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A review of circular economy disruption research: insights into industry 4.0 enabled circular economy framework for sustainability during turbulent times

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A R T I C L E I N F O

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A B S T R A C T

The implementation of the circular economy is negligible and painfully slow due to insufficient proof of tangible benefits and awareness of how to implement it. The current geo-political turbulence has the potential to further slow it down by diverting public sentiment and resources to national security.

This study systematically analyses 74 academic papers using the bibliometric (author co-citation analysis and bibliographic coupling) and content analysis (quality ranking and thematic coding) methods to explore how circular economy disruptions can be implemented and managed efficiently.

It identifies three thematic areas (conceptualisation, components, and challenges) where circular economy disruption research has evolved. Europe's thought leadership in this research field is evident, as is China's growing influence in emerging research areas such as circular entrepreneurship. It introduces green innovations and Industry 4.0 as enablers for a circular economy-based, resilient, and sustainable global economy.

This study proposes an Industry 4.0-enabled framework for circular economy disruption in which leadership support, digital infrastructure, and organisational resilience are critical antecedents to adopting Industry 4.0. Stakeholder engagement and consumer perceptions are key components of the proposed framework, while sustainability policies and regulations moderate the effectiveness of Industry 4.0 technologies in achieving a circular economy. The framework's implementation methodologies include a modular approach accommodating various enterprise scales and regional conditions. By implementing this framework, countries could reduce dependency on volatile supply chains and promote economic resilience through sharing and transferring circular economy know-how and Industry 4.0 technologies.

1. Introduction

The global economy needs to transition to a circular economy (CE) due to heightened environmental risks, the alarmingly fast depletion of finite resources, and the necessity for sustainable business practices (Sugg, 2022). The ongoing geo-political conflicts in Europe and the Middle East further added to the irreversible environmental damage. Neimark et al. (2024) estimate that emissions from just two months of the Gaza conflict exceeded the annual carbon output of more than 20 climate-vulnerable nations, highlighting the environmental toll of modern warfare. While comprehensive carbon accounting for the Russian invasion of Ukraine is lacking, analysts agree that its scale has had severe and lasting environmental consequences (Pearce, 2022). These conflicts form part of a wider pattern of global militarisation, which is now emerging as an existential threat to climate goals. NATO's planned rearmament alone could raise emissions by nearly 200 million tonnes annually, equivalent to adding a country the size of Pakistan to the world's carbon ledger (Gayle, 2025). As military spending rises sharply across Europe and beyond, this security-driven emissions surge risks undermining global climate action while intensifying the very conditions: scarcity, displacement, and conflict, that CE transitions are meant to mitigate.

Abbreviations: CE, Circular Economy; CED, Circular Economy Disruption; I4.0, Industry 4.0; CBM, Circular Business Models; SSC, Sustainable Supply Chain; CSC, Circular Supply Chain; SLR, Systematic Literature Review; PRISMA, Preferred Reporting Items for Systematic Literature Review and Meta-Analyses; LS, link strength; BEEP, Blockchain-Enabled E-commerce Platforms; SDGs, Sustainable development goals.

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Moreover, the cascading effects of global warming and geo-political conflicts manifest in fast-increasing prices of commodities (Iliyasu & Sanusi, 2024), food shortages (Muluneh, 2021), rising heat and pollution-related health issues, and population displacements (Lenshie et al., 2022). Such convergence of environmental and geopolitical crises demands not just technical improvements, but a fundamental shift in how we conceptualise and enact circularity. Circular Economy Disruption (CED) responds to this need by framing turbulence not as a barrier, but as a catalyst for systemic transformation.

Nonetheless, critical issues exist in practice. The global circularity rate stands at a mere 8.6 % (Circle Economy, 2022). Deloitte (2023) estimated that only 7.2 % of the 100 billion tons of virgin resources return to the global economy as recycled materials annually. To gauge the slow transition, Bain & Company (n.d.) claimed that the path to a circular business model (CBM) is uncharted territory for most companies, while Saha et al. (2024) argued that unawareness of CED deters firms' willingness to become circular.

Acknowledging the pressing issue, Kirchherr et al. (2023), in their editorial piece, argued that such slow progress is due to the focus of CE literature on challenges and barriers to adopting CE practices instead of how CE could be effectively operationalised. Addressing these issues requires a clearer understanding of how CED has been conceptualised, evolved, and studied in the existing literature, as well as how it might be effectively operationalised under conditions of turbulence. This informs our research questions:

RQ1: How has circular economy disruption (CED) research evolved?

RQ2: What are the main attributes of the current circular economy disruption (CED) research?

RQ3: How can circular economy disruption (CED) be operationalised during socio-economic and geo-political turbulence?

This review consolidates and critiques the emergent literature on CED using a combined bibliometric and content analysis approach. Unlike prior reviews that centre on CE implementation or technological affordances in isolation, our approach explicitly considers the role of turbulence, leadership, digital infrastructure, and policy in shaping CED. The resulting I4.0-enabled CED framework provides a novel contribution by integrating micro, meso, and macro-level enablers of disruptive circular transitions.

In the subsequent sections of this paper, we present the background and theoretical framing of CED (Section 2), outline the methodological approach (Section 3) and report the findings obtained from the reviews (Section 4). The discussion (Section 5) emphasises the contribution of these findings and the potential future research directions before concluding in Section 6.

2. Background

2.1. Conceptualising circular economy disruption (CED)

Blomsma et al. (2023a) define CED as a socio-technical transformation that enables a systemic, rapid, and widespread shift away from the dominant 'take-make-use-dispose' linear model towards more sustainable and regenerative circular practices. Their WaveS model conceptualises this process as occurring in both pre-implementation and post-implementation phases, reflecting the dynamic and often non-linear nature of circular transitions. Unlike incremental CE adoption strategies, CED foregrounds disruption, whether through crisis, innovation, or regulation, as a catalyst for deep and structural change across sectors and systems (European Commission, 2023; Henry et al., 2020).

It is argued that CED can enhance resource efficiency (Unruh, 2018) and reduce nations' exposure to geo-political shocks through localised and resilient supply chains (Hartley et al., 2024). CED can also deliver competitiveness (Fraccascia, 2019) and corporate social responsibility (CSR) (Alcayaga et al., 2019) while reducing environmental impact (Dey et al., 2023) and operating cost (Saha et al., 2021) for both old industries like textile and clothing (Saha et al., 2024) and new industries such as space tourism (Paladini & Saha, 2023).

The conceptual utility of CED lies in its potential to reframe disruption from a risk to an enabler of sustainability. Rather than treating turbulence as an obstacle, the CED lens encourages firms and policymakers to view crisis contexts as windows for rapid systemic innovation. This reframing is particularly relevant in volatile geopolitical and economic contexts, where traditional linear systems are proving increasingly fragile. However, the conceptual traction of CED remains limited by a lack of definitional precision and methodological consistency. We realise that it is frequently invoked in normative terms yet rarely operationalised in a way that enables systematic empirical investigation or theoretical development.

2.2. Research gap and review rationale

There is a significant uptake of research articles concerning the CE approach in different industries (Kumar et al., 2021), implementation challenges (Blomsma et al., 2023a; b), benefits and consumers' preference for sustainable products (Brasche et al., 2023). To this end, Saha et al. (2024) proposed a multilevel approach to capturing and understanding disruptions, encompassing micro (firm), meso (industry), and macro (national).

Yet, no study systematically addresses CED as a solution to accelerate CE implementation (Fernando et al., 2023a) during turbulent times or how firms should forecast and manage it (Droege et al., 2023). Given its novelty, only a handful of articles (e.g., Henry et al., 2023; Reike et al., 2023) empirically assessed the concept. Nonetheless, their generalisability suffers due to limited data and geographic scope (Neligan et al., 2023), sectoral focus (Arekrans et al., 2023), disproportionate attention to specific circular strategies (Blomsma et al., 2023b) and a lack of engagement with emerging innovation ecosystems and cross-sectoral applications (Kuhlmann et al., 2023).

In addition, the current literature lacks a comprehensive analysis of how CE principles can be effectively implemented across different socioeconomic systems to respond to such global challenges (Hartley et al., 2024). For instance, the current geopolitical turbulence can disrupt the stability of global manufacturing hubs in developing countries and their pursuit of sustainable development goals (SDGs). It is also apparent that there needs to be more conceptual studies and systematic literature review (SLR), although there are numerous SLRs in other fields of CE research (e.g. Lowe et al., 2024; Metic & Pigosso, 2022). Such absence of review articles limits conceptual clarity and leads to hegemonic scientific concepts regarding CE (Dzhengiz et al., 2023). These discrepancies between theoretical assumptions and empirical evidence highlight the need for a more nuanced understanding of CED. Therefore, we aim to clearly understand the CED research as industries transition from linear to circular and identify enablers to facilitate the transition during turbulent times.

The rationale of this study is multifaced: first, we target the critical knowledge deficit on the factors that stimulate CED. Investigating the methodological and theoretical underpinnings of CED research is essential to uncover these factors. Snyder (2019) suggested the need for rigorous literature reviews as the pace of CE research accelerates in a fragmented (Saha et al., 2024) and interdisciplinary manner.

In this case, an SLR enables a structured synthesis of how CED has been framed, studied, and applied, thereby informing questions about its evolution, dominant characteristics, and potential for operationalisation during periods of turbulence. This review, therefore, provides the foundation for a robust framework that can support resilient economic recovery as the global economy grapples with lingering productivity and supply chain disruptions stemming from geopolitical conflict and the legacy of the COVID-19 pandemic.

Secondly, the cascading effect of the recent geo-political conflicts in Eastern Europe and the Middle East is diverting policy focus away from environmental sustainability towards national security. It is suspected that the impetus of resourcing the circular transition in Europe and elsewhere will lessen as governments allocate more resources for defence. This could hinder the progress towards a circular economy and delay the necessary global response to environmental challenges. This research offers a roadmap for firms to maintain environmental commitments while coping with the resource constraints of increased national security spending.

Moreover, this review can guide international cooperation by demonstrating the benefits of CE practices. CE champions like the Netherlands (national circularity rate of 24.5 %) (Circle Economy, 2022) could form resource efficiency—and sustainability-focused global alliances as a non-traditional security measure to address heightened geopolitical risks. Such international alliances can enhance global stability by reducing dependency on volatile supply chains and promoting economic resilience through shared knowledge and technology transfers in CE frameworks.

In framing this review, the analysis draws attention to key insights for managers and policymakers: notably, the need to embed digital capabilities, foster stakeholder alignment, and anticipate regulatory shifts in navigating CED. Such insight affirms the growing relevance of CED in supply chain and logistics contexts, where uncertainty is becoming the norm.

3. Methodological approach

This research conducts an SLR (Bak et al., 2023) combined with bibliometric and content analysis. The epistemological position of the review is critical realism (Bhaskar, 1975) that embraces a mixed-method approach (Creswell & Clark, 2017) since our bibliometric methods follow a deductive and quantitative approach while the content analysis uses an inductive qualitative (Zawacki-Richter et al., 2020) strategy. The deductive approach of bibliometric review identifies overarching trends, assesses the relative impact of different articles, and provides a comprehensive picture of the field's intellectual structure. On the other hand, the content analysis introduces qualitative dimensions, enriching our understanding with contextual insights and depth.

3.1. Identification of literature

We applied the PRISMA approach to conduct the SLR. The initial search was conducted through the Scopus database (Donthu et al., 2021) on 17 November 2023 based on keywords ("Circular economy") AND (Disrupt*) for search within "the title, abstract and keyword".

We deliberately chose not to include interchangeably used keywords such as 'sustainable business models', 'resource efficiency', 'technological innovation', and 'digital transformation' to maintain the focus on the CED. Including these terms would have broadened the scope excessively, capturing a vast array of topics that, while relevant to CE, do not directly address our core interest in transformative and disruptive changes. Besides, keywords such as 'technological innovation' and 'digital transformation', often embedded within broader discussions of disruption, were already captured in our primary search term 'Disrupt*', ensuring that our review focused on literature where technology explicitly drives or results from disruptive changes. Fig. 1 represents the details of the selection process. The keyword search captured 365

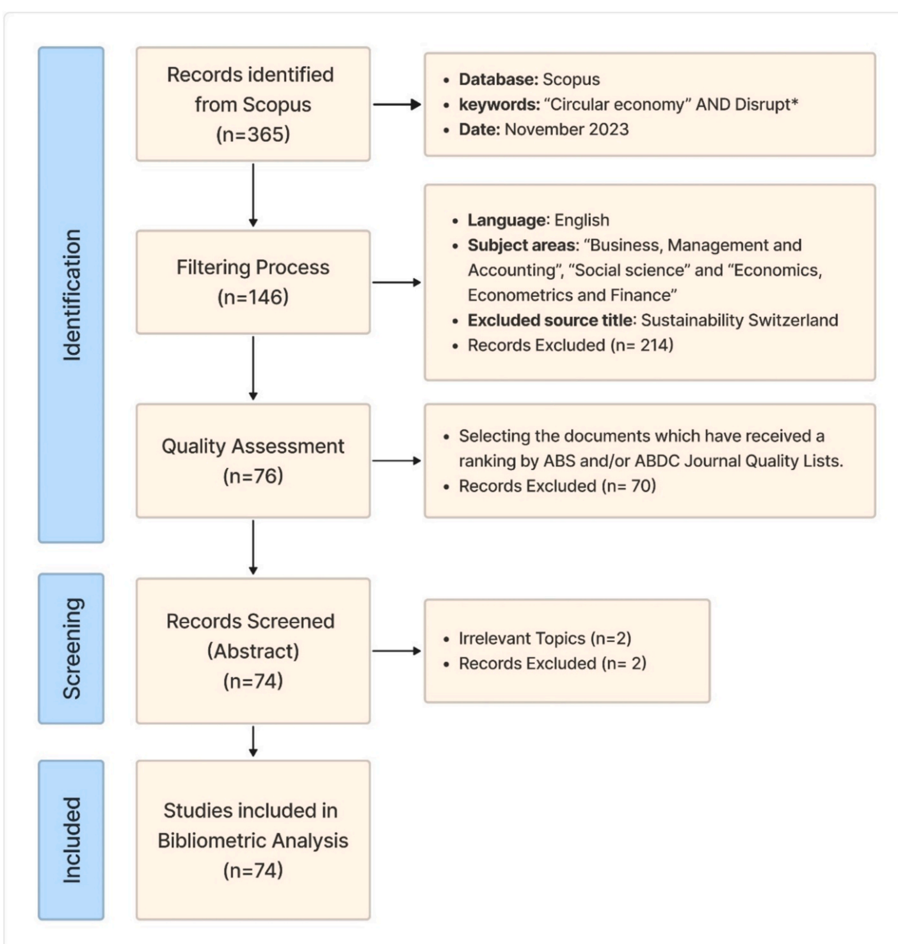

Fig. 1. Selection process based on PRISMA method ().
Source: Rethlefsen et al., 2021

articles.

Following a filtering and rigorous quality assessment process using the Chartered Association of Business Schools (CABS) and/or the Australian Business Deans Council (ABDC) journal quality lists, we selected 76 documents. During the final screening step, article abstracts were evaluated to ensure their relevance to the research questions. As a result, two documents were identified as irrelevant and subsequently removed from the sample. Finally, 74 documents were selected as a final sample for bibliometric analysis and content analysis (Table 1).

3.2. Bibliometric review process

In the bibliometric review, author co-citation and bibliographic coupling of documents are employed to uncover diverse citation patterns and cluster-related documents. The author co-citation analysis involves assessing the co-citation frequency of each author's work to achieve three key objectives: (i) identifying influential scholars in a specific research field, (ii) uncovering connections between scholars, and (iii) gaining insight into main ideas and development direction within the research domain (Donthu et al., 2021).

On the other hand, bibliographic coupling examines the degree of similarity between the reference lists of different academic articles. It involves identifying articles that cite similar references, indicating a shared conceptual foundation (Vogel et al., 2021) and revealing the emerging area in a specific field. The bibliometric analysis sheds light on the fundamental intellectual structure of the CED field and reveals the networks of collaborative communication among CE scholars (Saha et al., 2025). This analysis generates visual maps and co-citation networks using the VOSviewer (Van Eck & Waltman, 2017) tool.

3.3. Content analysis process

Content analysis is a systematic, methodical, and organised reading of literature for replicable and comprehensive interpretations of data (Moldavska & Welo, 2017). We set coding criteria for contributions to advancing CE implementation within critical thematic areas, analysing theoretical foundations, and suggesting innovative research directions, frameworks, or methodologies to progress CED research for each article. The coding process captured these articles' content (e.g., CBM, start-ups and public authorities' role in accelerating CE, barriers, and drivers, I4.0 to sustain CE practices, and methodological approaches).

Each article was independently ranked against the three RQs using 1 (low), 2 (medium) and 3 (high) scoring techniques to reach a total score of importance (Saha et al., 2025; Vogel et al., 2021). Responses scoring seven or higher are categorised as high, those falling between four and six are considered medium, and any score below four is labelled as low. The details of this categorisation are presented in Appendix 1. Two Postgraduate management students were trained to follow a comprehensive coding reference guide under the supervision of the first author, who independently examined all coded documents to adjust if there were discrepancies. And thus, we classified 74 articles into three categories: high (52), medium (16), and low (6).

4. Results and analysis

This section represents the findings of our bibliometric review and content analysis.

4.1. Bibliometric review: Evolution of CE-TC knowledge domain (RQ 1)

The citation analysis directly correlates with the content of the studies by mapping the intellectual structure of the CED research field. Through author co-citation analysis and bibliographic coupling, we can identify relationships between studies based on how frequently specific authors or papers are cited. This clustering of citations reveals key themes, methodologies, and theoretical frameworks within the

Table 1
Selected literature based on PRISMA method for bibliometric analysis and content analysis.

No	Authors	Source title	Journal index[a]	Relevance to review scope
1	Abdul-Hamid et al. (2021)	Journal of Cleaner Production	CABS 2 / ABDC A	High
2	Adelodun et al. (2021)	Journal of Cleaner Production	CABS 2/ ABDC A	High
3	Agarwal et al. (2022)	Journal of Asia Business Studies	CABS 1/ ABDC C	High
4	Åkerman et al. (2020)	Geoforum	CABS 2	High
5	Alcayaga et al. (2019)	Journal of Cleaner Production	CABS 2/ ABDC A	High
6	Andersson and Buser (2022)	Construction Management and Economics	CABS 2 / ABDC A	High
7	Bai et al. (2022a)	Industrial Marketing Management	CABS 1/ ABDC C	High
8	Bai et al. (2022b)	Operations Management Research	CABS 1/ ABDC C	High
9	Blomsma et al. (2023a)	Business Strategy and the Environment	CABS 3/ ABDC A	High
10	Carraresi and Bröring (2021)	Journal of Cleaner Production	CABS 2/ ABDC A	High
11	Chandel et al. (2024)	International Journal of Quality and Reliability Management	CABS 2 / ABDC A	Medium
12	Chaouni Benabdellah et al. (2023)	Benchmarking	CABS 1	High
13	Cherrafi et al. (2022)	TQM Journal	CABS 1	High
14	Cother (2020)	Action Learning: Research and Practice	CABS 1/ ABDC C	Medium
15	Dey et al. (2023)	International Journal of Production Research	CABS 3/ ABDC A	High
16	Droege et al. (2023)	Business Strategy and the Environment	CABS 3 / ABDC A	High
17	Dwivedi and Paul (2022)	Business Strategy and the Environment	CABS 3 / ABDC A	High
18	Dwivedi et al. (2023a)	International Journal of Logistics Management	CABS 3 / ABDC A	High
19	Dwivedi et al. (2023b)	Technological Forecasting and Social Change	CABS 3/ ABDC A	Medium
20	Esposito et al. (2017)	Thunderbird International Business Review	CABS 2/ ABDC B	Medium
21	Ethirajan et al. (2021)	Business Strategy and the Environment	CABS 3/ ABDC A	High
22	Faridi and Mir (2022)	Emerald Emerging Markets Case Studies	CABS 1	Low
23	Fernando et al. (2023a)	Journal of Science and Technology Policy Management	CABS 1	High
24	Fernando et al. (2023b)	International Journal of Logistics Research and Applications	CABS 1/ ABDC C	Medium
25	Finn et al. (2020)	International Journal of Technology Management and Sustainable Development	CABS 1/ ABDC C	High
26	Fraccascia (2019)	International Journal of Production Economics	CABS 3/ ABDC A	Medium
27	García-quevedo et al. (2020)	Business Strategy and the Environment	CABS 3/ ABDC A	High
28	Garmulewicz et al. (2018)	California Management Review	CABS 3/ ABDC A	Medium
29	Gavrila Gavrila and de Lucass Ancillo (2021)	Technological Forecasting and Social Change	CABS 3 / ABDC A	Medium
30	Giovanardi et al. (2023)	Journal of Cleaner Production	CABS 2 / ABDC A	Medium

(continued on next page)

Table 1 (*continued*)

No	Authors	Source title	Journal index[a]	Relevance to review scope
31	Gupta and Singh (2021)	International Journal of Logistics Research and Applications	CABS 1	High
32	Hatzfeld et al. (2022)	Journal of Cleaner Production	CABS 2 / ABDC A	High
33	Hosseini-motlagh et al. (2020)	Journal of Cleaner Production	CABS 2 / ABDC A	Medium
34	Julkovski et al. (2023)	Business Strategy and the Environment	CABS 3 / ABDC A	High
35	Kandasamy et al. (2023)	Operations Management Research	CABS 1/ ABDC C	High
36	Kahupi et al. (2021)	Journal of Cleaner Production	CABS 2 / ABDC A	High
37	Karmaker et al. (2023)	Journal of Cleaner Production	CABS 2 / ABDC A	High
38	Kayikci et al. (2022)	Journal of Enterprise Information Management	CABS 2/ ABDC A	High
39	Kirbac et al. (2023)	Foresight	CABS 1 / ABDC C	High
40	Kirchherr et al. (2023)	Business Strategy and the Environment	CABS 3/ ABDC A	High
41	Krstić et al. (2023)	British Food Journal	CABS 1 / ABDC B	High
42	Kuhlmann et al. (2023)	Business Strategy and the Environment	CABS 3 / ABDC A	High
43	Kunttu (2021)	Technology Innovation Management Review	CABS 1 / ABDC C	Low
44	Lapko et al. (2019)	Journal of Industrial Ecology	CABS 2	Medium
45	Lazarevic et al. (2022)	Journal of Cleaner Production	CABS 2 / ABDC A	High
46	Le et al. (2023)	European Journal of Innovation Management	CABS 1 / ABDC C	Medium
47	Lekan et al. (2021)	Economic Geography	CABS 4/ ABDC A	High
48	Liaros (2020)	Smart and Sustainable Built Environment	ABDC C	Low
49	Liu et al. (2022)	Operations Management Research	CABS 1/ ABDC C	High
50	Mukherjee et al. (2021)	Operations Management Research	CABS 1 / ABDC C	High
51	Nandi et al. (2021)	International Journal of Logistics Research and Applications	CABS 2	High
52	Nandi et al. (2023)	Industrial Management and Data Systems	CABS 1	High
53	Närvänen et al. (2021)	Industrial Marketing Management	CABS 3 / ABDC A	High
54	Neligan et al. (2023)	Business Strategy and the Environment	CABS 3/ ABDC A	High
55	Niskanen et al. (2020)	Journal of Cleaner Production	CABS 2/ ABDC A	High
56	Norris (2019)	Business History	CABS 4/ ABDC A	Medium
57	Pasteris et al. (2022)	Journal of Cleaner Production	CABS 2/ ABDC A	Low
58	Piyathanavong et al. (2022)	Operations Management Research	CABS 1/ ABDC C	High
59	Rajala et al. (2018)	California Management Review	CABS 3/ ABDC A	High
60	Reike et al. (2023)	Business Strategy and the Environment	CABS 3 / ABDC A	High
61	Rollin et al. (2022)	Journal of Cleaner Production	CABS 2 / ABDC A	Low
62	Sajjad et al. (2024)	Journal of Retailing and Consumer Services	CABS 2 / ABDC A	High
63	Saritas and Proskuryakova (2017)	Foresight	CABS 1/ ABDC C	Low
64	Sehnem et al. (2022a)	Sustainable Development	ABDC C	High
65	Sehnem et al. (2022b)	Business Strategy and the Environment	CABS 3/ ABDC C	High
66	St. Clair et al. (2023)	Journal of Cleaner Production	CABS 2/ ABDC A	High
67	Sugg (2022)	Journal of Fashion Marketing and Management	CABS 1/ ABDC B	High
68	Talens Peiró et al. (2020)	Journal of Cleaner Production	CABS 2/ ABDC A	Medium
69	Unruh (2018)	California Management Review	CABS 3/ ABDC A	Medium
70	Van Opstal and Borms (2023)	Journal of Cleaner Production	CABS 2/ ABDC A	High
71	Vargas-Sánchez (2018)	Worldwide Hospitality and Tourism Themes	CABS 1/ ABDC C	Medium
72	Vines et al. (2023)	Journal of Cleaner Production	CABS 2 / ABDC A	High
73	Xin et al. (2022)	Operations Management Research	CABS 1/ ABDC C	High
74	Yazdani et al. (2019)	Management Decision	CABS 2/ ABDC B	High

[a] We followed CABS 2021 journal ranking as this quality process was conducted during November-December 2023. The CABS 2024 ranking was not available at this time.

literature, allowing us to connect citation patterns to the substantive content of the research.

4.1.1. *Author co-citation analysis (cited authors)*

The author co-citation analysis (Fig. 2) illustrates the network of co-cited authors, revealing the interconnected relationships among them, while the inter-cluster connections and co-citation relationships reveal the cross-pollination of ideas between clusters (Donthu et al., 2021). Fig. 2 represents a network containing 52 nodes and 1281 links; each node indicates an author, and each node's size reflects the author's citation frequency. The thickness of the lines denotes the link strength (LS), indicating the frequency of joint citations between two authors and the strength of their association.

The most prominent cluster (green) showcases a dense network of authors (e.g., Mangla S.K. (49 citations, LS 2284) with substantial node sizes and thick interconnecting lines, indicating a high degree of co-citation. This suggests that the authors in the green cluster are central figures within this research domain, frequently referenced in the literature, and likely contributing foundational theories or widely accepted methodologies. In contrast, the blue cluster (e.g., Gunasekaran A. [58 citations, LS 2696] and Ivanov D. [50 citations, LS 2258] shows slightly less connectivity compared to the green, implying that the authors in this cluster represent an emerging field or a sub-discipline gaining traction (e.g., I4.0 technologies on sustaining CE practices), but perhaps not as established as the one represented by the green cluster. Although less established than the green cluster, the authors in this group are rapidly gaining influence, reflecting a growing interest in the application of digital transformation tools to improve CBM and enhance supply chain sustainability.

The red cluster stands out due to several nodes with strong linkages (e.g., Kirchherr J. [60 citations, LS 1451]), forming a tight-knit community of highly cited authors (e.g., Bocken, Hekkert and others). The visualisation also reveals thinner lines stretching between clusters, indicating inter-cluster connections and co-citation relationships between authors in red (e.g., Geissdoerfer), green (e.g., Mangla), blue (e.g., Gunasekaran) and yellow (e.g., Sarkis) clusters with a different research focus. These links point to the cross-pollination of ideas for novel research directions. For instance, authors like Kirchherr J. and Geissdoerfer M. in the red cluster are linked to Mangla S.K. in the green cluster and Gunasekaran A. in the blue cluster, indicating significant

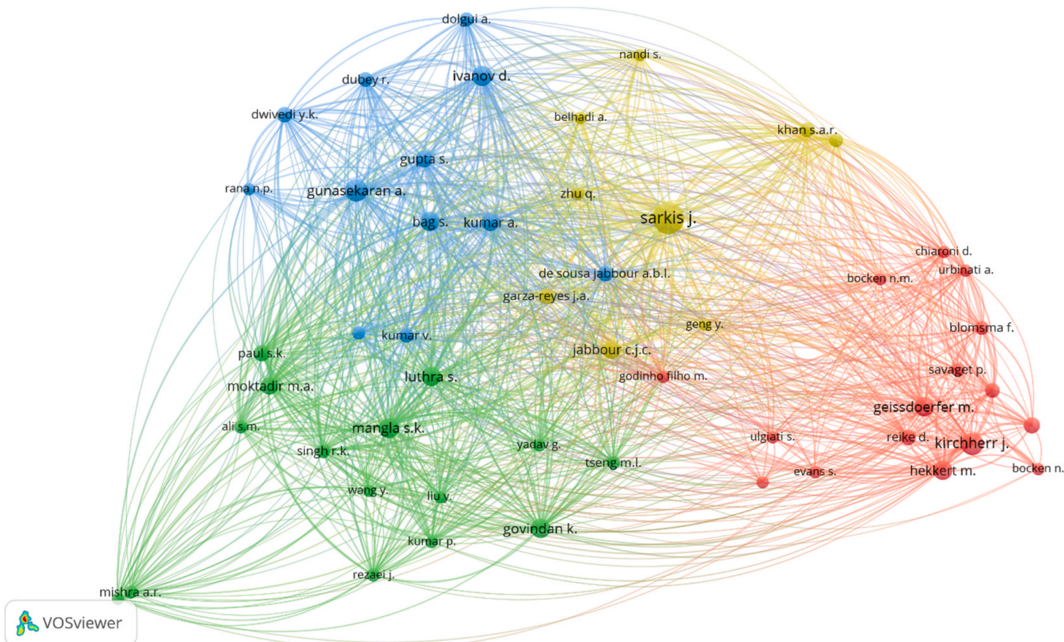

Fig. 2. Co-citation of authors (UoA: Cited Authors).

cross-disciplinary collaboration. These inter-cluster connections demonstrate how different areas of CED research, such as policy frameworks, circular business models (CBMs), and digital innovations, are influencing each other, leading to novel research directions that integrate these themes. Here, we see that the works of highly cited authors form part of a larger research cluster (e.g., Mangla and Gunasekaran for supply chain resilience and technological enablers). The correlation between citation analysis and study content is evident in how these co-cited authors have shaped the field, providing insights into key concepts of CSC and I4.0.

Fig. 2 also reveals the geographical and sectoral leadership in CED research. European researchers dominate discussions on policy and regulatory frameworks for CE implementation, while Chinese researchers are increasingly contributing to areas like circular entrepreneurship and the application of I4.0 in emerging sectors. The geographic distribution (further discussed in Section 3.2) of the research focus indicates the global nature of CED research and the varying priorities across regions.

Thus, the author's co-citation analysis reveals the intellectual landscape of CED research, highlighting key thought leaders, emerging subfields, and the cross-pollination of ideas that drive innovation in the field. These insights provide a foundation for understanding the

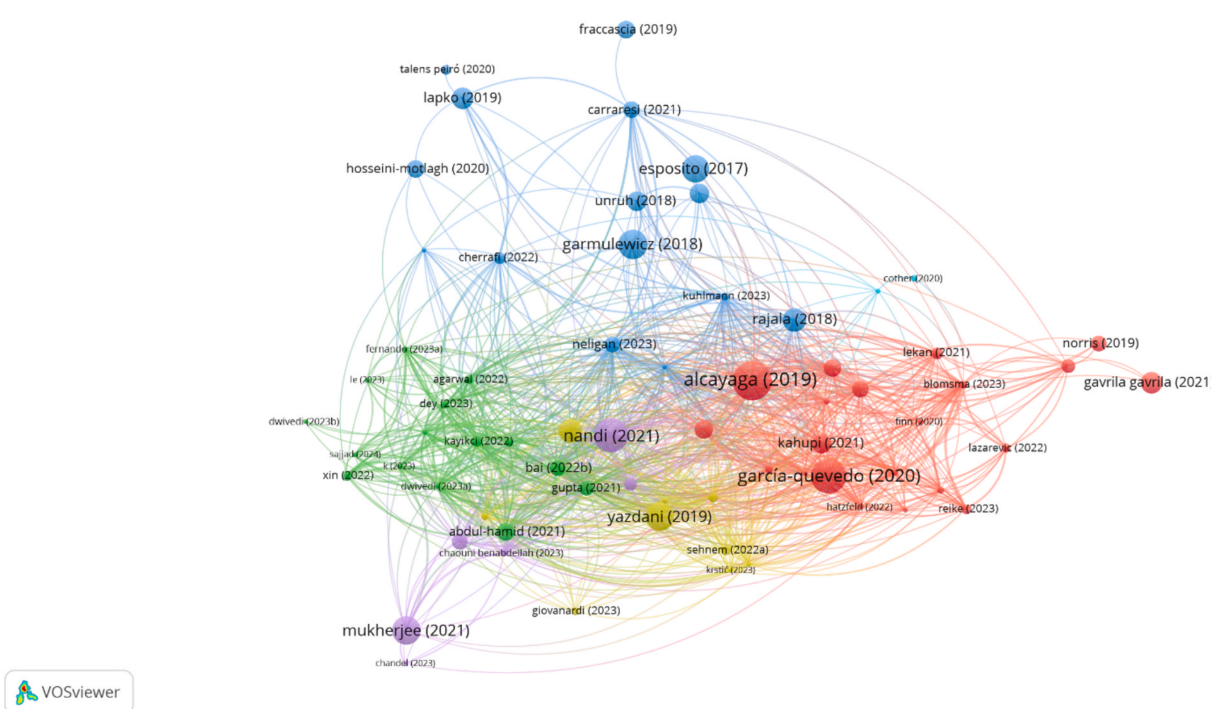

Fig. 3. Bibliometric coupling (UoA: documents).

evolution of CED research and identifying future directions, particularly in integrating I4.0 technologies with CE principles.

4.1.2. Bibliographic coupling (documents)

Bibliometric coupling analysis groups documents based on shared references to reveal the intellectual cohesion within specific research clusters. We applied the VOSviewer software to produce a bibliometric map of 74 documents (Fig. 3); however, only 68 documents were subjected to analysis, as it is the most extensive set of connected items.

Based on Fig. 2, the bibliometric coupling analysis represents six clusters formed by 929 links. Table 2 presents the composition of each cluster, including authors, primary topic, methodology, and total link strength (LS) of the articles. By categorising literature into these clusters, we bridge the gap between quantitative citation analysis and the qualitative themes emerging from the studies. This process ensures that the citation analysis reveals intellectual relationships and the substantive content trends in CED research, such as the influence of I4.0, policy-driven circular practices, and green innovation.

The LS of a document indicates the degree of relatedness between documents within each cluster. A higher link strength indicates a stronger relationship between the documents, suggesting they share a larger number of references in common. For example, Blomsma et al. (2023a) have the highest LS (121) in Cluster 1 (red), as it shares a significant number of references with other documents in Cluster 1. We also found that Cluster 1 focuses heavily on conceptualising CED and developing CBMs. This document appears to be a seminal work in conceptualising CED. In Cluster 2 (green), Bai et al. (2022b) and Gupta & Singh (2021) are impactful works (LS 116 and 112, respectively) in the assessment of the implications of I4.0 on CE implementation. These works highlight the transformative potential of digital technologies in enhancing supply chain resilience and operational sustainability.

With a similar focus, Neligan et al. (2023) occupy the second-highest LS (109) in Cluster 3 (blue), and Nandi et al. (2021, 2023) have the two highest LSs in Cluster 5 (purple). On the other hand, Cluster 4 (yellow) focuses on the risk assessment of the CSC. Ethirajan et al. (2021) tops the table in this cluster with 128 LS, whereas Bai et al. (2022a) and Yazdani et al. (2019) influence this stream of literature with their empirical works receiving 116 and 82 LS, respectively. Cluster 6 (turquoise) is the smallest, with two publications: Sehnem et al. (2022a) (LS 11) and Cother (2020) (LS 2), indicating a nascent or highly specialised field of research on circular entrepreneurs. It is intriguing that Droege et al. (2023), Närvänen et al. (2021) and Van Opstal and Borms (2023) from Cluster 1 also discussed circular entrepreneurship (Table 2).

Fig. 3 shows that the authors in the red cluster (e.g., Alcayaga et al., 2019; Garcia-Quevdo, 2020; Kahupi et al., 2021) provide foundational frameworks that have shaped subsequent research. In contrast, the green and blue clusters focus on the technological impacts of I4.0 on CBM and CSC. Documents in these clusters, such as Bai et al. (2022b) and Gupta & Singh (2021), highlight how digital technologies enhance operational efficiency and sustainability within CSCs. The clustering of these documents reveals the thematic diversity within CED research, with a strong focus on how technological innovation drives the adoption of circular practices in industries.

We also apply the density visualisation (Fig. 4) technique to present the concentration of specific attributes (e.g., documents, keywords, or authors) within a network based on the frequency of their occurrence or the strength of their links. Fig. 4 presents the gradation from yellow to green and blue, suggesting a spectrum of relevance or interconnectedness. In the centre (yellow), we have highly connected works such as Nandi et al. (2021), Alcayaga et al. (2019), and García-Quevedo et al. (2020) as central nodes, indicating high connectivity and influence within the CED knowledge network. Moving outward, the interconnectedness and, presumably, the shared reference count diminish. Norris (2019) and Gavrila Gavrila and de Lucas Ancillo (2021) might draw on different literature or contribute new perspectives (in this case, circular entrepreneurs or stakeholder engagement) that have not yet

Table 2
Analysis of Clusters data.

Count	Author	Main topic	Method	Link strength
		Cluster 1 (Documents 21)		
1	Blomsma et al. (2023a)	Conceptualisation of circular disruption	Concept framework	121
2	Alcayaga et al. (2019)	Circular business model	Literature review	114
3	Kirchherr et al. (2023)	Conceptualisation and characterisation of circular disruption	Literature review	104
4	Närvänen et al. (2021)	Circular Entrepreneurship	Qualittaive interview (n = 9)	92
5	Niskanen et al. (2020)	The role of stakeholders in speed up CE	Literature review	88
6	Hatzfeld et al. (2022)	Circularity challenges	Case study (n = 2)	69
7	García-quevedo et al. (2020)	Barriers to develop CE	SME survey (n = 441)	66
8	Droege et al. (2023)	Circular Entrepreneurship	Qualitative interviews (n = 24)	66
9	Julkovski et al. (2023)	Circular business model	Two countries comparative case study (interviews data, n = 22)	63
10	Van Opstal and Borms (2023)	Circular Entrepreneurship	Quantitative survey (n = 165)	55
11	Reike et al. (2023)	The role of stakeholders in speed up CE	Qualitative interviews (n = 29)	51
12	Lekan et al. (2021)	Challenges to develop CE	Qualitative interviews (n = 13)	48
13	Andersson and Buser (2022)	Challenges to develop CE	Qualitative interviews (n = 31)	39
14	Adelodun et al. (2021)	The impact of CE on sustainability	Literature review	38
15	Kahupi et al. (2021)	The role of stakeholders in speed up CE	Qualitative interviews (n = 15)	37
16	Akerman et al. (2020)	Circular business model	Qualitative interviews (n = 14)	31
17	Lazarevic et al. (2022)	Policy and Regulatory Frameworks to develop CE	Literature review	27
18	Vines et al. (2023)	Policy and Regulatory Frameworks to develop CE	Case study (n = 1)	24
19	Finn et al. (2020)	Drivers to develop CE	Case study	21
20	Norris (2019)	Circular business model	Case study	6
21	Gavrila Gavrila and de Lucass Ancillo (2021)	Drivers to develop CE	Qualitative interview (n = 20)	3
		Cluster 2 (Documents 15)		
1	Bai et al. (2022b)	Impact of I4.0 technologies on sustaining CE practices	Case study	116
2	Gupta and Singh (2021)	Impact of I4.0 technologies on sustaining CE practices	Literature review	112

(continued on next page)

Table 2 (continued)

Count	Author	Main topic	Method	Link strength
3	Abdul-Hamid et al. (2021)	Drivers of I4.0 in the sustaining CE practices	Literature review	97
4	Dwivedi et al. (2023b)	CE practices in supply chains	Literature review	94
5	Kayikci et al. (2022)	Circular supply chain	Literature review	88
6	Agarwal et al. (2022)	Sustainable supply chain management	Quantitative survey (n = 29)	64
7	K et al. (2023)	Barriers to the adoption of CE	Quantitative	64
8	Karmaker et al. (2023)	Improve SSC by I4.0	Quantitative survey (n = 200)	65
9	Dey et al. (2023)	Improve SSC by disruptive technologies	Quantitative survey (n = 280)	62
10	Piyathanavong et al. (2022)	Improve SSC by I4.0	Case studies (n = 3)	61
11	Fernando et al. (2023a)	Improve SSC by disruptive technologies	Quantitative survey (n = 130)	55
12	Xin et al. (2022)	Improve SSC by I4.0	Quantitative	56
13	Sajjad et al. (2024)	Customer behaviour towards circular products	Quantitative survey (n = 994)	30
14	Le et al. (2023)	Business model innovations (BMI)	Quantitative survey (n = 467 samples)	18
15	Dwivedi et al. (2023b)	Sustaining CE practices by disruptive technologies	Literature review	4
		Cluster 3 (Document 15)		
1	Kirbac et al. (2023)	Theoretical roots of CSC	Literature review	115
2	Neligan et al. (2023)	Digitalisation as a driver of circular business models	Quantitative survey (n-895)	109
3	Kuhlmann et al. (2023)	Circular business model innovation	Case studies (n = 2)	90
4	Cherrafi et al. (2022)	Digital technologies as an enabler to support sustainable supply chain management	Qualitative interviews (n = 15)	45
5	Rajala et al. (2018)	Develop more competitive closed-loop systems by business model innovators	Qualitative interviews (n = 35)	40
6	Carraresi and Bröring (2021)	How does business model redesign foster resilience in emerging circular value chains?	Case studies (n = 4)	40
7	Fernando et al. (2023b)	Digital technologies as an enabler of sustainable supply chain	Literature review	19
8	Garmulewicz et al. (2018)	Disruptive Technology (3D printing) as an Enabler of the Circular Economy	Case studies (n = 3)	16
9	Lapko et al. (2019)	Moving towards circular supply chain	Qualitative interviews (n = 10)	16
10	Vargas-Sánchez (2018)	Challenges and opportunities of Tourism industry from transition towards CE	Literature review	15
11	Unruh (2018)	Disruptive Technology (3D printing) as an Enabler of the Circular Economy	Qualitative interviews (n = 12)	13
12	Hosseini-motlagh et al. (2020)	Moving towards circular supply chain	Case study (n = 3)	5
13	Esposito et al. (2017)	Examine how the circular model is pushing companies to come up with disruptive technology	Literature review	2
14	Fraccascia (2019)	Mapping the physical and monetary flows resulting from Industrial symbiosis business model among companies	Case study (n = 2)	1
15	Talens Peiró et al. (2020)	Waste management and Critical raw materials	Case study (n = 1)	1
		Cluster 4 (Document 9)		
1	Ethirajan et al. (2021)	Risk assessment of adopting sustainable circular supply chain	Literature review	128
2	Bai et al. (2022a)	Risk assessment of adopting sustainable circular supply chain	Quantitative	116
3	Liu et al. (2022)	Improve SSC by disruptive technologies	Quantitative Survey (n = 277)	111
4	Yazdani et al. (2019)	Risk assessment of adopting sustainable circular supply chain	Quantitative	82
5	St. Clair et al. (2023)	Risk assessment of adopting sustainable circular supply chain	Observational workshop	73
6	Krstić et al. (2023)	Risk assessment of adopting sustainable circular supply chain	Quantitative	48
7	Sehnem et al. (2022a)	The role of startups to accelerate CE	Qualitative interviews (n = 50)	46
8	Sugg (2022)	Challenges to develop CE	Qualitative interviews (n = 3)	28
9	Giovanardi et al. (2023)	Role of the Internet of Things (IoT) to support CE principles	Qualitative interviews (n = 8)	15
		Cluster 5 (Documents 6)		
1	Nandi et al. (2021)	Investigate the relationship between the circular digital supply chains and Blockchain Technology (BT)	Qualitative interviews (n = 24)	133
2	Nandi et al. (2023)	Digital supply chain	Concept framework	132
3	Chaouni Benabdellah et al. (2023)	Investigate the role of BT in shaping circular digital supply chain	Literature review	77
4	Dwivedi and Paul (2022)	Provide a framework for digital supply chains	Qualitative interviews (n = 5)	58
5	Mukherjee et al. (2021)	Evaluate the significance of	Literature review	31

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Table 2 (*continued*)

Count	Author	Main topic	Method	Link strength
		blockchain-enabled supply chains		
6	Chandel et al. (2024)	Versatility of blockchain technology in disrupting business processes	Literature review	9
		Cluster 6 (Documents 2)		
1	Sehnem et al. (2022a)	Circular Entrepreneurs	Qualitative interviews (n = 50)	11
2	Cother (2020)	Circular Entrepreneurs	Quantitative Survey (n = 5)	2

been as widely referenced but are beginning to gain traction in the literature. Through density visualisation, we demonstrate the prominence of certain topics within CED literature while highlighting newer areas of inquiry that are likely to become more influential over time.

4.1.3. *Key topic areas and Cluster overlaps*

Bibliographic coupling allows us to group studies based on shared references, which helps to identify thematic clusters within the literature. Studies that cite similar references are likely to explore related topics. We identified seven key topics (from conceptual exploration to applied implementation challenges) present across different clusters (Table 3). Examining these overlapping themes provides a comprehensive perspective of CED research. This demonstrates how citation patterns reflect the content of the studies by aligning quantitative citation data with the qualitative themes emerging from the studies.

For instance, the roles of I4.0 are evident across clusters 2, 3, and 4, each examining different aspects of such technologies. Cluster 2 presents how I4.0 can be practically applied for operational advantages, while Cluster 3 expands the discussion to the broader impact of digital transformation on CBMs. CBM is also significant within Clusters 1, 2, and 3, with the most extensive discussion in Cluster 3. Improving SSC through I4.0 is a common thread that also overlaps in Clusters 2, 3, 4, and 5, with Cluster 5 entirely dedicated to exploring this intersection. Table 3 shows that 48 % of documents have undertaken digital tech and risk managing its adoption as a critical enabler for CED. At the same time, Cluster 4 focuses on the risks and strategic management involved in implementing I4.0 within supply chains. Such an overwhelming presence of I4.0 technologies reflects a keen interest in how digitalisation and innovation can redefine CED business models.

Similarly, there is widespread acknowledgement of stakeholders' role (Clusters 1, 2, and 4) in CE development. As Kirchherr et al. (2023) critiqued earlier, the recurring themes of barriers to CE development are present across Clusters 1 to 4. The overlaps also indicate current research trends and areas where further investigation could benefit CED. Thus, we traced the evolution of these research themes by connecting the citation frequency with the substantive content trends in CED research. We discussed these themes in detail in the following content analysis section.

While the clustering and topics presented in Tables 2 and 3 group documents based on thematic areas, a temporal perspective reveals how key research topics have evolved in response to external factors and technological advances (Table 4). For example, early works like Esposito et al. (2017) and Unruh (2018) laid the groundwork by examining how disruptive technologies, such as 3D printing, reshape CBMs. These early studies focused on the theoretical potential of digital innovations in circular practices. By the early 2020s, CED research evolved to address global challenges like climate change, trade wars, and geopolitical conflicts, exposing the fragility of global supply chains.

This period, from 2020 to 2022, saw a shift toward the practical application of I4.0 technologies, such as blockchain, AI, and IoT, in enabling circular practices. Studies by Bai et al. (2022b) and Gupta & Singh (2021) exemplify this shift, as they examined how digital technologies enhance supply chain resilience and mitigate reliance on global value chains. The increased importance of I4.0 is reflected in Table 3, where disruptive technologies and I4.0 account for 38 % prevalence across Clusters 2, 3, and 5. This evolution also corresponds with policy-driven initiatives, such as the European Green Deal and China's Circular Economy Action Plan, which accelerated research into circular entrepreneurship (e.g., Sehnem et al., 2022a) and stakeholder engagement (e.g., Reike et al., 2023).

As the field continued advancing, the focus broadened to include risk management and supply chain resilience, especially in response to

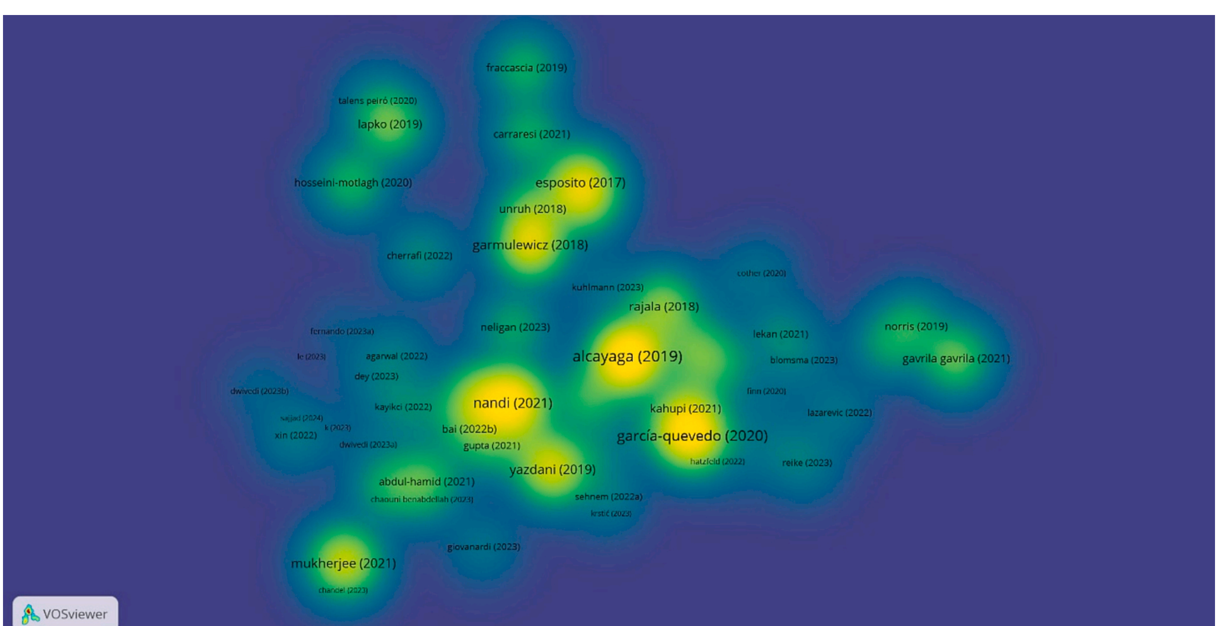

Fig. 4. Density visualisation according to link strengths (UoA: documents).

Table 3
Topic prevalence and cluster overlaps.

	Main topics	Prevalence of topic across all clusters (%)	Topic overlaps	Overarching themes
1	Impact of disruptive technologies and I4.0	38	Clusters 2 (34 %), 3(34 %), 4(10 %), 5(100 %)	Digitalisation as an enabler of CED
2	Conceptualisation of CED	18	Clusters 1 (10 %), 6 (100 %)	Concept of CED
3	CBM	15	Clusters 1 (22 %), 2(6 %), 3(60 %)	Key components of CED
4	Indicators (barriers, drivers, and challenges) to develop CE	10	Clusters 1 (26 %), 2 (6 %), 3(6 %), 4 (23 %)	Challenges to CED
5	Risk assessment of adopting digital technology	10	Cluster 4 (57 %)	Digitalisation as an enabler of CED
6	Role of stakeholders in CED	9	Clusters 1 (37 %), 2 (6 %), 4 (10 %)	Key components of CED
7	Impact of CE on sustainability	1	Cluster 1 (5 %)	Concept of CED

external shocks like the COVID-19 pandemic and the Russian invasion of Ukraine. Studies by Krstić et al. (2023) and St. Clair et al. (2023) are notable examples of CSC to mitigate risk in the food supply chain. This period, from 2023 to the present, is characterised by a growing emphasis on risk mitigation and circular entrepreneurship, as seen in Cluster 4 (57 % prevalence for risk assessment) and Cluster 5 (100 % overlap for digital supply chains and blockchain technology). Table 4 presents the temporal evolution of research topics in three different periods between 2017 to the present day.

4.2. *Content analysis: Attributes of CED research (RQ2)*

Our bibliometric analysis laid the foundation for the content analysis. In our content analysis, we discovered major research themes, geographical scope, methodological approaches and industries adopting CED. Fig. 5 displays these attributes of CED research.

4.2.1. *Key thematic focus of CED research*

Considering the thematic overlaps identified through bibliographic analysis, we categorise those aforementioned seven key topics (Table 3) into four overarching themes: (i) the concept of CED, (ii) key components of CED, (iii) digitalisation as an enabler of CED and (iv) challenges to CED.

The concept of CED (5 %) primarily focuses on defining its principles and positioning it within sustainability discourse. Early contributions, such as Blomsma et al. (2023a) and Kirchherr et al. (2023), establish the theoretical foundation, while research like Neligan et al. (2023) evaluates its environmental, economic, and social impacts. A significantly larger portion of the literature (40 %) (e.g., Carraresi and Bröring, 2021; Kirbac et al., 2023; Rajala et al., 2018) is dedicated to the key components that drive CED implementation. Central to this discussion are CBMs (21 %), which explore strategies for sustainable value creation across industries. Another essential component is the role of stakeholders (18 %) in accelerating CED adoption, highlighting the contributions of startups, policymakers, and consumers (Närvänen et al., 2021; Lazarevic et al., 2022). The role of digitalisation as an enabler of CED (35 %) is another dominant research theme. I4.0 technologies (10 %) are recognised for their role in improving efficiency, resource optimisation, and CSCs (Bai et al., 2022a; Dwivedi et al., 2023a; Gupta and Singh, 2021). Disruptive technologies (12 %), such as IoT and AI, are further explored in supply chain management to enhance sustainability (Dey et al., 2023; Karmaker et al., 2023). A growing area of interest is Blockchain Technology (BT) and Viable Circular Digital Supply Chains (VCDSCs) (14 %), where research investigates the role of blockchain-based traceability in reducing risks and improving supply chain transparency (Mukherjee et al., 2021; Nandi et al., 2021).

Despite these advancements, 20 % of research highlights challenges in CED adoption, with circular supply chain risks (10 %) and barriers to CE (10 %), such as policy gaps, technological constraints, and resistance to change (Ethirajan et al., 2021; Sugg, 2022). Recognising these challenges, we propose an I4.0-enabled CED framework that provides companies with a structured approach to mitigating these barriers in Section 4.3.

While these thematic insights provide a comprehensive understanding of CED research, the methodological approaches employed in the literature reveal notable limitations. The field remains heavily reliant on qualitative methods, particularly case studies (32 %) (e.g., Bai et al., 2022a; Kuhlmann et al., 2023), which primarily focus on firm-level and regional applications of CE principles. Research on barriers to adoption, stakeholder collaboration, and CBMs predominantly employs qualitative methods. In contrast, quantitative approaches (23 %)—including surveys (15 %) (e.g., Liu et al., 2022) and statistical modelling techniques such as structural equation modelling (SEM) (e.g., Dey et al., 2023) and stepwise weight assessment ratio analysis (SWARA) (e.g., Yazdani et al., 2019)—have been used to assess the impact of I4.0 and risk factors associated with CE adoption. However, the lack of longitudinal studies and big data analytics restricts our ability to track CED adoption over time and evaluate its long-term impact across industries.

Table 4
Temporal evolution of research topics according to external influences.

Time period	Key research topics	External influences	Representative studies	Focus area	Number of articles
2017–2019	Conceptualisation and Early Adoption of CED	Early environmental awareness and focus on resource efficiency and sustainable business practices.	Esposito et al. (2017), Lapko et al. (2019), Rajala et al. (2018)	Examining how disruptive technologies (e.g., 3D printing) enable circular models. Mapping the early adoption of CBMs.	10
2020–2022	Technological Disruption (Industry 4.0) and Circular Business Models (CBMs)	Political instability (e.g., trade wars and geopolitical tensions), COVID-19 pandemic, regulatory shifts (e.g., the European Green Deal and China's Circular Economy Action Plan), climate change, and resource scarcity.	Bai et al. (2022b), García-Quevedo et al. (2020), Närvänen et al. (2021)	Investigating how Industry 4.0 technologies (e.g., AI, blockchain, IoT) support CE and enhance circular business models. Focus on stakeholder engagement and barriers to CE adoption.	33
2023 – Present	Risk Management and Supply Chain Resilience	The need for resilient CSC supported enabled by I4.0 as the result of geopolitical conflicts (e.g., the Russian invasion of Ukraine), the COVID-19 pandemic, and environmental crises (e.g., climate change and disaster-related disruptions)	Krstić et al. (2023), St. Clair et al. (2023)	Addressing risks in circular supply chains, particularly in response to geopolitical events and COVID-19. Exploring how blockchain and other digital technologies mitigate supply chain risks.	25

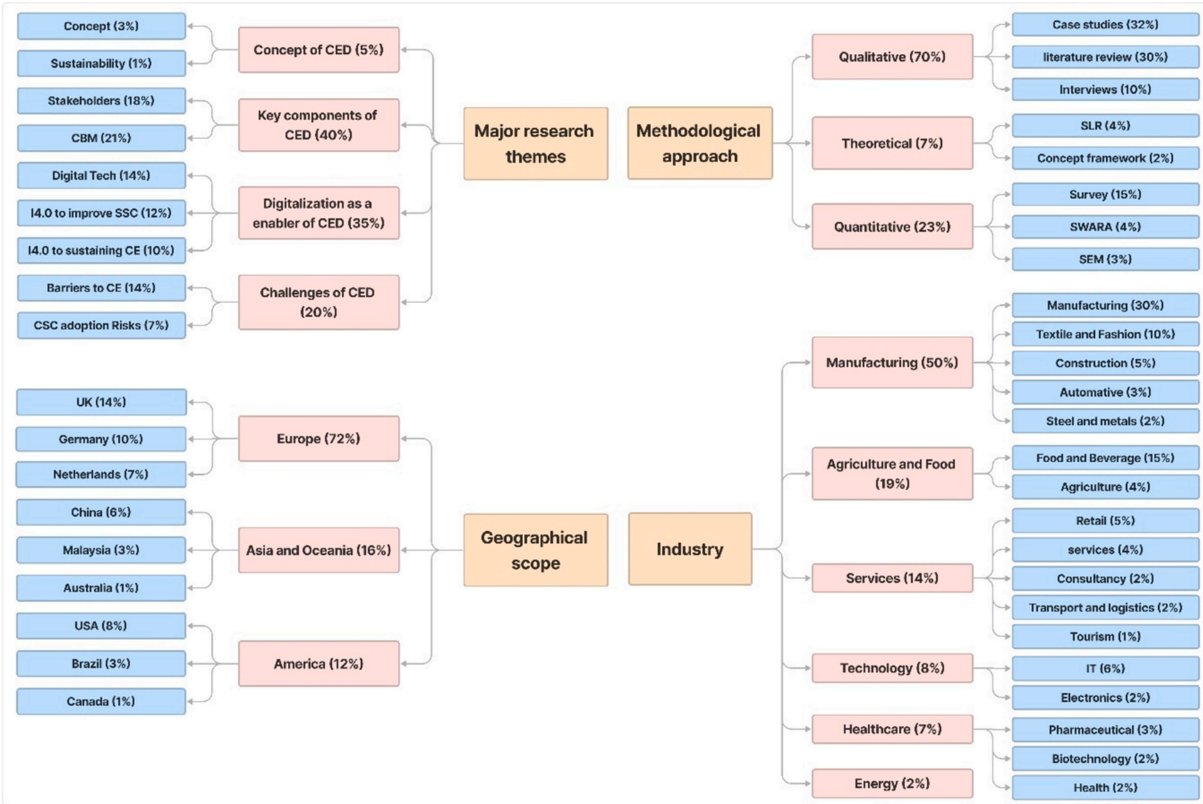

Fig. 5. Main themes and subtopics, geographic scope, industry, and methodology with their frequency.

4.2.2. *Geographic scope and regulatory influence*

Our geographic scoping assessment positions Europe (72 %) as the leader of CED research. We identified three critical elements for Europe's success so far: (i) institutional environment, (ii) academia-industry collaboration, and (iii) favourable consumer attitude to sustainable products (Julkovski et al., 2023). Europe's advanced policy frameworks, such as the European Green Deal, Right to Repair, Ecodesign for Sustainable Products Regulation (ESPR) and the Circular Economy Action Plan (European Commission, 2023), have established a fertile ground for research and innovation. European academic institutions have also contributed a substantial volume of literature, as indicated by thought-leading publications (e.g., Hatzfeld et al., 2022; Kuhlmann et al., 2023; Närvänen et al., 2021), and collaborated with industry to support the practical application of research findings. And a cultural shift toward sustainability pivots consumer preference for more sustainable products and services. The regulatory push and pull factors (e.g., social expectations) create a robust framework for CED across various European industries.

Despite initial concerns that the UK's departure (Brexit) from the EU might slow its progress towards circularity (Horton, 2024), the reality has shown continued commitment and adaptation to CE principles. For example, the UK has actively maintained its environmental standards by implementing the Circular Economy Package (CEP), which was adopted while still a member of the EU. The package includes directives addressing recycling and waste reduction through sustainable product design and consumer behaviour. The UK government has made only minor technical adjustments to these EU directives to ensure compliance within its own legislative framework (Gov.UK, 2020). The pioneering work of the Ellen Macarthur Foundation, as the world-leading circular think tank, also supports the UK's soft power in global sustainability policy. While it is inspiring to observe the academic stride of Asia and Oceania (16 %) (e.g., Cother, 2020; Kayikci et al., 2022) for circularity, the lag in the Americas (12 %) (e.g., Kahupi et al., 2021; Rajala et al., 2018) is evident. This variation in regional engagement with CE principles is also reflected at the industry level. In the following section, we examine how CE research is distributed across industries, highlighting key areas of focus, emerging trends, and gaps that warrant further investigation.

4.2.3. *Sectoral trends in circular economy disruption research*

The distribution of CED research across industries presented in Table 5 reveals a heavy concentration in manufacturing (50 %), particularly in general industrial production (30 %), where circularity is explored in materials reuse, industrial waste reduction, and digital supply chain integration. While sectors like textile and fashion (10 %) and construction (5 %) are gradually adopting circular strategies. However, the automotive industry (3 %) is trying to reduce its ecological footprint by recently moving to circular design principles, electrification, and integrating sustainable materials in vehicle manufacturing (Ahuja et al., 2020). Key pieces of legislation (e.g., the Resource Conservation and Recovery Act) in the automotive industry are also paving the path for circularity. However, caveats exist as these focus on the environmental aspects of recycling End-of-life vehicles (ELVs) but do not specifically impose formal requirements on steel recycling (World Economic Forum, 2024). Similarly, steel and metals (2 %) remain underexplored despite their significant environmental impact.

Agriculture (4 %) and food (15 %) are the second most (19 %) evaluated industries (e.g., St. Clair et al., 2023). Among others, services (14 %) (Cherrafi et al., 2022), technology (8 %) (Van Opstal and Borms, 2023), and healthcare (7 %) (Carraresi and Bröring, 2021) are prominent. The energy industry, however, is evaluated in only 2 % of the publications (Finn et al., 2020). Future CE literature should focus on this issue as the most significant contributor to environmental pollution. The uneven distribution of research across industries indicates a strong focus on tangible production processes, while service-oriented and highly regulated industries lag behind.

Building on the thematic and sectoral insights discussed in this section, it is essential to examine how the key components and challenges of

Table 5
Main themes of CED research.

Industry	Focus areas and representative references
Manufacturing (50 %)	General Manufacturing (30 %) – CE adoption in industrial production (Kuhlmann et al., 2023; Bai et al., 2022b; Liu et al., 2022; Karmaker et al., 2023; Dey et al., 2023). Textile & Fashion (10 %) – Circular strategies in textile and apparel industry (Reike et al., 2023; Sugg, 2022; Saha et el., 2021; 2024). Construction (5 %) – Sustainable materials and circular practices (Ethirajan et al., 2021). Automotive (3 %) – CE in vehicle production and recycling (Rajala et al., 2018; Cherrafi et al., 2022; Unruh, 2018). Steel & Metals (2 %) – Recycling and reuse in metal production (Piyathanavong et al., 2022; Nandi et al., 2021).
Agriculture and Food (19 %)	Food & Beverage (15 %) – CE in food production and waste reduction (St. Clair et al., 2023; Kayikci et al., 2022; Närvänen et al., 2021; Julkovski et al., 2023). Agriculture (4 %) – CE applications in sustainable farming (Yazdani et al., 2019; Krstić et al., 2023; Mukherjee et al., 2021).
Services (14 %)	Retail (5 %) – Sustainable retail practices and circular supply chains (Gavrila Gavrila and de Lucas Ancillo, 2021; Andersson and Buser, 2022; Van Opstal & Borms, 2023) General Services (4 %) – CE integration in various service-oriented businesses (Neligan et al., 2023; García-Quevedo et al., 2020). Consultancy (2 %) – CE in consulting firms and business advisory (Cherrafi et al., 2022; Dwivedi et al., 2023a; Dwivedi and Paul, 2022). Transportation & Logistics (2 %) – Role of CE in logistics and supply chain efficiency (Dwivedi et al., 2023a). Tourism (1 %) – Sustainability in tourism and hospitality (Cherrafi et al., 2022).
Technology (8 %)	IT Industry (6 %) – Digitalization and CE principles in IT (Sehnem et al., 2022a; Van Opstal & Borms, 2023). Electronics Industry (2 %) – Circular strategies in electronic waste management (Cherrafi et al., 2022; Unruh, 2018)
Healthcare (7 %)	Pharmaceuticals (3 %) Circular models in pharma industry (Cherrafi et al., 2022) Health (2 %) – CE implications in healthcare services (Sehnem et al., 2022a). Biotechnology (2 %) – Sustainable practices in biotech (Sehnem et al., 2022b; Carraresi and Bröring, 2021).
Energy (2 %)	CE applications in sustainable energy practices (Finn et al., 2020).

CED manifest across different industries as sector-specific dynamics shape the adoption, implementation, and scalability of circular strategies. While CBMs (21 %) and stakeholder involvement (18 %) are widely recognised as essential drivers, their implementation differs by industry. For instance, manufacturing and technology sectors emphasise resource optimisation and waste reduction, whereas fashion and retail focus on reuse and resale platforms. Similarly, stakeholder roles vary, with public authorities and policymakers playing a dominant role in highly regulated sectors such as healthcare and energy, while consumer engagement is more critical in the retail and food industries.

Conversely, challenges in CED adoption (20 %), such as CSC risks (10 %) and structural barriers (10 %), manifest differently. Industries with complex supply chains, such as automotive and electronics, face higher risks due to technological limitations and fragmented value chains. In contrast, agriculture and food industries struggle with policy gaps (e.g., lack of standardised regulations on food waste valorisation and secondary raw materials) and infrastructural barriers (i.e., limited cold chain logistics for food redistribution and inadequate waste processing facilities) that hinder scalability. Moreover, while technology-intensive sectors (e.g., logistics, IT) leverage I4.0 technologies to mitigate these risks, traditional industries (e.g., construction, steel) lag due to capital-intensive transitions and regulatory uncertainties. These variations highlight the necessity of industry-specific CED strategies, which our I4.0-enabled CED framework (section 4) seeks to address by providing sector-tailored adaptation pathways.

4.2.4. Green innovation for CED

Green innovation (i.e., business model, product, and process) is widely recognised as a key enabler of CED (Saha et al., 2024, 2025). Technology has emerged as the most dominant factor (Gupta & Singh, 2021; Karmaker et al., 2023) influencing green innovation, with 48 % of reviewed articles (Table 3). I4.0 technologies are essential for enhancing resource traceability, reducing waste, and optimising production efficiency (Garmulewicz et al., 2018). In CBM-driven sectors, digital platforms such as Blockchain-Enabled E-commerce Platforms (BEEP) are already being used to improve consumer trust and transparency in the second-hand and refurbished goods market (Jain et al., 2022). Companies such as Amazon Renewed, Laptops Direct, and Back Market demonstrate how blockchain and digital certification systems can enhance market confidence in pre-owned electronic goods, promoting circular consumption (Passingham, 2024).

Despite these advancements, several critical barriers hinder the scalability of green innovations. Financial constraints remain the most significant challenge, limiting firms' ability to invest in digital infrastructure and advanced sustainability solutions (Ethirajan et al., 2021). Beyond financial limitations, technological barriers (e.g., limited access, expertise, and digital infrastructure) prevent many firms, particularly SMEs, from adopting circular innovations at scale (Narula et al., 2023).

An often-overlooked but equally significant barrier is the negative perception of digitalisation and green innovation within organisations. Decision-makers frequently resist I4.0 adoption due to uncertainties regarding its tangible benefits (Piyathanavong et al., 2024). The perception that digital circular strategies require high initial investment, complex integration, and uncertain returns leads many firms to delay or abandon digital transformation efforts (Kandasamy et al., 2023). Additionally, cultural and organisational inertia within industries slows down the shift toward circular and digitally enabled business models (Kayikci et al., 2022).

4.3. A framework for I4.0 technology enabled CED for turbulent times (RQ3)

The increasing complexity and volatility of global markets, exacerbated by environmental concerns and geopolitical disruptions, necessitate a structured, technology-enabled framework for sustaining CED. Drawing on insights from our bibliometric and content analyses, our framework synthesises the seven key topics derived from the bibliometric analysis and the four overarching themes categorised from the content analysis (Table 3). Our framework in Fig. 6 presents that leadership support, digital infrastructure, organisational resilience and willingness have a bidirectional relationship and are antecedents to adopting I4.0. At the same time, stakeholder engagement and consumer perception mediate how I4.0 influences CED. Sustainability policies and regulations act as moderators that can either accelerate or hinder the effectiveness of I4.0 technologies in achieving CE goals.

The framework is grounded on well-recognised technology acceptance theories, e.g., the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Davis, 1993; Kiel et al., 2017), since negative perceptions and insufficient proof of tangible advantages (Piyathanavong et al., 2022) are critical hindrances for adopting I4.0. The technology acceptance theories help us understand the extent to which individuals within organisations recognise the benefits of adopting I4.0 to enhance CE practices. This will also allow us to identify how performance and effort expectancies, social influence, and facilitating conditions will influence the adoption of our proposed model.

4.3.1. Leadership support for digital infrastructure development

The successful adoption of I4.0 in CE practices depends on the

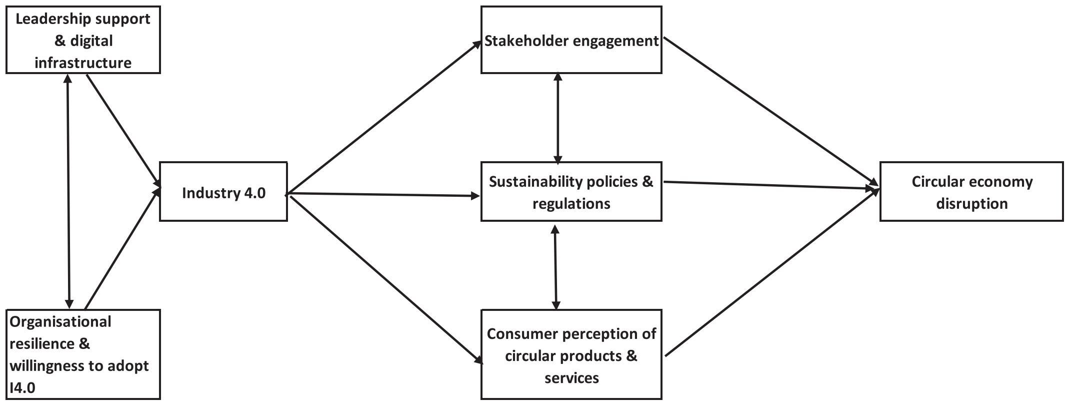

Fig. 6. I4.0 enabled CED framework for turbulent times.

interplay between leadership support and digital infrastructure development. Leadership provides the strategic vision and policy alignment necessary to drive digital transformation while fostering stakeholder collaboration to integrate businesses, policymakers, and supply chain partners into the transition toward circularity (Kuhlmann et al., 2023). Effective leadership becomes even more essential in adapting corporate governance structures to balance legacy systems with technological innovation in uncertain economic and geopolitical landscapes to mitigate regulatory and operational risks (Henry et al., 2020; 2023). Moreover, as disruptions expose vulnerabilities in traditional linear supply chains, leadership's willingness to champion digital transformation is crucial for deploying enabling technologies for operational agility and resilience (Rusch et al., 2023).

At the same time, digital infrastructure serves as the technological foundation that operationalises CE strategies by enhancing transparency and resource optimisation. I4.0 solutions improve supply chain resilience, minimise waste, and enhance material traceability (Dwivedi et al., 2023a). Additionally, 3D printing and digital platforms facilitate production reconfiguration, reducing resource dependency and promoting sustainable supply chain strategies (Fernando et al., 2023b).

However, disparities in digital infrastructure investment across industries and regions exacerbate inequalities in CE adoption (Dey et al., 2023). To eliminate such inequalities, cross-sector collaboration and targeted investment strategies must be implemented to ensure the scalable and equitable implementation of I4.0 technologies. In this context, leadership must proactively mobilise financial and policy resources to bridge digital infrastructure gaps and enhance industrial resilience against global disruptions.

4.3.2. Mediating role of stakeholder engagement and consumer perception

Collaboration among key actors (e.g., startups, entrepreneurs, public authorities, and businesses) ensures that digital transformation in CE is not only technologically feasible but also scalable and resilient to external shocks. Startups and entrepreneurs are particularly vital in pioneering new CBMs and integrating I4.0 solutions into CE practices. Their innovation drives adaptability, and without their active participation, digital transition efforts remain fragmented and difficult to implement at scale (Närvänen et al., 2021).

Similarly, businesses and supply chain actors drive the large-scale implementation of smart technologies to enhance efficiency, resource optimisation, and transparency. These capabilities are essential for helping industries stay resilient and adaptable in the face of economic and geopolitical turbulence. On the other hand, public authorities and policymakers further shape this landscape by designing sustainability policies and economic incentives that enable smoother transitions to I4.0-driven circularity (Reike et al., 2023). In uncertain regulatory environments, strong institutional support helps businesses overcome the risks associated with investing in digital CE solutions.

Beyond stakeholder engagement, consumer perception of circular products and services is another key mediator influencing the market acceptance of digitally enabled CBMs. Firms may struggle to scale their solutions effectively if consumers perceive circular offerings as lower quality, unreliable, or expensive (Saha et al., 2024, 2025). Technologies such as blockchain-based traceability systems and AI-driven transparency tools can help alleviate these concerns by providing verifiable product histories, ensuring quality assurance, and enhancing consumer trust in refurbished, remanufactured, or subscription-based circular goods. This is particularly relevant during geopolitical disruptions, where resource scarcity and supply chain instability make consumer trust in circular alternatives.

4.3.3. Sustainability policies & regulations as a moderator for I4.0-enabled CED

Sustainability policies and regulations serve as moderators, either accelerating or hindering the effectiveness of these technological advancements. Well-designed policy frameworks provide incentives, enforce compliance, and establish standardisation (Dey et al., 2023). For example, Europe's right-to-repair laws and eco-design regulations have incentivised businesses to integrate with CE standards. In contrast, policy gaps, misaligned regulations, or a lack of enforcement create barriers for firms attempting to integrate digital solutions (Saha et al., 2021, 2025). This contrast is particularly noticeable in the U.S. automotive industry (mentioned earlier), where policy influence on circularity and digital adoption remains inconsistent.

Moreover, regulatory inconsistencies across global markets create adaptation challenges for multinational firms, particularly during turbulent times when policy shifts and economic uncertainties further complicate the implementation of I4.0-driven circular practices. These disparities highlight the need for globally coordinated policies to ensure that firms across different economies can effectively leverage I4.0 to navigate turbulent times.

4.3.4. Applicability of the I4.0-enabled CED framework

Our framework can support national economies in turbulent times as it employs insights into technology acceptance and implementation dynamics. By reducing dependency on imported raw materials, CED promotes reusing, refurbishing, and recycling existing materials. However, the proposed framework requires comprehensively mapping various I4.0 technologies to specific sustainability goals (e.g., economic resilience, social equity, and environmental restoration) to ensure that each technological application directly contributes to one or more sustainability objectives. For example, adopting blockchain and AI can provide real-time supply chain transparency during geopolitical conflicts to reduce dependency on vulnerable global supply chains (e.g., the impact of the Iran-Israel war and the Russian invasion of Ukraine's energy markets). Similarly, IoT can improve resource tracking and operational resilience during environmental crises, such as natural disasters that disrupt supply chains. Such mapping exercises can deal with negative perceptions and criticisms regarding the clear benefits of the I4.0-enabled CED. Thus, the framework provides practical pathways for businesses and policymakers to implement I4.0 technologies effectively for tangible improvements across various dimensions of sustainability.

For the scalability and practical applicability of our framework, we propose a modular adaptation approach that accommodates various enterprise scales, industry sectors, and regional economic conditions. For instance, a small textile manufacturer in Bangladesh might deploy the framework for supply chain transparency and waste reduction, while a large electronics producer in China may integrate advanced AI and blockchain to enhance product lifecycle management and comply with strict environmental regulations for its European export markets.

Managers can begin with a stakeholder analysis to identify all relevant parties affected by or involved in the framework's implementation. This should be followed by a cost-benefit analysis to evaluate the economic feasibility and potential environmental benefits of adopting the framework. Based on these analyses, the framework must be piloted in targeted sectors under real-world conditions. These pilots would serve as a basis for refining the framework and demonstrating its efficacy before wider application. This tiered adaptation allows the framework to be customised and applied flexibly according to organisational contexts. It is envisaged that innovation and competitiveness delivered by such a framework can reduce local industries' geo-political shock exposure as they adapt to resource fluctuations and market dynamics.

5. Discussion

Our bibliometric study demonstrates the multidimensional and fragmented nature of the academic research on CED. Through various clustering, we observed that recurring themes such as the impact and risk management of I4.0 and stakeholders' role in CED are becoming prominent, while pioneering earlier research focused on conceptualisation, impact assessment, promoting CBM and identifying drivers and challenges to CED. We also find Sarkis J., Kirchherr J., Gunasekaran A., Ivanov D., and Mangla S.K. as thought leaders in advancing academic knowledge in CBM, SSC, and the impact of I4.0 to support circular strategies.

Furthermore, the findings solidify Europe's position as the leader of CED research. It appears that significant regulatory push and stakeholder engagement in sustainability discourse have successfully directed European academia and industry towards a more circular path. The notable academic engagement from Asia (and in particular from China) is inspiring for a sustainable future, given this region's critical role as a global manufacturing hub. In terms of industry, manufacturing and agriculture are rightly ahead of assessing CED due to their significant environmental footprint and socio-economic contributions.

5.1. Pathways for academic growth in CED research

Our assessment suggests that the trajectory of CED research is significantly shifting from foundational conceptualisations towards a more dynamic integration of advanced technologies and stakeholder involvement. The noticeable trend toward exploring the implications of disruptive technologies and I4.0 within the CE framework will increasingly focus on how these cutting-edge technologies can be harnessed. This will involve understanding and engaging diverse stakeholders, from policymakers to consumers, to eliminate negative perceptions of I4.0 and ensure that ethical and judicial use of these technologies is broadly supported and successfully implemented for CED.

We also shortlist three key areas (circular entrepreneurship, technological risk management, and firms' resilience in adopting CE) in which academic growth is expected for speedy and successful CED. The works of Carraresi and Bröring (2021), Ethirajan et al. (2021), and Norris (2019) can be foundational for future research in these areas. We also suggest that future research focus more on the service, health care, and energy industries. One critical aspect of our finding is limited research (8 %, Fig. 5) on circularising the IT industry which consumes substantial energy and generates e-waste.

As the field evolves, there is a growing emphasis on the practical implementation of CBMs and the operational challenges associated with scaling them. One major criticism is their excessive reliance on subsidies, raising concerns about long-term viability (Bodenheimer et al., 2022). However, some circular businesses are proving that scalability and profitability are achievable, as seen in Vinted's recent success. The platform, a leader in the used fashion industry, reported its first-ever profit of €17.8 million, with revenue surging 61 % to €596.3 million—driven by the cost-of-living crisis, increasing environmental awareness, and high-profile social media endorsements (Hooker, 2024). This signals that CBMs can thrive under the right economic and social conditions. Given Europe's strong leadership in CED research, it is well-positioned to drive these evolving discussions and shape future industry strategies.

However, impactful research on these critical industries requires suitable and effective methodological approaches. The limited depth and breadth of data (Table 2) captured in this review may have contributed to the negative perceptions and lack of evidence of tangible benefits observed earlier by Piyathanavong et al. (2022). Similar to the generalisability and applicability question, limited data hinder the theorisation process of CED research across various dimensions. As analytical models used in the reviewed literature integrated multiple variables and complex relationships among them, small data may not have provided enough information on all relevant variables or their interactions, leading to oversimplified models that fail to capture the complexity of the real-world CED.

5.2. Circular economy disruption (CED) for a turbulent world: Our contributions

Snyder (2019) presented three limitations (methodological transparency, restrictive literature search, and underutilisation of data) in review studies. From the onset, our effort was to eliminate such limitations from our review. Therefore, we have meticulously documented each step of our literature review process for clarity and replicability of our study. Accordingly, we have included various data visualisations and provided thorough explanations and discussions of their meanings. This method enhances the comprehensibility of our findings, allowing readers to grasp the full implications of the data presented (Fan et al., 2022). To overcome the narrow literature scope and hegemonistic conceptualisation, we expanded our search to include a wider range of reputed journals and did not apply a time span. Such a rigorous approach ensures that our review captures a more comprehensive range of insights and contributes to a deeper understanding of the field.

Our method synergistically combined the bibliometric and content analysis to comprehensively examine selected literature. The bibliometric analysis allowed us to map out the research landscape, highlighting key focus areas and emergent themes in the vast corpus of CE literature. Key findings from this stage, such as prominent authors, influential papers, and the prevalence of specific topics, directly informed the subsequent content analysis phase, in which we qualitatively interpret the theoretical implications and practical suggestions. This iteration between the two methods ensured that insights from one phase reinforced and validated findings from the other. For instance, identifying Cluster 5 on 'disruptive technologies and I4.0' in the bibliometric phase led to a targeted qualitative review of articles (e.g., Nandi et al., 2021, 2023) within that cluster to understand the theoretical underpinnings and practical applications being discussed. The interlinking of quantitative and qualitative findings ensured a transparent reporting of processes and enhanced the reliability and credibility of our findings.

Due to its thematic scope and methodological affinities, our study is broadly convergent with recent reviews (e.g., Hunger et al., 2024; Garrido et al., 2024; Manikandan et al., 2024). Our methodological approach (e.g., Bak et al., 2023) and findings on green innovation (e.g., Narula et al., 2023) and digital technologies (e.g., Ai et al., 2024).

Yet, our contributions are unique and multifaceted. First, the bibliometric review identified the research trend, its current trajectory, key thematic areas, thought leaders, adopted methodological approach, and emerging areas of CED research. Emerging researchers may use these insights to align their studies with the evolving dynamics of the field. Highlighting the strengths and limitations of existing methodological approaches, we inform future studies to refine their research strategies for enhanced robustness. Besides, our review helps inspire collaborations and mentorships with leading figures in the field. Our findings can also aid academic and funding institutions in strategically allocating resources to the most promising areas of CE research to promote academic growth and more impactful collaboration with industries.

Secondly, this review consolidates and synthesises existing research on the disruptive potential of CE practices across various industries, highlighting how these practices can deliver environmental benefits as well as respond effectively to geo-political crises. This aligns with emerging views (Hartley et al., 2024) on the need for a broader conceptualisation of CED that extends beyond environmental sustainability to include its socio-economic impacts.

Most importantly, this review makes a significant theoretical and practical contribution by introducing an I4.0-enabled CED framework (Fig. 6) that redefines how CE models can operate amidst socio-economic and geopolitical turbulence. Traditional CE models primarily focus on environmental and social dimensions, often overlooking the disruptive impact of geopolitical and economic instability. In contrast, our proposed framework integrates advanced digital capabilities while embedding stakeholder dynamics to enhance adaptability, resilience, and scalability. Beyond its theoretical advancements, it offers businesses and policymakers a robust, actionable guide to drive sustainability-oriented innovation and long-term competitive advantage in an increasingly volatile world.

6. Conclusion

Technology has always driven transformation, but it is the convergence of external forces that shapes how societies respond to innovation. The adoption of I4.0 technologies for CED is no different. Our review demonstrates that the CE is not just a theoretical model but a practical approach for addressing pressing global challenges, from environmental degradation to resource scarcity. Yet, just as historical transformations required tools to drive change, the circular economy today relies on the support of I4.0 technologies to realise its full potential. These technologies—blockchain, AI, IoT, and others—are not ends in themselves but essential enablers that help organisations implement circular models more effectively.

Looking ahead, our proposed I4.0-enabled CED framework provides a practical guide for implementing circular economy strategies that are both adaptive and scalable. The framework shows how circular business models can thrive through careful integration of digital tools while addressing broader sustainability goals. As economies around the world seek ways to become more sustainable, our framework offers a pathway toward resilience and long-term competitiveness, especially in times of environmental, social, and geopolitical turbulence.

CRediT authorship contribution statement

Krishnendu Saha: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Atefeh Karami:** Writing – original draft, Investigation, Formal analysis, Data curation. **Veronica Ohah Linus:** Writing – original draft, Investigation, Formal analysis.

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.clscn.2025.100227.

Data availability

Data will be made available on request.

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