long-term impact assessment in decision-making involves enhancing impact assessment tools and methodologies to capture the long-term effects of policies and decisions.

Tackling the lack of systematic circular initiatives requires a comprehensive policy framework, clear roadmaps for transitioning to a CBBE, and encouraging multi-stakeholder collaboration, including the development of economically feasible circular routes for materials and improved recycling technologies.

## 5. Conclusions

This article presents the results of a grey literature analysis on the barriers and potential improvements associated with transitioning to a CBBE. Keeping the focus on grey literature made it possible to review the part of the literature that is not peer-reviewed but is an excellent source of recent progress on many topics since industry, governments, and private companies produce valuable findings that often risk not being annotated.

In total, we identified 193 different barriers that hinder the transition from a carbon-intensive linear economy to a CBBE (RQ1). The identified barriers were thematically divided into six clusters where cultural and structural barriers were the most prominent. In addition, we found that most of the barriers were allocated to material processing and product manufacturing stages of the value chain followed by barriers associated with end-of-life management and the system as a whole (RQ2). Using a cut-off criterion 51 barriers were found to be most often mentioned in

different grey literature sources indicating that the industry recognises these barriers as more pressing (RQ3). The lack of incentives for consumer behaviour change in the cultural cluster and the lack of stakeholder collaboration in the structural cluster were the most frequently mentioned barriers in the literature reviewed.

The list of identified barriers serves to highlight and acknowledge the impediments and bottlenecks within existing systems, thereby empowering the development of efficient strategies to overcome these challenges. In many cases, complex solutions and collaborative and integrated approaches involving stakeholders from various sectors and disciplines will be required. Although we have summarized the potential solutions proposed by the industry, further research is needed to assess the solutions and identify the most efficient pathways to transition to a CBBE. Policymakers can leverage this insight to craft impactful policies and incentives aimed at boosting the transition to a more sustainable economic paradigm.

Our study has some limitations despite its contribution to the literature. We acknowledge that the reproducibility of our approach may lead to a different result (i.e., the list of the grey literature records) due to the unstructured nature of the databases, platforms, and websites used in the search, as well as the unstructured metadata describing the records (such as keywords, authors, language, abstract or summary, etc.).

It is also worth mentioning that the nature of the transition to a CBBE poses several trade-offs. Therefore, a comprehensive approach that balances social, environmental, and economic factors is necessary to ensure sustainability and inclusivity in the whole industry. Additionally, the transition requires strong collaborations among policymakers, educational institutions, and public opinion leaders to promote sustainable development. To overcome this limitation, follow-up activities are needed, e.g., in the form of workshops, interviews and surveys, to collect feedback from as well as to consolidate the findings with quadruple helix stakeholders.

#### CRedit authorship contribution statement

**Elina Dace:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Cascavilla:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Marco Bianchi:** Writing – review & editing, Methodology, Investigation. **Elisa Chioatto:** Writing – review & editing, Investigation. **Emy Zecca:** Writing – review & editing, Methodology, Investigation. **Luana Ladu:** Writing – review & editing, Methodology, Investigation. **Gülşah Yılan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

#### 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2024.05.029>.

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