Digital technologies and the circular economy: charting a shared journey toward sustainable development

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Abstract

Purpose – The research aims to identify the practical benefits of implementing Digital Technologies (DTs) and the Circular Economy (CE) for Sustainable Development (SD) by enabling informed decision-making.

Design/methodology/approach – The research consists of 148 articles, including quantitative (61), qualitative (52) and literature review studies (35), covering various fields such as ecology, supply chain management, marketing and circular business models, sourced from WOS, Scopus and Direct Science. Science-mapping techniques have been employed to analyse citations in published articles, measure their impact and identify leading and emerging trends in the literature.

Findings – The study demonstrates that artificial intelligence (AI) is developing intelligent devices and processes that analyse large datasets to identify patterns, verify and report on organisational activity, enabling real-time decision-making. Furthermore, companies that excel in CE principles – a system focused on minimising waste and making the most of resources – are more likely to engage with Industry 4.0, which refers to the integration of DTs such as the Internet of Things (IoT), automation and data exchange in manufacturing. This subsequently results in improved financial outcomes and more rational decision-making. In addition, the research highlights limited connections within Industry 5.0 – an industry phase emphasising collaboration between humans and machines – with a particular focus on CE and SD.

Originality/value – This research provides a unique overview in exploring DTs and CE across environmental performance, financial metrics, accounting relationships and the impact of computer-based analysis on decision-making, thus highlighting significant gaps in the literature. Moreover, this study offers practitioners interesting insights to improve financial outcomes, resource use, DT and CE adoption and decision-making processes.

Keywords Digital technologies, Circular economy, Sustainable development, Decision-making, Literature review

Paper type Literature review

1. Introduction

Environmental management aims to sustain society's environmental balance (Xiao, 2025) by meeting human needs, promoting resource development and conserving natural resources (Pearce and Turner, 1991; Long *et al.*, 2025). Current economic systems prioritise gross domestic product (GDP) and organisational gains but overlook negative impacts on global

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resources and issues related to sustainable management, such as environmental change, food security and biodiversity, which require a more practical approach (UNEP, 2021).

Digital technologies (DTs) and Circular economy (CE) offer advantages, including tracking product waste, transforming waste into resources, reducing resource use, reusing waste and products, redesigning products and reducing carbon emissions (Jørgensen *et al.*, 2023; Sànchez-Garcia *et al.*, 2024; Nazir *et al.*, 2025; Singh *et al.*, 2025; Fusillo *et al.*, 2025). The United Nations Environment Programme (UNEP, 2021) emphasises DTs and CE for sustainable growth, efficient resource allocation, precision agriculture and resource traceability.

Meanwhile, the European Commission (2019a, b) demonstrates that DTs and CE enhance resource profitability, generate employment and boost GDP through information systems, data analytics, innovative technologies, optimising production, reducing waste and improving economic, environmental and social outcomes (Long *et al.*, 2025). This study examines DTs, CE and SD in depth and develops a framework that integrates these concepts to support decision-making informed by the existing literature. It offers a systematic understanding of the key principles of DTs and CE for addressing sustainability and supporting decision-making. This systematic literature review (SLR) provides an overview of DTs related to CE for SD, using a transparent and scientific process to minimise bias through extensive searches and science-mapping techniques to analyse citations, impact, trends and emerging topics (Denyer and Tranfield, 2009).

Several issues contribute to the growth of this study, including increasingly complex environmental challenges affecting ecosystems, biodiversity and human health, which make sustainability efforts highly relevant. Furthermore, decision-makers often lack a holistic understanding of sustainability, which leads to ineffective decisions (Bakhsh *et al.*, 2024). Traditional decision-making processes hinder sustainability initiatives by not allowing immediate adjustments, especially in critical forecasting situations where accuracy is vital.

Although many decision-forecasting techniques are available (Alkaraan *et al.*, 2023), none incorporate DT and CE to reveal opportunities for business analytics. These interconnected factors highlight the necessity for further investigation into environmental protection, focusing on identifying gaps and developing a framework for applying DT and CE to decision-making. The study presents a framework that also consolidates various perspectives and theoretical viewpoints to help explain how DTs and CE can overcome SD challenges. Accordingly, the study poses the following research question.

RQ. To what extent can the relationship between DTs and CE support SD and enable informed decision-making?

This research is unique in exploring DTs and CE across environmental performance, financial metrics, accounting relationships and the impact of computer-based analysis on decision-making, thus highlighting significant gaps in the literature.

The study analysed 148 articles, evaluated the potential of DTs and CE as strategic tools for addressing climate change and resource management issues and emphasised their importance in high-risk decision-making. It makes a significant contribution to knowledge by identifying factors influencing DT adoption and proposing a decision-making framework. It offers practitioners an overview to improve financial outcomes, resource use, DT and CE adoption and decision-making processes, thereby strengthening the SD context. It highlights the connection between DTs and CE for sustainability and encourages future research and practice. Overall, it provides a scientific foundation for policy and industrial development, fostering informed decisions for sustainability. The study also focused on an accountability approach to support managers in adapting to market and environmental uncertainties and in enhancing operations. Furthermore, the study endorses policies requiring DTs and CE in sustainability strategies. The guidelines help policymakers recognise the potential of DTs and CE to enable a multidisciplinary future.

The paper is organised as follows: firstly, an introduction; secondly, definitions and an overview of DT, CE and SD; thirdly, findings and discussion; and ultimately, a conclusion, limitations, practical implications and future research.

2. Digital technologies

The concept of "digital technology" has received considerable attention from practitioners and scholars across disciplines such as engineering, information systems and management (Valenduc and Vendramin, 2017). However, no single widely accepted definition of DTs exists, as DTs' boundaries are rapidly evolving and it is difficult to provide a sound conceptualisation (Rossato and Castellani, 2020). According to Hinings *et al.* (2018), the term "digital" refers to the conversion of analogue information into the binary language by computers. Hence, digitisation has the potential to decouple information types from the storage, transmission and processing technologies (Alkaraan *et al.*, 2023). Digitalisation initiatives across business models, services, or products are creating new value-creating opportunities and revenues, as seen in Industry 4.0 (Garay-Rondero *et al.*, 2020; Agrawal *et al.*, 2025).

A digital platform is a shared set of services and architecture that supports complementary offerings (Awan *et al.*, 2021). Digital infrastructure comprises tools and systems characterised by communication, collaboration and computing capabilities that support innovation processes (Feroz *et al.*, 2023; Agrawal *et al.*, 2025). Specifically, these technologies involve connecting objects via Internet-connected equipment with sensors and actuators to develop new applications or improve existing ones (Nazir *et al.*, 2025). Most of the DTs studied are related to social media, mobile devices, analytics, cloud computing and IoT (Awan *et al.*, 2021). Notably, the growing pervasiveness of DT has drawn attention to so-called new-age technologies that fall under the Industry 4.0 or IoT paradigm (Jørgensen *et al.*, 2023) and scholars, researchers and practitioners have focused on the impacts of DTs within organisations, particularly on processes and structural effects (Nazir *et al.*, 2025; Agrawal *et al.*, 2025; Alkaraan *et al.*, 2023). The rise of new DTs enables firms to pursue new opportunities and integrate these technologies into their business models, resulting in positive financial and non-financial outcomes. In this regard, DTs provide value when companies unlock their embedded potential through their business models (Agrawal *et al.*, 2025; Alkaraan *et al.*, 2022, 2023) or when firms leverage such technologies to uncover new ways to create value (Nazir *et al.*, 2025). DTs play a key role in creating SD at the economic, social and environmental levels, triggering strategic reactions by organisations that employ DTs to change value-creation and value-capture mechanisms (Singh *et al.*, 2025).

2.1 Circular economy

The Ellen MacArthur Foundation (Ellen MacArthur and Heading, 2019) has substantially advanced CE practices across various domains, including sustainable design and formation. CE aims to maximise economic benefits and minimise pressure on non-renewable resources. CE is "beneficial for regenerative product or parts by purpose and plan" (EMF, 2012, p. 7) and considers the potential for crossovers within supply chains (Barnabè and Nazir, 2021, 2022).

CE is an economic framework based on the R principles: reduce, reuse, recycle, remanufacture, redesign and recover (Goyal *et al.*, 2021; Nazir and Doni, 2024). Reduce refers to the design stage of products, in which product producers are responsible for minimising the use of products or components (Barnabè and Nazir, 2021, 2022). Reuse is a non-destructive process that extends the lifespan of a second-hand item (Nazir and Doni, 2024) and retains a significant portion of its embodied energy. Recycling involves extracting secondary raw materials from end-of-life products (Nazir *et al.*, 2025). Implementing high-quality closed-loop recycling poses challenges compared with downcycling (European Commission, 2019a, b). Remanufacturing involves restoring used products to near-new quality through reprocessing or replacing components, thus maximising value recovery (Nazir and Capocchi, 2024). Redesign includes a form of reuse that involves minor operations before reusing the product (e.g. polishing, repackaging and refilling) (Barnabè and Nazir, 2021, 2022). Maintenance and repair extend a product's operational life by reducing or preventing downtime (Nazir and Doni, 2024).

In other words, the CE relies on circulating products or parts within the technical cycle at their maximum value for as long as feasible, using the following circular strategies (Barnabè and Nazir, 2021, 2022). Circular strategies encompass two dimensions (Hansen and Revellio, 2020): downstream circular service strategies, which focus on closing product life cycles to preserve value over time and upstream circular design strategies – such as designing for reparability – which modify a product's architecture, including physical goods, digital hardware and software, to enhance the effectiveness and capability of cycling. Progress towards a CE is crucial and DTs play a fundamental role (Fusillo *et al.*, 2025) in optimising material flows across value chain stages, enhancing energy efficiency and effectively managing supplies.

2.2 Sustainable development

The concept of SD has evolved over more than 30 years. The 1972 United Nations (UN) Conference on the Human Environment in Stockholm, Sweden, contributed to this evolution by emphasising that safeguarding the human environment is a vital part of the development agenda. Following that conference, the UN Environment Programme Secretariat was established to promote international environmental cooperation (Handl, 2012). Globally, countries began establishing and strengthening their environmental institutions. In 1970, the United States established the Environmental Protection Agency (EPA) to unify federal research, monitoring and enforcement of environmental laws and to supervise air, water and waste to protect human health.

Furthermore, the World Commission on Environment and Development published a report titled "Our Common Future", also known as the Brundtland Report, in 1987. This landmark document argues that establishing separate environmental institutions is not enough, as environmental issues are integral to all development policies. Since the phrase "sustainable development" gained prominence after the 1987 publication of Our Common Future, the report defines SD as "progress that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The next milestone in the evolution of SD was the 1992 UN Conference on Environment and Development in Rio de Janeiro, also known as the Earth Summit. Its main contribution was to recognise the equal importance of both environment and development.

Moreover, the UN Agenda 2030 was established in 2015 to broadly address the world's critical economic, social and environmental challenges, comprising 17 SDGs and 169 targets and to provide a global roadmap for tackling interconnected issues such as poverty reduction, inequality and climate action (UN, 2015). Recently, the European Green Deal, a significant initiative by the European Commission, has set sustainability targets and strategic directions (European Commission, 2019a, b). The main aims of these organisations are to create a system that supports environmental management strategies, such as cleaner production, pollution remediation and environmental management; identify overconsumption of resources worldwide and locally; and improve energy productivity (Nazir *et al.*, 2024).

Additionally, Industry 5.0 allows businesses to take positive steps towards more environmentally friendly operations (Ghobakhloo *et al.*, 2024) with greater access to data, more efficient technologies, and better-informed decision-making. Whether it's using renewable energy efficiently, ensuring their end-of-life products become part of the CE, or minimising waste, Industry 5.0 will help manufacturers protect the Earth for future generations (Kannan *et al.*, 2024). However, adoption meets challenges such as high initial investment, integration with existing systems, and workforce reskilling. Despite these obstacles, the transition to Industry 5.0 presents a vital opportunity for manufacturers who seek not only to adapt but to lead in sustainable innovation for years to come (Kannan *et al.*, 2024). However, the European Commission has stated that the fifth industrial revolution is already in progress. Like Industry 4.0, which focused solely on developing industrial production technologies to increase profitability and productivity. Industry 5.0 aims to acknowledge the global manufacturing sector's significant impact and leverage it to drive major societal change (Fraga-Lamas *et al.*, 2021). Industry 5.0 involves addressing climate change, enhancing conditions for human workers and making product lifecycle management more flexible and intelligent. Industry 5.0 does not replace 4.0; rather, it is a necessary evolution that balances the digital advancements of the fourth industrial revolution with the human need for purposeful, sustainable and resilient work (see Table 1).

Technological advances drove the fourth revolution; values will guide the fifth. Instead of solely innovating for profit and efficiency, new cyber systems will focus on making manufacturing more sustainable, human-centric and resilient. With the rise of the Internet of Things (IoT) and the growth of automation and artificial intelligence, connectivity among machines was a key focus of Industry 4.0 (Ghobakhloo *et al.*, 2024). In contrast, Industry 5.0 will prioritise enhanced collaboration between humans and machines through technologies. Alongside making industrial production more human-centric, Industry 5.0 will emphasise a better understanding and more effective addressing of customer needs – ranging from strengthening supply chain resilience to creating interactive products and improving the overall customer experience.

3. Findings and discussions

The SLR uses various systematic methods to answer the question: To what extent can the relationship between DTs and the CE support SD and enable informed decision-making? Initially, we focused on creating a systematic approach to collecting data and examining available published literature, including origin, titles, references and keywords (De Bellis, 2009) to identify specific research areas (Fetscherin and Usunier, 2012), represent measures and assess a particular field over time (Fetscherin and Heinrich, 2015). The research was

Table 1. Key differences between Industry 4.0 and Industry 5.0

Focus	Industry 4.0	Industry 5.0
Core Focus	Industry 4.0 focuses on technology (how to make machines smarter)	Industry 5.0 focused on humans (how technology can better serve humanity)
Human Role	In 4.0, humans are frequently supervisors or are sidelined by automation	In 5.0, humans are “cobots” (collaborative robots), partnering to combine human creativity with robot accuracy
Sustainability	Supports a more sustainable manufacturing process through essential decision-making	Industry 5.0 actively prioritises reducing carbon footprints, utilising renewable energy, and establishing circular economies
Customisation	Industry 4.0 facilitates mass production with some customisation	Industry 5.0 facilitates advanced, on-demand personalisation
Resilience	Industry 4.0 resilience highlights the need for production systems and supply chains to go beyond decision-making tools and ensure the availability of key organisational components	Industry 5.0 concentrates on creating resilient supply chains that can better endure crises through human-led, adaptable, and sustainable processes
Technologies	Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning, Big Data and Analytics, Cloud Computing, and Cyber-Physical Systems	Collaborative Robots (Cobots), Human-Centric AI, Digital Twins and Simulation, Sustainable Energy Systems: Technologies aimed at cleaner production

conducted within the field of business economics (see Appendix). Scientific mapping techniques were used to carry out the analysis (see Figure 1 below).

A fundamental method for scientific mapping is citation analysis, which assumes that citations reflect intellectual connections between publications, as one article cites another (Appio *et al.*, 2014). The more citations an article receives, the greater its impact. According to Hjørland (2013), co-citation analysis is a science-mapping technique that presumes that works frequently cited together share similar themes (Rossetto *et al.*, 2018). Co-citation analysis can then uncover the underlying ideas of a study and its thematic clusters (Liu *et al.*, 2015). More specifically, two articles are linked when one appears in the reference list of the other. Co-citation analysis, however, excludes current or specialised articles from its theme clusters and concentrates solely on highly cited publications. Co-citation analysis is suitable for business researchers aiming to identify key works and theoretical foundations (Donthu *et al.*, 2021).

Bibliographic coupling, instead, is based on the idea that two articles cite the same reference and share similar content (Kessler, 1963; Weinberg, 1974). Articles are grouped into thematic clusters based on standard references and the analysis is most effective when applied to a specific time period (Donthu *et al.*, 2021). When academics wish to explore broader themes and new developments, this type of analysis is often the most suitable. Furthermore, co-word analysis relies on "words." The study was conducted in the context of publications, with a particular focus on "keywords." If keywords are unavailable, the complete text, abstracts, or article titles are used to extract words. The purpose of this technique is to identify and share a thematic connection. However, when words are too general, it can be difficult to assign them to specific thematic groups (Chang *et al.*, 2015). Moreover, when words are used in multiple contexts, it is essential to understand the underlying relationships between them.

Therefore, co-word analysis is advisable to use as a complement to co-citation or bibliographic coupling analyses. When significant "words" from a publication's implications and future research directions are incorporated into the analysis, co-word analysis can anticipate future research on the subject. By first assessing the thematic coupling derived from previous techniques, co-word analysis can help elaborate on past trends (co-citation) and present trends (bibliographic coupling), as well as the future of a research field. Finally, co-

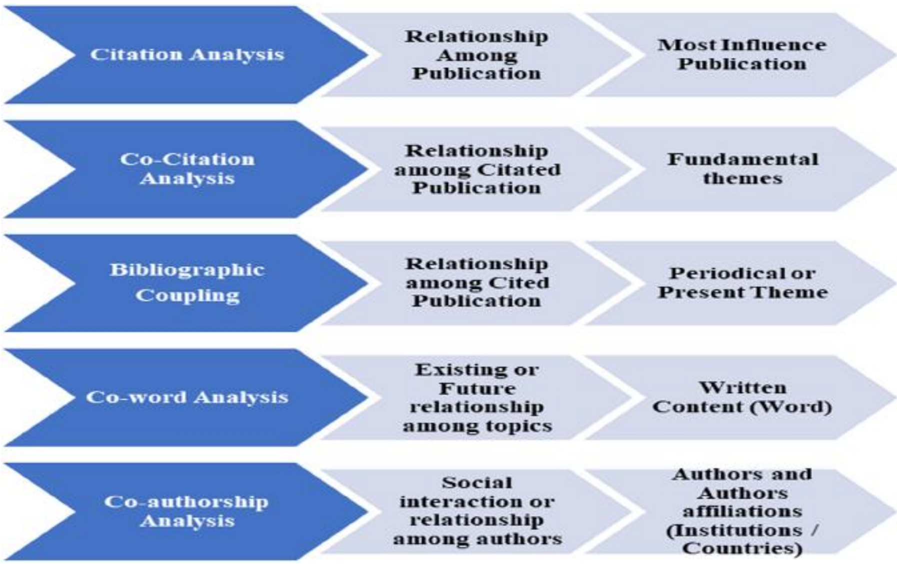

Figure 1. Mapping techniques. Source: Authors' collaboration

authorship analysis examines collaborations among researchers. Understanding how academics engage with one another is crucial, as co-authorship is a formal form of intellectual cooperation among researchers (Acedo *et al.*, 2006; Cisneros *et al.*, 2018). When scholars collaborate, significant advances can be achieved in the field of study. By implementing co-authorship research, we can identify which regions' collaborations are most prevalent and where research should be encouraged in other regions. It is also possible to specify the period during which collaborations grew, enabling the determination of the intellectual development trajectory.

To address the RQ, conducting an SLR and identifying the primary outcomes are beneficial. This analysis can evaluate the state of the evidence in a specific field by delimiting and rationalising the research problem (Donthu *et al.*, 2021). SLR differs from traditional narrative reviews in the sense that SLR adopts "a replicable, scientific and transparent process to minimise bias through exhaustive literature searches of published and unpublished studies and by providing an audit trail of the reviewer's decisions, procedures and conclusions" (Denyer and Tranfield, 2009). The rationale for SLR is to reduce bias that the researcher might introduce when evaluating evidence. In particular, research identifies a smaller set of publications within a larger pool of studies by analysing articles against predetermined criteria, enabling conclusions to be drawn.

These techniques aid in analysing published citations and articles to measure their impact, understand leading trends in literature (e.g. leading authors, journals), explore the conceptual structure of the literature (Donthu *et al.*, 2021) and identify emerging trends. The methods applied included: (1) Citation analysis, (2) Co-Citation analysis, (3) Bibliographic coupling, (4) Co-word analysis, (5) Co-authorship analysis and content analysis. For this purpose, VOSviewer is used to visualise research networks within the DTs, CE and SD literature. A series of charts, tables and figures accompanied by textual descriptions has presented the results, synthesising the data obtained and helping to answer the research question.

Table 2 illustrates the number of publications on DTs, CE and SD over the past decade. The figure shows that the number of publications is increasing annually, indicating an emerging research area. Recently, the highest number of articles was published in 2024, compared to other years, while from 2015 to 2019, the publication trend in this area remained steady. Citations reliably represent the impact of published articles, as well as the frequency with which papers are cited in other works (Rossetto *et al.*, 2018) and are used to establish the relationship. Move forward to publication as per the journal index.

Table 2. Year-wise publications

Year	Number of publications per year	Percentage of increment
2015	1	0.675675676
2016	1	0.675675676
2017	2	1.351351351
2018	2	1.351351351
2019	1	0.675675676
2020	3	2.027027027
2021	4	2.702702703
2022	16	10.81081081
2023	27	18.24324324
2024	71	47.97297297
2025	20	13.51351351
Total	148	100

$$\text{Average Article Citations in the Journal} = \frac{\textit{Total citations}}{\textit{Number of Artices}}$$

The study calculates citations for each journal by using the total citations of each journal's articles as the reference for citation counts, then dividing by the number of articles. Nevertheless, the Journal of Cleaner Production has more publications than others (see Figure 2). On the other hand, Business Strategy and the Environment rank second among publications. However, from a citation perspective, Business Strategy and Environment rank higher than those in the Cleaner Production Journal. That indicates that a few players have taken the lead in conceptualising this emerging topic; this finding suggests that research on the CE, DTs and SD may be far from saturated and there is significant room for improvement in terms of conceptual development and cross-fertilisation from other research fields (See below the 62% of articles published).

The research trends thus align with the theme of increased collaboration and its effects, as seen in the table of top publishing journals, which covers over 62% of the articles. The table includes papers introducing the concepts of DTs, CE and SD, primarily published after 2014. Table 3 lists the top publishing journals that cover over 62% of the articles and we have also included the Q1 SJR journals (see Figure 3).

Interestingly, India and Italy, countries that have published articles in the domain of DTs, CE and SD, reflect the efforts the countries have been taking since CE action plans (European Commission, 2020) and the Green Deal (European Commission, 2019a), inspiring not only new practices and evidence but also authors covering the geographical contexts and jurisdictional performances. While India has a considerable population, good universities and many scientists, it has only one more publication than Italy. According to the country articles' citation rankings, Austria ranks first, the United Kingdom second and China last. Articles published between 2014 and 2025 include comparisons between countries or continents, such as Europe and China, as well as between developed and developing countries. However, most of the countries belong to the European region. Move forward to the most influential authors (see Figure 4).

The citation analysis was used to identify the most influential scholars, and the following criteria were established in VOSviewer: an author must have at least 3 documents and 20

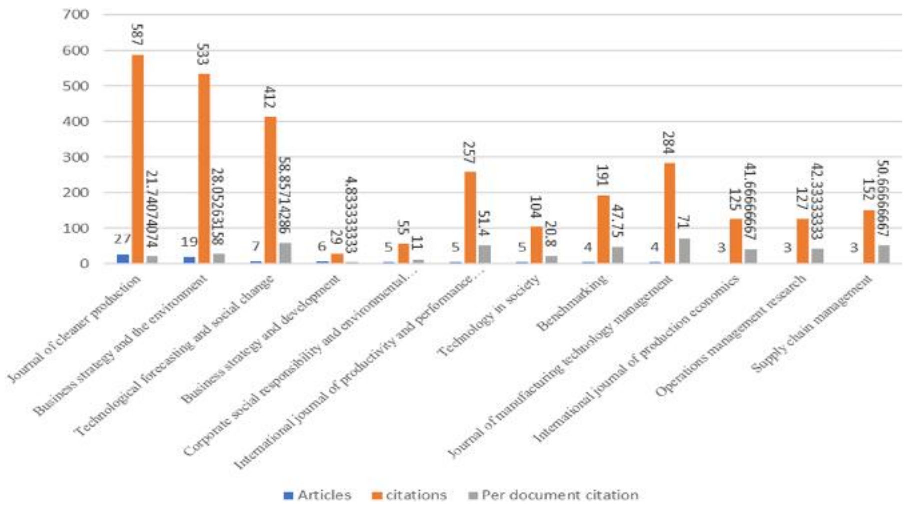

Figure 2. Publications per journal. Source: Authors' collaboration

Table 3. List of top publishing journals that cover over 62% of the articles

No	Source	Articles	Ranking ABS	SJR-Q	Publisher
1	*Journal of Cleaner Production*	27	1	Q1	Elsevier
2	*Business Strategy and The Environment*	19	3	Q1	Wiley-Blackwell
3	*Technological Forecasting and Social Change*	7	3	Q1	Elsevier
4	*Journal of Manufacturing Technology Management*	4	1	Q1	Emerald
5	*International Journal of Productivity and Performance Management*	5	1	Q1	Emerald
6	*Benchmarking*	4	1	Q1	Emerald
7	*Supply Chain Management*	3	3	Q1	Emerald
8	*Operations Management Research*	3	1	Q1	Springer Nature
9	*Corporate Social Responsibility and Environmental Management*	5	1	Q1	Wiley-Blackwell
10	*Technology in Society*	5	2	Q1	Elsevier
11	*Business Strategy and Development*	6	1	Q1	Wiley-Blackwell

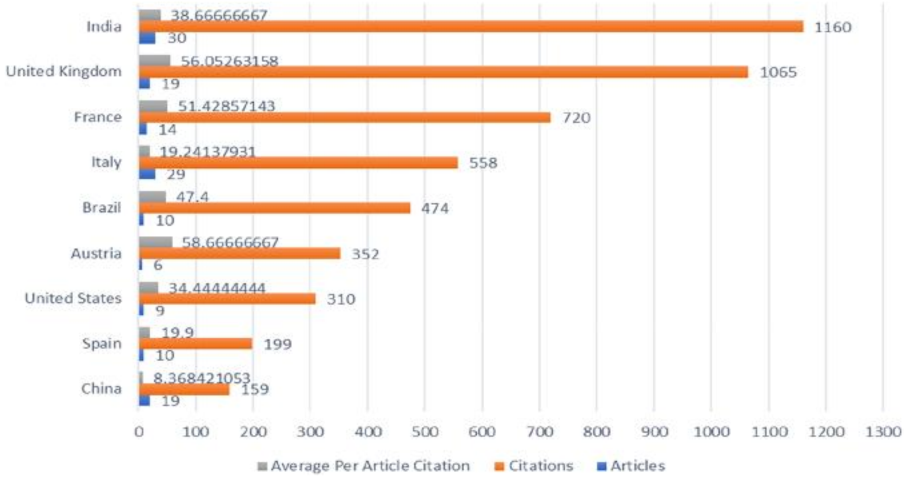

Figure 3. Country-wise articles published. Source: Authors' collaboration

citations. Out of 494 authors, 7 met the requirements. We found that scholar Hussainey has three publications in DTs, CE and SD, ranking first with 297 citations. In contrast, Baumgartner and Schoggl secured second place with 255 citations and three publications (as noted in the sole-author citations) (see Figure 5).

Individual authors' citations were analysed using authors as the unit of analysis. Therefore, the SLR established the following criteria: a minimum of 40 citations per author and a total of 20,330 authors. The study meets the threshold of 20, indicating that 20 authors have at least 40 citations each. Sarkis has secured 90 citations, ranking first, while Ivanov, Kirchherr and Upadhyay have 40 citations and rank last, based on the citation threshold. Moving forward to the co-cited references table, which identifies co-citations in the documents using a threshold of at least five citations and shortlists 18 articles. For this, we set a query with a minimum

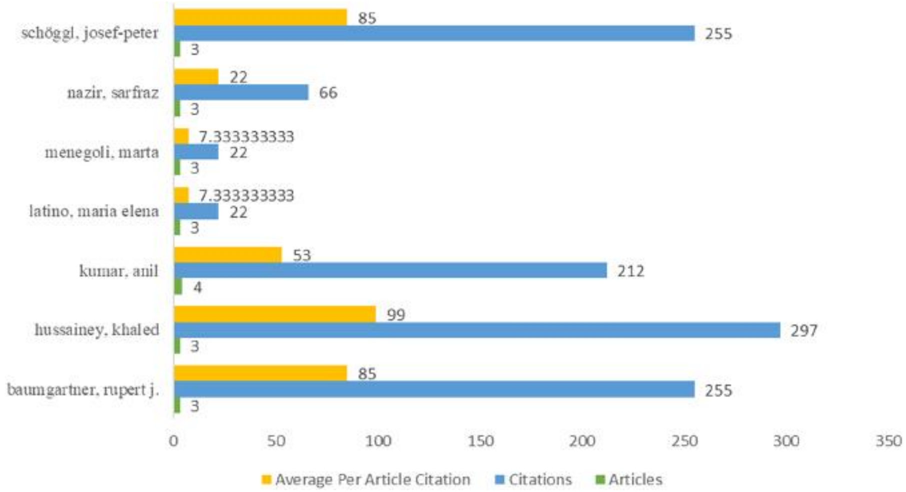

Figure 4. Most influential authors. Source: Authors' collaboration

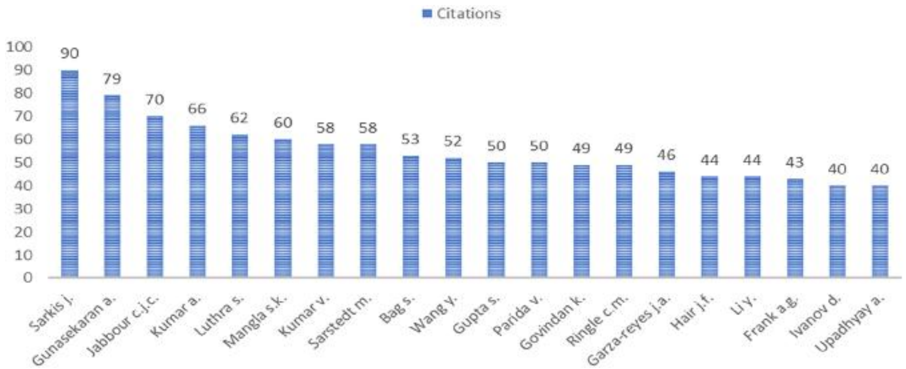

Figure 5. Individual author citations. Source: Authors' collaboration

citation threshold of 5; of the total 11,098 references, only 18 met the threshold. See the map and table of co-cited references below (see Figure 6).

Table 3 provides a list of the 18 articles that are most frequently co-cited. Kirchherr *et al.* (2017) characterise CE as a regenerative framework in which resource reduction, waste outflow and energy spillage are limited by diminishing techniques and material consumption is reduced by closed-loop cycles and accomplished through continuing frameworks such as maintenance, fixing, reusing, remanufacturing, restoring and reducing (Ghisellini *et al.*, 2016). Geissdoerfer *et al.* (2017) characterise SD as the stable incorporation of economic performance, social comprehensiveness and ecological benefits for present and future outcomes. DTs, CE and SD are rising topics that have attracted growing research attention. Chinese and European researchers have embraced this idea, leading to exponential development in production (Murray *et al.*, 2017; Büchi *et al.*, 2020), which reflects the expanded enthusiasm of organisations, policymakers, NGOs and the government in these areas (Awan *et al.*, 2021; Saberi *et al.*, 2019). Move forward to Table 3 co-cited reference.

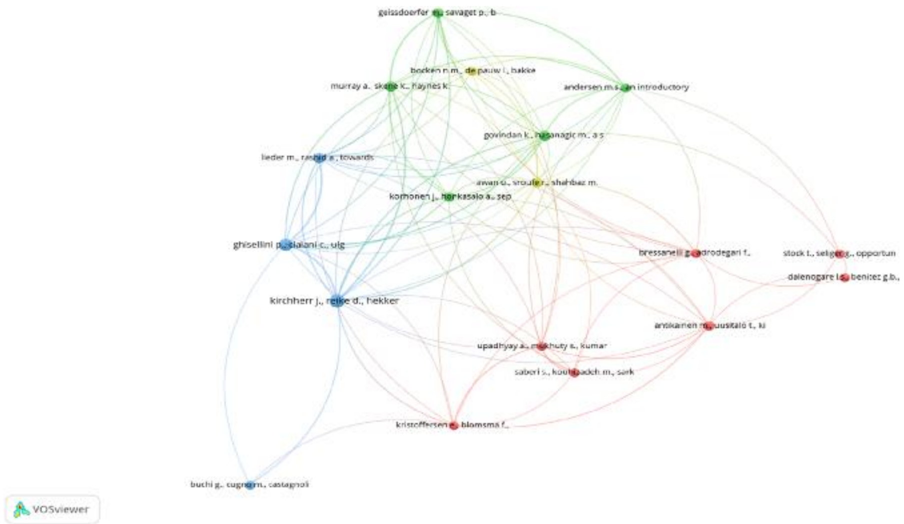

Figure 6. Mapping of co-cited authors. Sources: VOSviewer, Authors' collaboration

To respond to the primary research question: To what extent can the relationship between DTs and the CE support sustainable development and facilitate informed decision-making? It is evident from this literature review that the gap for exploration in this research is compelling, despite the concept of relationships. Particularly, in Table 3, Kirchherr *et al.* (2017) hold the first co-citation rank, cited 12 times in other studies, while Ghisellini *et al.* (2016) rank second, cited 10 times. Other studies, such as Govindan and Hasanagic (2018), Lieder and Rashid (2016) and Murray *et al.* (2017), are cited 7 times in other studies (see Table 4 and see Figure 7)

The study utilised bibliographic analysis to identify a document for established visualisation. The minimum number of citations per document was 40 across 148 papers. The study meets the threshold of 29, indicating that 29 documents have at least 40 citations. The most extensive set of connected items comprises 25 items, divided into five clusters (see Table 5).

The use of DTs such as artificial intelligence (AI), big data analytics, the Internet of Things (IoT) and blockchain technology is increasingly regarded as a critical enabler, not only for traditional operations (Lerman *et al.*, 2022) and supply chain management (Nazir *et al.*, 2025; Agrawal *et al.*, 2025) but also for sustainable and circular product management (Piscicelli, 2023; Wynn and Wiegand, 2025). For instance, DTs monitor products and parts across multiple life cycles at the industrial level (Calderón Monge *et al.*, 2024). With this capability, AI may identify new business opportunities and sources of competitive advantage. Surprisingly, studies on conceptual frameworks addressing AI, machine learning, big data, cloud computing, information systems and CE in relation to SD are limited (Sahoo *et al.*, 2023; Tiwari and Khan, 2020; Calderón Monge *et al.*, 2024). A gap remains in expertise on effectively leveraging AI to support the operational aspects of circular practices and to uncover new CE potential. Consequently, questions remain unanswered about whether, under what conditions and how AI can enhance companies' competitive performance by improving the leveraging of circular strategies. The study used the keyword co-occurrence. The study established a threshold for the minimum co-occurrence of Keyword 5 and found that 33 keywords were divided into 4 clusters; see the key cluster below (see Figure 8).

The first cluster shows strong co-occurrence between the keywords "circular economy" (66 occurrences) and "sustainable development" (52 occurrences). Furthermore, the second

Table 4. Co-cited references

ID	Cited reference	Citations
1	Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualising the Circular Economy: An Analysis of 114 Definitions. *Resources, conservation and recycling*, *127*, 221–232	12
2	Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A Review of the Circular Economy: The Expected Transition to a Balanced Interplay Between Environmental and Economic Systems. *Journal of Cleaner Production*, *114*, 11–32	10
3	Govindan, K., & Mia Hasanagic. (2018). A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. *International Journal of Production Research* 56, no. 1–2: 278–311	7
4	Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51	7
5	Murray, A., Skene, K., & Haynes, K. (2017). The circular economy: an interdisciplinary exploration of the concept and application in a global context. *Journal of Business Ethics*, *140*, 369–380	7
6	Antikainen, M., Uusitalo, T., & Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of the circular economy. *Procedia Cirp*, *73*, 45–49	6
7	Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy: A New Sustainability Paradigm? *Journal of Cleaner Production*, *143*, 757–768	6
8	Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and Its Limitations. *Ecological economics*, *143*, 37–46	6
9	Andersen, M. S. (2007). An introductory note on the environmental economics of the circular economy. *Sustainability science*, *2*(1), 133–140	5
10	Awan, U., Sroufe, R., & Shahbaz, M. (2021). Industry 4.0 and the Circular Economy: A Literature Review and Recommendations for Future Research. *Business Strategy and the Environment*, *30*(4), 2038–2060	5
11	Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product Design and Business Model Strategies for a Circular Economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320	5
12	Bressanelli, G., Adrodegari, F., Perona, M., & Saccani, N. (2018). Exploring how usage-focused business models enable circular economy through digital technologies: Sustainability, *10*(3), 639	5
13	Büchi, G., Cugno, M., & Castagnoli, R. (2020). Smart factory performance and Industry 4.0. *Technological Forecasting and Social Change*, *150*, 119,790	5
14	Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. *International Journal of Production Economics*, *204*, 383–394	5
15	Kristoffersen, E., Blomsma, F., Mikalef, P., & Li, J. (2020). The Smart Circular Economy: A Digital-Enabled Circular Strategies Framework for Manufacturing Companies. *Journal of Business Research*, *120*, 241–261	5
16	Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, *57*(7), 2117–2135	5
17	Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in Industry 4.0. *procedia CIRP*, *40*, 536–541	5
18	Upadhyay, A., Mukhuty, S., Kumar, V., & Kazancoglu, Y. (2021). Blockchain technology and the circular economy: Implications for sustainability and social responsibility. *Journal of Cleaner Production*, *293*, 126,130	5

Source(s): VOSviewer, own elaboration

highlighted "digital technologies," with 18 occurrences and the third cluster, "Industry 4.0," with 26 occurrences, respectively indicating that the CE and SD have a strong relationship, whereas DTs have a weak relationship. In addition, AI can precisely predict product demands and influence decision-making (Okorie *et al.*, 2018; Nazir *et al.*, 2025). AI can assist in circular product design by providing specific information on resources to reduce resource utilisation

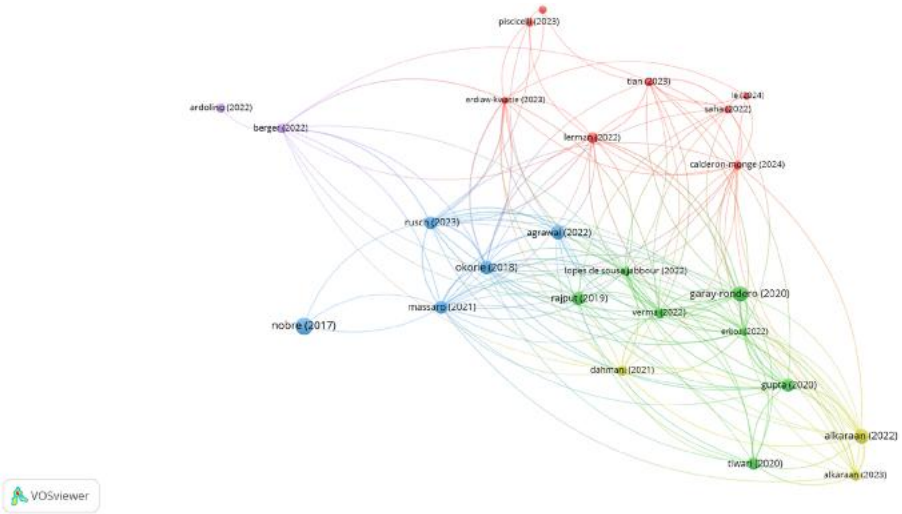

Figure 7. Bibliographic coupling analysis. Sources: VOSviewer, Authors' collaboration

and increase material efficiency. Product designers and top-level management play a key role in developing circular products. According to Lu *et al.* (2020), the current disclosure framework in corporate securities law has minimal impact on reducing opacity in AI systems and there is a strong advocacy for implementing a practical disclosure framework for AI products and services to combat AI opacity. Therefore, an advanced disclosure framework can enhance transparency, minimise stakeholder risks, stabilise capital markets and foster long-term sustainability.

Figure 9 presents the most popular keywords. Among them are CE subtopics such as recycling, reuse, supply chain management, waste management and eco-efficiency. The figure also highlights the links of Industry 4.0 with SD, CE and DTs. Artificial intelligence (AI) is a game-changer in the era of Industry 4.0, enabling the development of intelligent devices that interpret vast amounts of data collected from various machines at different stages of manufacturing. These data are then categorised to identify patterns and correlations, empowering real-time decision-making. This potential of AI to enhance decision-making instils confidence in the roles of manufacturing, remanufacturing, designing, redesigning, selling and reselling across different industries (Calderón Monge *et al.*, 2024; Nazir *et al.*, 2025). Recent studies underscore the importance of integrating these DTs to create a CE that is both economically and environmentally sustainable (Verma *et al.*, 2022a, b; Le *et al.*, 2026). For more information, the study explored the relationship between Industry 4.0, and CE and SD.

Figure 10 shows that organisational ambidexterity improves collaboration between Industry 4.0 technologies and CE techniques, greatly enhances sustainable value creation and financial performance across various industry sectors (Alkaraan *et al.*, 2023; Virmani *et al.*, 2024). Industry 4.0 offers valuable insights for scholars, designers and managers on how to implement sustainable product design strategies and meet customer expectations (Dahmani *et al.*, 2021). It also suggests that firms excelling in ESG are more likely to provide adequate Industry 4.0 disclosures, leading to better financial outcomes (Alkaraan *et al.*, 2022).

Figure 11 states that AI has strong relationships with the DTs, SD and CE. Moreover, AI is also closely linked to Industry 4.0. AI technologies in waste recycling systems can identify recyclable and recoverable products and materials through image recognition and analyse user behaviour data (Sánchez Garcia *et al.*, 2024). AI-based optimisation techniques are already

Table 5. Clusters of bibliographic coupling analysis

Document	Citations	Total link strength	Title	Findings
Cluster 1				
Lerman *et al.* (2022)	95	32	Smart green supply chain management: A configurational approach to enhance green performance through digital transformation	The findings indicate that smart supply chains enhance green performance through external and internal Green Supply Chain Management activities. Digital transformation and specific green operations, such as green purchasing, play crucial roles
Tian and Guo (2023)	58	20	The role of digital transformation practices in the operations improvement in manufacturing firms: A practice-based view	This study enhances understanding of digitalisation in operations management by illustrating how digital transformation practices affect operational efficiency across different competitive levels. It also provides valuable guidance for managers and policymakers on how to adopt these practices effectively
Saha *et al.* (2022)	49	15	The interplay of emerging technologies in pharmaceutical supply chain performance: An empirical investigation for the rise of Pharma 4.0	The study reveals that while emerging technologies positively impact pharmaceutical supply chain performance across manufacturing, distribution, and consumption processes, complex barriers hinder their effectiveness. This underscores the need for a strategic framework to advance Pharma 4.0 and sustain supply chains
Erdiaw-Kwasie *et al.* (2023)	40	33	Does circular economy knowledge matter in sustainable service provision? A moderation analysis	The study emphasises that organisational factors and knowledge are essential for adopting CE practices and promoting sustainable service provision through longevity, sharing, and ownership. These findings highlight the importance of CE indicators in predicting sustainable outcomes and informing managerial strategies
Le *et al.* (2024)	40	6	Corporate social responsibility, green innovation, environmental strategy and corporate sustainable development	The findings indicate that Corporate Social Responsibility directly enhances sustainable corporate development by shaping environmental strategies and promoting biodegradable innovations. This research provides a framework for managers to adopt effective ecological strategies that foster sustainable growth in the marketplace

(*continued*)

Table 5. Continued

Document	Citations	Total link strength	Title	Findings
Sánchez-Garcia *et al.* (2024)	45	3	Revolutionising the circular economy through new technologies: A new era of sustainable progress	New technologies such as blockchain and artificial intelligence are crucial in advancing CE by improving resource efficiency and optimising supply chains. They also encourage sustainable business models and collaborative innovation. Their integration promotes ethical considerations and bolsters the growing bioeconomy, providing substantial economic and environmental benefits
Piscicelli (2023)	53	5	The sustainability impact of a digital circular economy	An SLR analysis of 48 published scientific articles from the last five years to identify the digital circular economy's first-, second, and third-order sustainability effects. The research underscores the urgency of addressing the gaps in the literature, particularly the limited attention given to social and economic impacts and rebound effects. It also calls for a more balanced consideration of negative (vs. positive) effects and a solid assessment of actual (vs. expected) impacts
Calderón Monge *et al.* (2024)	57	21	The role of digitalisation in business and management: a systematic literature review	The growth of AI in marketing is a thrilling prospect. The results of immersive technologies need to be evaluated in terms of their value to the client. The impact of technology on facilitating client relations is another frontier of investigation. Specifically, AI is a relatively new technology compared to others like AR and VR, which means analysing its impact on digital consumer behaviour patterns is a broad area of study. The fusion of AI and marketing will undoubtedly grow, so investigating the consumer journey enabled by AI can help academia gain insights into AI's benefits. Some other research topics in this field include applying intelligent algorithms to an in-depth study of automated marketing concepts and examining how multichannel AI systems can help develop more intelligent technology

(*continued*)

Table 5. Continued

Document	Citations	Total link strength	Title	Findings
Cluster 2				
Tiwari and Khan (2020)	128	24	Sustainability accounting and reporting in Industry 4.0	This research developed an empirical formulation that maps Industry 4.0 attributes, selected material topics, and their disclosures within the Global Reporting Initiative framework. The empirical formulation, a significant step, segmented the Industry 4.0 framework in India into three levels of maturity, each aligned with the appropriate triple bottom-line topics under the Global Reporting Initiative. This empirical formulation requires further research to establish its validity, as it is an overly optimistic representation by the members of the two focus groups. The interview respondents stressed a cautious approach, highlighting potential challenges and the need for careful planning, especially in AI-based predictive analytics and automation, which may require a lengthy maturity path
Gupta *et al.* (2020)	145	53	Dynamic capabilities and institutional theories for Industry 4.0 and digital supply chain	The findings indicate that coercive institutional pressures influence firms' intentions to adopt Industry 4.0 and digital supply chain practices, which are driven by regulatory demands for digital integration and sustainability
de Sousa Jabbour *et al.* (2022)	60	51	'Better together': Evidence on the joint adoption of circular economy and Industry 4.0 technologies	Adopting CE alongside Industry 4.0 technologies enhances overall performance and positively impacts social outcomes, whereas the isolated adoption of Industry 4.0 technologies does not affect social performance
Verma *et al.* (2022a, b)	86	52	Identifying and prioritising impediments of Industry 4.0 to sustainable digital manufacturing: A mixed-method approach	This study shows that Industry 4.0 factors help managers identify key sustainability challenges for digital transformation. It also offers guidance on prioritising relevant sustainability factors to transition their organisations effectively into digitally enabled entities
Garay-Rondero *et al.* (2020)	232	55	Digital supply chain model in Industry 4.0	The exploration reveals a lack of a comprehensive conceptual framework for Supply Chain Management that integrates Industry 4.0 elements. This study

(*continued*)

Table 5. Continued

Document	Citations	Total link strength	Title	Findings
				proposes a new model emphasising interconnectivity and collaboration among decentralised supply chains to enhance value through digital integration
Erboz *et al.* (2022)	40	61	The partial mediating role of supply chain integration between Industry 4.0 and supply chain performance	The study indicates that Industry 4.0 positively influences both Supply Chain Integration [SCI] and Supply Chain Performance [SCP] by enhancing SCI, thereby improving SCP. Furthermore, SCI partially mediates the relationship between Industry 4.0 and SCP, suggesting that improvements in SCI facilitate better SCP outcomes driven by Industry 4.0 initiatives
Rajput and Singh (2021)	150	21	Industry 4.0 – challenges to implement the circular economy	The ISM hierarchical model and impact matrix analysis reveal that digitalisation and semantic interoperability are critical barriers with high influence and low dependence, hindering improvements in resource efficiency and sustainability in the CE. As industry professionals and researchers, your role in addressing these barriers is crucial. Additionally, cyber-physical systems standards, sensor technology, and design challenges are recognised as significant barriers to achieving CE within Industry 4.0, and your expertise is needed to overcome them
Cluster 3				
Massaro *et al.* (2021)	146	38	Industry 4.0 and Circular Economy: An exploratory analysis of academic and practitioners' perspectives	The study emphasises Industry 4.0's transformative potential on the CE through enhanced resource efficiency and innovative business models. It also identifies existing barriers that necessitate collaborative stakeholder engagement and integrated design approaches. The findings suggest important implications for both practical applications and future research in the field
Rusch *et al.* (2023)	164	51	Application of digital technologies for sustainable product management in a circular economy: A review	Deductive and inductive analyses of the examples revealed the potential of DTs across the product life cycle, as enablers of CE strategies, and in specific production management

(*continued*)

Table 5. Continued

Document	Citations	Total link strength	Title	Findings
				activities. The application of DTs often results in only incremental improvements, such as enhanced efficiency in existing processes, while more radical forms of improvement remain relatively scarce. There is significant potential to increase adoption and optimise DTs across various Strategic Product Management (SPM) areas to accelerate the transition towards a more sustainable CE
Agrawal *et al.* (2022)	166	29	Nexus of circular economy and sustainable business performance in the era of digitalisation	The study highlights that digitalisation is crucial for developing sustainable circular products and that customer involvement is essential for innovation. It also suggests adopting a product-service system to enhance the transition to a CE and digitalisation
Okorie *et al.* (2018)	185	63	Digitisation and the Circular Economy: A Review of Current Research and Future Trends	The findings indicate a growing body of CE research but highlight a significant gap in studies focusing on DTs facilitating CE. The paper proposes a CE-DT framework to address these gaps and promote a more integrative approach to future research
Nobre and Tavares (2017)	302	3	Scientific literature analysis on big data and Internet of things applications on circular economy: a bibliometric study	Bibliometric analysis highlights China and the USA as leading nations in research interest, whereas Brazil and Russia lack studies despite being major greenhouse gas emitters. The findings suggest a disconnect between industry initiatives and scientific research, indicating potential research gaps for future investment
Cluster 4				
Alkaraan *et al.* (2023)	90	48	Sustainable strategic investment decision-making practices in UK companies: The influence of governance mechanisms on synergy between Industry 4.0 and circular economy	The study highlights that organisational ambidexterity enhances the synergy between Industry 4.0 technologies and CE techniques. This synergy, influenced by governance mechanisms, significantly boosts sustainable value creation and financial performance across various industry sectors

(*continued*)

Table 5. Continued

Document	Citations	Total link strength	Title	Findings
Dahmani *et al.* (2021)	87	32	Smart circular product design strategies towards eco-effective production systems: A lean eco-design Industry 4.0 framework	The paper presents a framework that integrates Lean design, Eco-design, and Industry 4.0 strategies to guide manufacturers in creating eco-efficient products that satisfy customer expectations. This approach provides valuable insights for scholars, designers, and managers on implementing sustainable product design strategies
Alkaraan *et al.* (2022)	201	45	Corporate transformation toward Industry 4.0 and financial performance: The influence of environmental, social, and governance (ESG)	The result reveals that strategic investment decision-making (SIDM) practices for CTTI 4.0 are increasingly adopted across industries and positively influence financial performance, particularly when supported by strong environmental, social, and governance (ESG) practices and suggests that firms excelling in ESG are more likely to engage in adequate CTTI 4.0 disclosure, leading to improved financial outcomes
Cluster 5				
Berger *et al.* (2022)	73	18	Digital battery passports to enable circular and sustainable value chains: Conceptualisation and use cases	The development of the Digital Product Passport (DBP) concept, comprising 54 data points across four key categories, aims to enhance sustainable, circular value chains for electric vehicle batteries. This framework stimulates scientific discussion, serves as a guide for creating other digital product passports, and, significantly, assists policymakers and practitioners in practically implementing sustainable practices
Ardolino *et al.* (2022)	68	1	Analysis of the COVID-19 pandemic's impacts on manufacturing: a systematic literature review and future research agenda	This paper examines the significant effects of the COVID-19 pandemic on the manufacturing sector through the lens of operations management. It emphasises practical adaptations and identifies future research opportunities. It outlines open questions and potential research directions across organisational, process, and technology dimensions

Note(s): *The column Documents displays only the first author of the publication
Source(s): VOSviewer, own elaboration

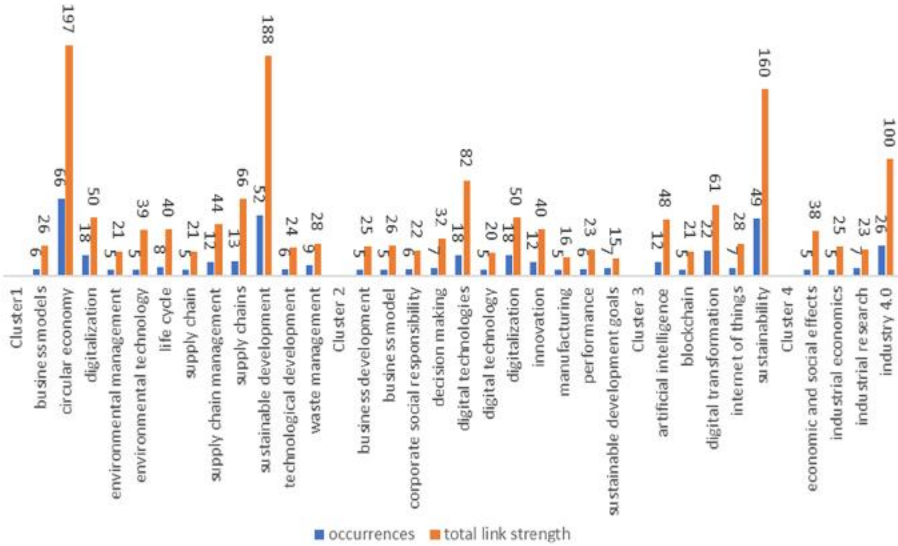

Figure 8. Co-occurrence of keywords. Sources: Authors' collaboration

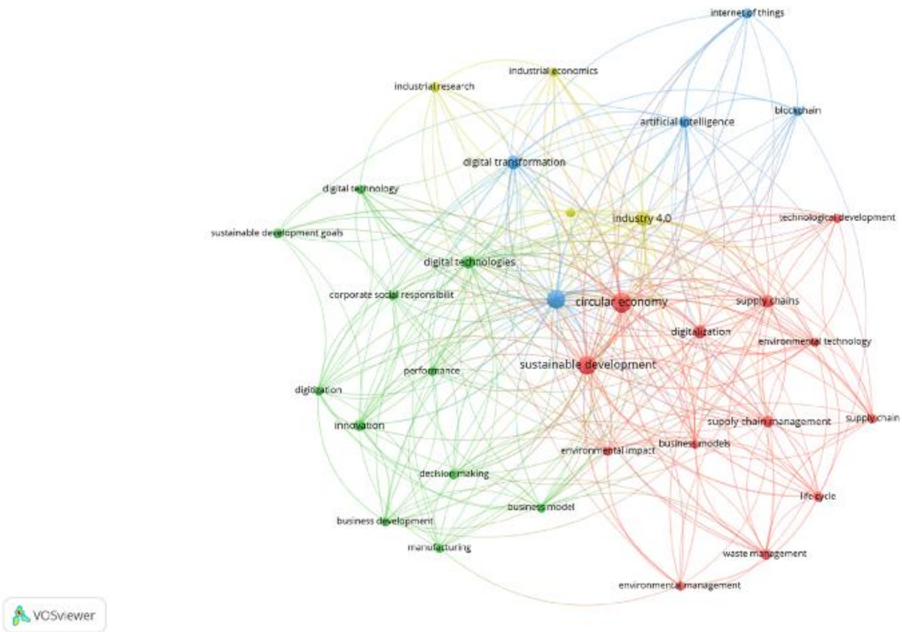

Figure 9. Keywords mapping. Sources: VOSviewer, authors' collaboration

being employed in waste collection systems to analyse incoming waste materials, the sizes of waste bins and the types of waste collection vehicles required.

Figure 12 shows that Blockchain technology has strong relationships with CE, SD and Industry 4.0. Blockchain technology is crucial in advancing CE by improving resource

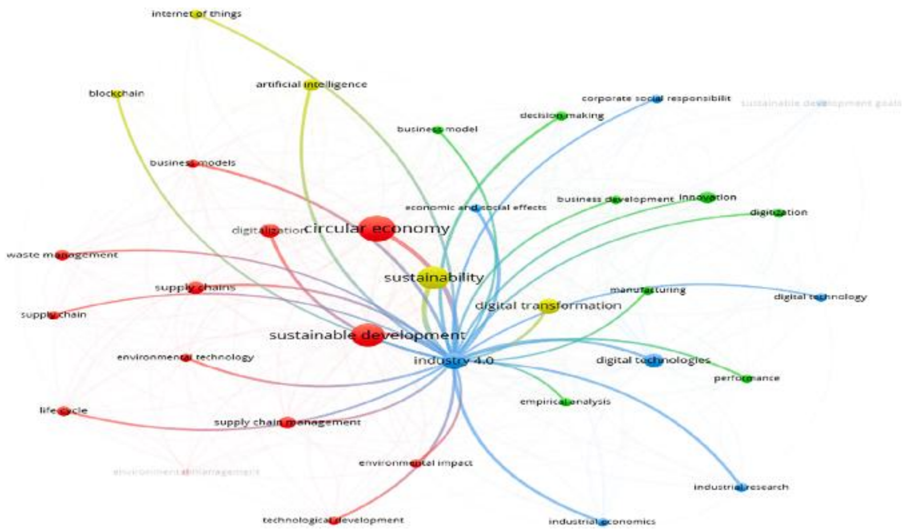

Figure 10. Industry 4.0 relationship with CE & SD. Sources: VOSviewer, authors' collaboration

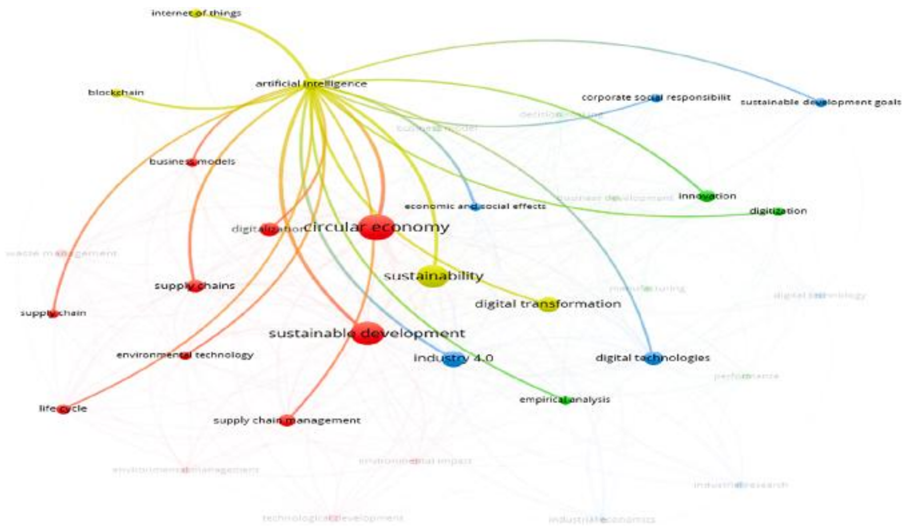

Figure 11. Artificial Intelligence relationships with CE & SD. Sources: VOSviewer, authors' collaboration

efficiency and optimising supply chains. Blockchain technology encourages sustainable business models, product life cycles and collaborative innovation. Additionally, integration promotes ethical considerations and bolsters the growing bioeconomy, providing substantial economic and environmental benefits (Sánchez Garcia *et al.*, 2024).

Internet of Things technologies enable real-time monitoring and data collection, allowing companies to optimise resource utilisation and enhance operational efficiency (Sánchez Garcia *et al.*, 2024 and see Figure 13). Designing for circularity is a new trend among companies seeking to improve the sustainability of their products and services and reduce material use.

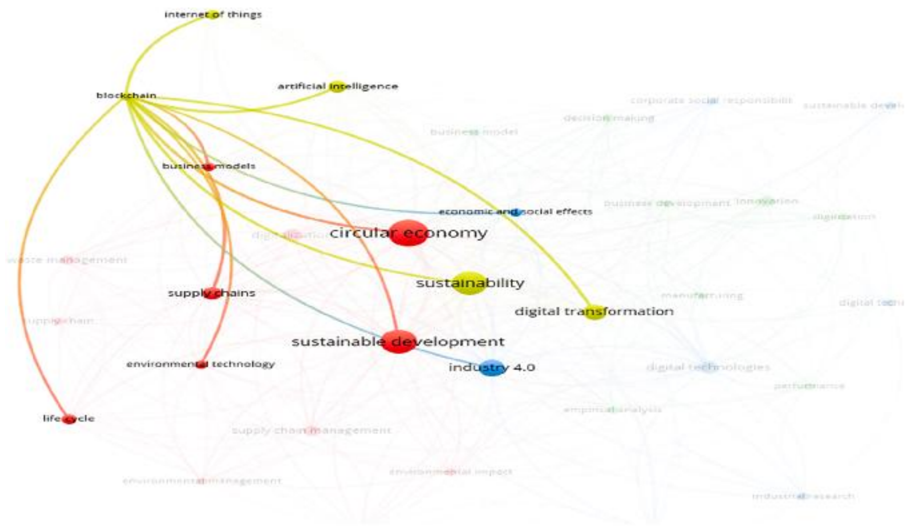

Figure 12. Blockchain technology relationships with CE & SD. Sources: VOSviewer, authors' collaboration

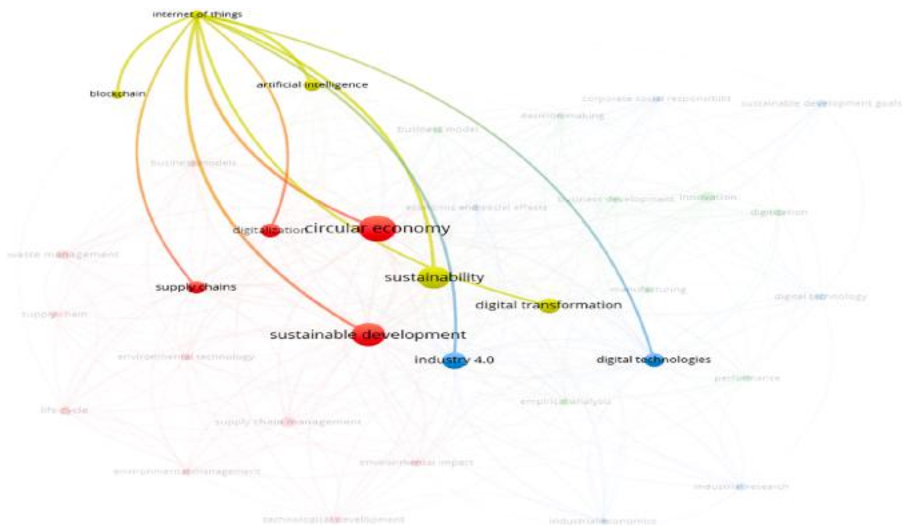

Figure 13. Internet of Things relationships with CE & SD. Sources: VOSviewer, authors' collaboration

Big data analytics, which collects massive amounts of data throughout a product's lifecycle, is a key component of big data (Figure 14). Conventional tools cannot manage, store, or analyse this data. In contrast, analytics employs tools and techniques to transform unstructured data into valuable business insights (Rusch *et al.*, 2023). Therefore, big data analytics, advanced simulations and digital twinning enhance a firm's production, cost and handling efficiency across the supply chain (Alvarez-Aros and Bernal-Torres, 2021). See the table below (Table 6) on the relationship between Industry 4.0 and the CE principles with references on SD.

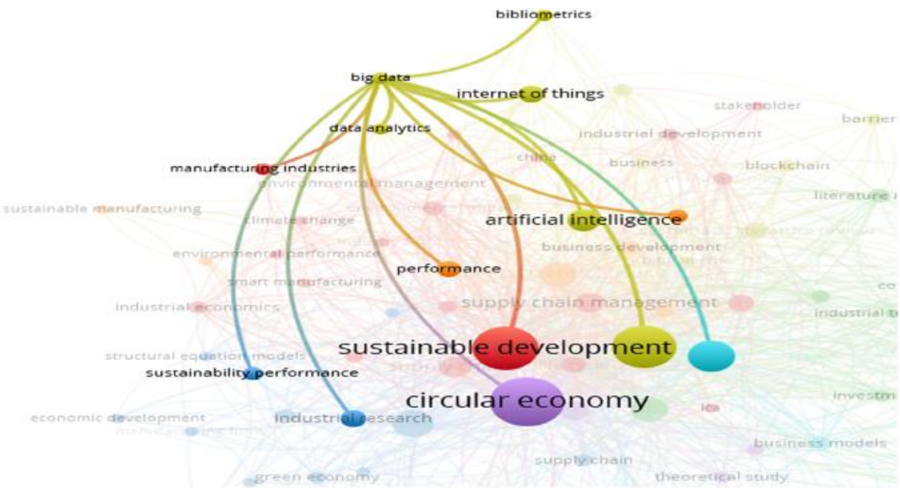

Figure 14. Big data relationships with CE & SD. Sources: VOSviewer, authors' collaboration

(1) The CE reduction principle is linked to enhancing resource efficiency throughout all stages of the product lifecycle and is a practical way to adopt DTs and CE for SD. Improving production and energy efficiency has proven benefits of Industry 4.0 (IEA, 2017; Dahmani *et al.*, 2021; Alkaraan *et al.*, 2023) and serves as a sustainable value driver. DTs applied monitoring, optimisation and automated data control to forecast, track, trace and collect materials, all of which strongly support the CE reduction principle. Furthermore, AI is well-connected with waste generators and collectors to boost waste recovery efficiency (Nazir *et al.*, 2025).

(2) Reuse: DTs are to facilitate product reuse through resale and second-hand markets. Used products in good condition can extend their lifespan when purchased by second-hand buyers. DTs primarily support the relocation of used products by identifying reusable items and selling them to second-hand customers. However, many functions, such as track-and-trace, monitoring and collection, are considered helpful for identifying and providing product information ready for reuse, including in-use data, real-time conditions and location (Wynn and Jones, 2022).

(3) Recycle: DTs focus on fundamental changes in product and service design, production processes and user behaviour, aiming to eliminate wasteful practices and replace non-renewable materials with recycled or renewable alternatives. It emphasises DTs related to data analysis, collection and integration rather than automation. Additionally, AI can assess the stability and quality of various design models and accelerate the design process by reducing the number of prototypes required (Neri *et al.*, 2025; Piedra-Muñoz *et al.*, 2025; Nazir *et al.*, 2025). It can also be employed to identify suitable renewable or recycled raw materials to replace non-renewable options (Neri *et al.*, 2025).

(4) Repurposes/Remanufacture: The repurposing approach focuses on using DTs to promote industrial symbiosis, where product waste is transformed into resources for other sectors. Companies often lack the knowledge to engage in cross-sectoral exchanges of waste, materials and services, which involve sharing information across multiple industries to help companies uncover new opportunities. Data shared on

Table 6. Industry 4.0 and the CE: An overview with references to SD

Technologies	Descriptions	Circular economy principles	Sustainable development	Sources
Artificial Intelligence	Artificial intelligence is the creation of computers capable of learning, making decisions without human intervention, and self-correcting in ways that imitate human intelligence	*Reduce* - Reduce Energy consumption - Reduce water consumption	*Economic Performance* - Competitive Advantage	- Wynn and Wiegand (2025) - Wynn and Jones (2022)
Blockchain Technology	Blockchain technology is a digital, distributed, and decentralised ledger in which transactions are recorded and added in chronological order to create permanent, unchangeable records. Blockchain also supports smart contracts, which are pieces of code that are automatically and independently executed by computers	- Cradle-to-Grave - Reduce material consumption - Raw materials turnaround - Reduce carbon emissions - Reduce waste in production and processing	- Long-range planning - R & D - Cost of living - Product Cost Saving - Profitability	- Agrawal *et al.* (2025) - Roshan *et al.* (2024) - Mohapatra *et al.* (2024)
The IoT	The IoT enables wireless communication between human devices, computers, and sensors, making data accessible from any location. The technology is a highly sophisticated and widely distributed networked system composed of multiple intelligent objects that can generate and share information	- Reduce unavoidable waste by-products - Cradle-to-Cradle - Cradle-to-Gate - Just-in-time manufacturing *Reuse/Resale*	- Operational Efficiency - Risk management - Profit margin - Total stakeholder returns	- Sahoo *et al.* (2023) - Bai *et al.* (2023) - Alkaraan *et al.* (2023)
Simulation Technology	Industry 4.0 encompasses various types of technologies. Simulation technology involves creating a computer-generated model that closely mimics the behaviour of a real-world system or process	- Renewable Energy - Reuse products, parts, materials - Product by product - Reuse water	- Green Market Potential *Social Performance*	- Alkaraan *et al.* (2024) - Sánchez-Garcia *et al.* (2024)
Additive Manufacturing	Additive manufacturing is a disruptive innovation that aims to produce product components without specialised, sophisticated equipment. It involves fusing materials to form a three-dimensional model from a digital design, thereby accelerating production timelines and connecting engineers, designers, and customers	- Reuse plastic Packaging - Redistribute - Technical cycle - Operate circular business models - Material efficiency - product-as-a-service models	- Job Creation - Community development - Social stability - Quality of life - Equal opportunity	- Nazir *et al.* (2025) - Nazir *et al.* (2024) - Barnabè and Nazir (2021)
Cloud Computing	Cloud computing is a technology that provides a range of online services and enables remote access to information stored elsewhere	*Recycle* - Waste To Energy Productivity - Recyclability	- Law and Ethics - Human Right - Knowledge Sharing	- Barnabè and Nazir (2022)

(*continued*)

Table 6. Continued

Technologies	Descriptions	Circular economy principles	Sustainable development	Sources
Cyber-Physical System	A cyber-physical system is a technological computer system that integrates components and machines in the manufacturing process through the exchange of data and instructions via physical processes, cyberspace, control, and sensing. This technology helps collect real-time data to prioritise manufacturing orders, optimise tasks, and identify maintenance needs	- Waste Material Recycling - Hazardous materials recycling - Packaging, Plastic, recycling - Downcycling - Recycle- raw materials - Horizontal recycling - Open-loop recycling Recycle by Circularity *Remanufacture/Reproduce* - Reproduce by original parts or material - Repair products and parts - Resource Digitalisation Producer - Supplier Responsibility - Re-engineer products and components - Refurbish - Design for durability - End-Of-Life - Design for disassembly *Redesign* - Redesign old products and parts - Repurpose products and parts, services - Extend the Product Life Cycle - Eco-design - Regenerative energy - water, and waste productivity - Repair - Sharing - Cybernetics - Design circular products, components	- Cultural Identity - Stakeholders' satisfaction - New business opportunity - Poverty elevation - Health and wellbeing - Labor rights - Community relationship *Environmental Performance* - Resource Preservation - Reduce Energy consumption - Reduce water consumption - Reduce Pollution - Reduce carbon emissions - Environmental Protection - Habitat Restoration and Preservation - Lower use of version material - Improve material transparency	- Virmani *et al.* (2024) - Agrawal *et al.* (2022) - Yadav *et al.* (2024) - Neri *et al.* (2025) - Piedra-Muñoz *et al.* (2025) - Bücker *et al.* (2025) - Sun *et al.* (2025)
Big Data Analytics	Big data analytics helps process large amounts of data from various sources, including both structured and unstructured data, to support decision-making and facilitate data mining, predictive analytics, and other applications			

(*continued*)

Table 6. Continued

Technologies	Descriptions	Circular economy principles	Sustainable development	Sources
		- Cascading *Recover* - waste recovery - Waste hierarchy - Recover Product, Parts - Waste to the energy recovery rate - Recover natural resources from waste - Reverse Logistics - Lifecycle Care Services Footprint - Lean manufacturing - Landfill diversion	- Climate change mitigation - Reduction GHGs - Deforestation - Biodiversity	

information platforms can support real-time waste-to-resource matching, reduce uncertainty in by-product availability and ensure suitable quality for further use (Nazir *et al.*, 2025).

(5) Redesign: The redesign process uses DTs to extract functional parts from non-functional products, repairing and rebuilding products into new products similar to the originals. DTs can support the entire redesign process, which involves identifying functional parts, disassembling, repairing, reselling and rebuilding the products into a new design. Track-and-trace provides insights into the availability and condition of used products and spare parts, enabling companies to tailor redesign processes to minimise waste and material consumption while optimising process efficiency.

(6) Recover: DTs facilitate predictive and prescriptive maintenance. The recovery mechanism employs DTs to extend the lifespan of machines and products by performing customised maintenance tasks on devices before failures occur. DTs can support detection, condition-based maintenance and automatic task scheduling for products and machines and can accurately predict with prescribed actions. Move forward to figure out Industry 5.0's relationship with CE & SD.

Figure 15 illustrates the link between Industry 5.0 and the CE for SD. Industry 5.0 is a term used to describe the next stage of the industrial revolution, focusing on the relationship between humans and machines in manufacturing (Leng *et al.*, 2022). Industry 5.0 builds on the advances of Industry 4.0, which highlighted the integration of robotic systems, the Internet of Things (IoT) and Big Data analytics to enhance manufacturing processes (Leng *et al.*, 2022; Fraga-Lamas *et al.*, 2021). However, Industry 5.0 further emphasises the importance of human involvement and interaction in manufacturing (Li and Duan, 2025). The European Union has recently begun implementing this concept, but further research and industry development are still necessary.

Firm-level green initiatives are recognised as effective methods for enhancing financial performance (Alkaraan *et al.*, 2022), but implementing them also presents challenges, including increased costs (Alkaraan *et al.*, 2022). From a practical standpoint, the financial feasibility of CE practices is vital for building confidence among businesses and investors in CE (Nazir *et al.*, 2024). The research emphasised the need for increased financing and investment in CE activities, but the idea of DTs was absent. The transition to CE is highly complex, involving many stakeholders and factors that directly or indirectly influence both financial and technological systems. Addressing the financial constraints faced by CE practices requires more than focusing on firms' and financiers' behaviour (see Figure 16).

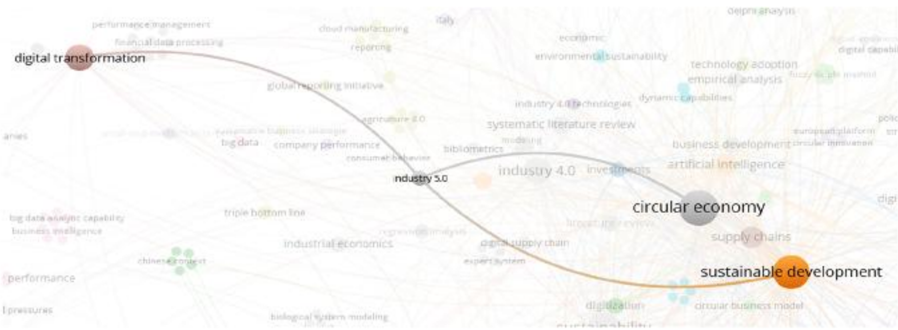

Figure 15. Industry 5.0 relationship with CE & SD. Sources: VOSviewer, authors' collaboration

Figure 16. Financial performance links with CE & SD. Sources: VOSviewer, authors collaboration

According to Carnegie *et al.* (2021), accounting should be viewed as a technical, social and ethical practice. This perspective has been shaped by recent developments that emphasise the importance of integrating sustainability issues into accounting practices. At the same time, the traditional definition of accounting no longer meets contemporary societal needs. Carnegie *et al.* (2021, p. 18) define accounting as: "Accounting is a technical, social and moral practice concerned with the sustainable utilisation of resources and proper accountability to all stakeholders to enable the flourishing organisation, people and nature". In this context, AI is seen as new methods, practices, technologies, or approaches that alter how accounting data is collected, processed, analysed and reported. These innovations aim to enhance the effectiveness, efficiency, accuracy and relevance of accounting processes and information, thereby better meeting stakeholders' needs and supporting decision-making (Nazir *et al.*, 2025). These advancements in AI can potentially transform the nature of accounting standardisation and the preparation and consumption of corporate reporting information. AI offers new methods for measuring, recording, verifying, analysing and reporting organisational activity in corporate reports (Tiwari and Khan, 2020). Recently, Nazir and Doni (2024) and Barnabè and Nazir (2021, 2022) emphasised the nexus between CE and integrated reporting (IR), yet they overlooked governance and the role of AI. CE and AI-based reporting can benefit the corporate information market by enabling users to access extensive datasets of corporate reports at no cost. While no comprehensive research on the interaction between CE and IR practices has been published, the concept of AI has not been considered. Recently, EFRAG introduced new ESRS5 standards related to the CE, but AI standards are still lacking (see Figure 17).

Figure 18 highlights not only the relationship between rational decision-making and computer-based analysis, but also the relationships with CE, SD and financial performance. However, the ReSOLVE framework, developed by the Ellen MacArthur Foundation, includes Regenerate, Share, Optimise, Loop, Virtualise and Exchange to promote circularity in the built environment. This approach not only focuses on building materials and advanced techniques but also requires new business models to support the socioeconomic system in enabling circular practices.

Industries categorise additional information extracted from quantitative and qualitative articles, focusing on the relationships among DTs, CE and SD research across sectors. From an industrial relationship perspective, most industries have strong links with CE and DTs for SD.

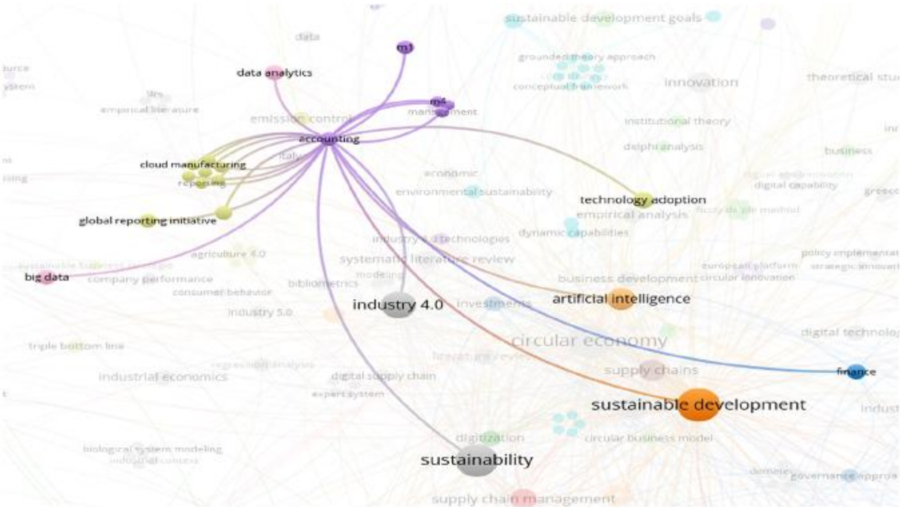

Figure 17. Accounting links with CE & SD. Sources: VOSviewer, authors' collaboration

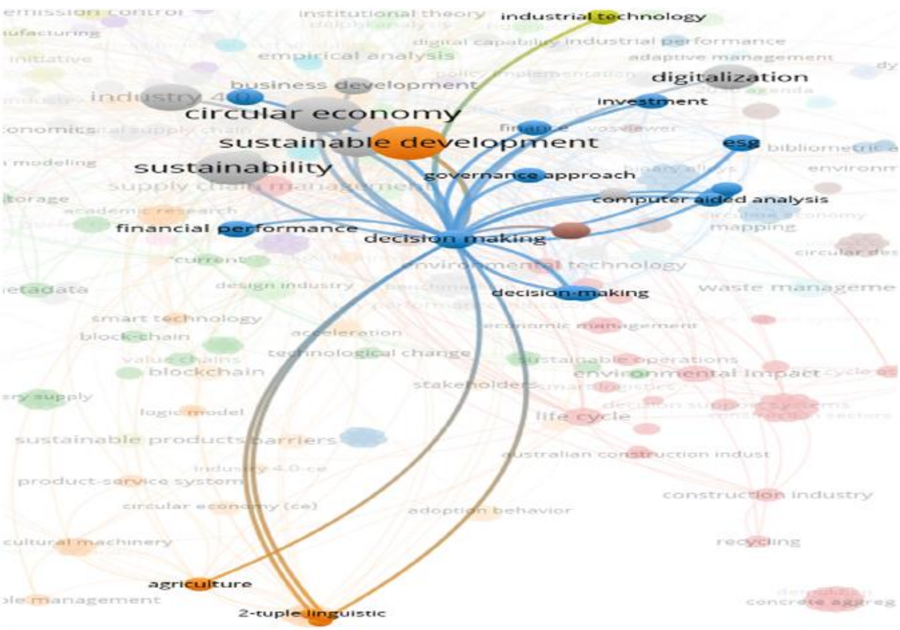

Figure 18. Computer-based analysis impact on decision making. Sources: VOSviewer, authors' collaboration

For instance, Kristoffersen, a renowned researcher in sustainability, examined manufacturing industry firms (Kristoffersen *et al.*, 2020). In some cases, the investigation considered companies from all industries, with certain exceptions, excluding the financial sector (see Figure 19).

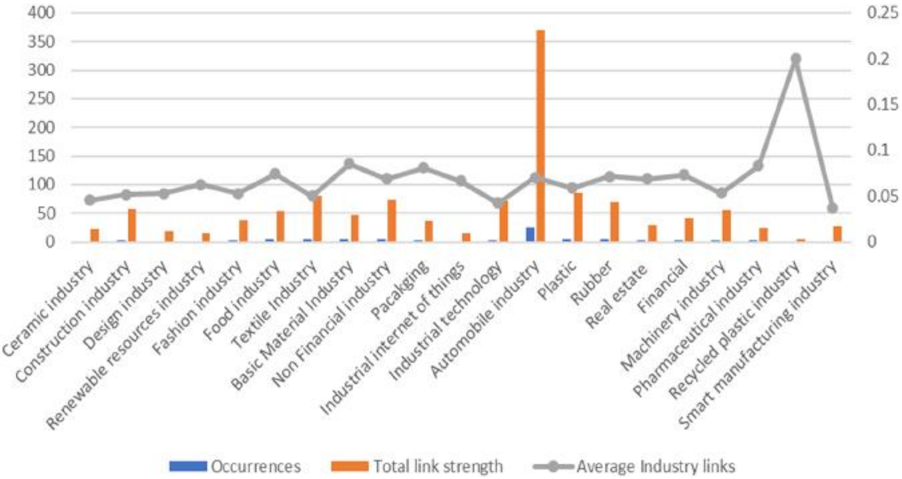

Figure 19. Actively participated industries. Sources: Authors' collaboration

Figure 20 emphasises the theoretical relationship with DTs, CE and SD, advocating for a deeper understanding of how DTs can support various CE strategies. It also finds that institutional theory has a stronger link compared to others. Specifically, it presents a novel approach to identifying how DT-enabled digital functions can enhance CE performance. The study offers a comprehensive theoretical SD and CE framework by reviewing IoT, big data, AI, blockchain and general DTs. After analysing papers and creating keyword links and occurrence metrics, the study identified key digital functions of DTs and highlighted both conceptual and empirical papers that appeared at least 3 times. There were overall links with occurrences and an average theoretical link appearance.

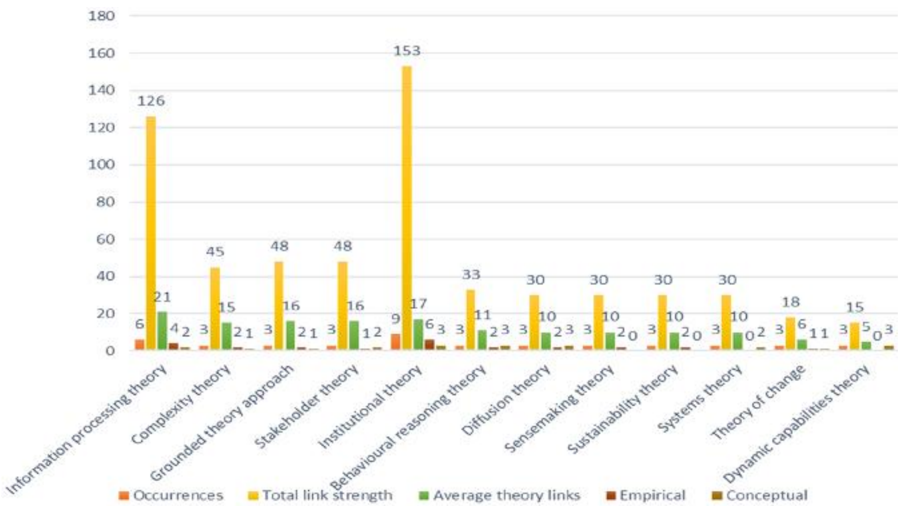

Figure 20. Theory-wise relationships with DTs, CE & SD. Sources: Authors' collaboration

Jabbour *et al.* (2019) employed stakeholder theory to develop a comprehensive business model for corporate environmentalism (CE) and an integrated framework for green human resources. Nazir *et al.* (2024) utilise institutional theory to empirically validate a firm's performance through the implementation of CE and advanced data analytics capabilities. CE can be understood as one of several complementary strategies for SD (Rusch *et al.*, 2023), envisioning a regenerative system that minimises natural resource consumption (Rusch *et al.*, 2023; Geissdoerfer *et al.*, 2017). Our analysis builds upon and utilises the CE-R principles to ensure comprehensive coverage of CE strategies. The frameworks of DTs, CE and SD uncover several mechanisms through which DTs can currently enhance CE performance. The combined framework expands the "capability mapping" of CE strategies (Nazir *et al.*, 2024), establishes a functional layer for the "DT-Base-CE framework" (Kristoffersen *et al.*, 2020) and enhances the CE "cross-section occurrence map" (Nazir *et al.*, 2025) by incorporating functions from a broader range of DTs and CE perspectives. Move forward to the combined framework (see Figure 21).

In the combined framework, "reducing" is a cost-effective step in circular models, while "reuse" refers to using a component or parts again for the same or a different purpose. The term "recycle" is crucial in CE but is considered when material reuse is impossible (Ellen MacArthur and Heading, 2019). AI-related CE models and practices address global challenges and help to redesign an inclusive, diverse and distributed economy that leads to SD. This research will benefit first movers in developing these activities within their organisations and in disclosing them to stakeholders to support rational decision-making.

4. Conclusions

This paper used systematic analytical strategies to explore the links among DTs, CE and SD. It carefully untangled developments in these areas and identified the most relevant scholarly works. The study suggests that CE, DTs and SD together can provide organisational pathways. These pathways increase resource productivity and create a framework for effective resource consumption management. Stakeholders have affirmed the need to shift business networks to pursue new AI-driven circular business models. Firms aim to improve the effectiveness, efficiency, accuracy and relevance of accounting processes and information, thereby better meeting stakeholders' needs and supporting decision-making.

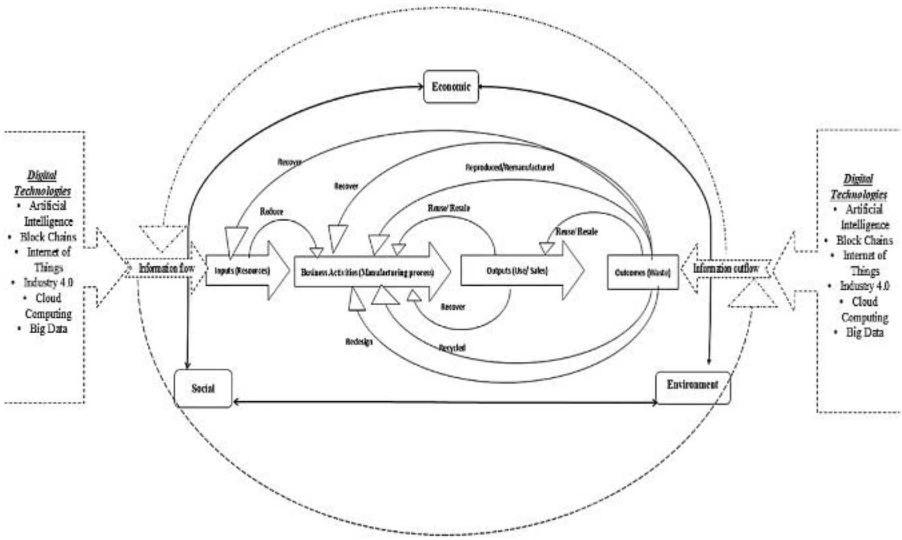

Figure 21. Combined framework. Source: Authors' collaboration

Empirical research on AI, IoT, big data and CE remains limited (Tiwari and Khan, 2020; Calderón Monge *et al.*, 2024). Currently, there is insufficient expertise in using AI to support operational circular practices or to find new CE opportunities. Some scholars, together with policymakers, advocate AI-driven circular business models to reduce environmental impacts (Agrawal *et al.*, 2025; Alkaraan *et al.*, 2022, 2023; Nazir *et al.*, 2025), yet some international organisations do not mandate them due to a lack of official guidance. Advances in AI may transform accounting standardisation through streamlining how organisations measure, record, verify, analyse and report their activities (Tiwari and Khan, 2020). CE- and DT-based reporting could benefit the corporate information market by providing users with free access to large datasets (Nazir and Capocchi, 2024). However, research on how CE and integrated reporting interact is limited and the specific contribution of DTs remains underexplored. Recently, EFRAG introduced ESRS5 standards for CE, but DT-specific standards have not been created. Expertise is still needed to use DTs effectively in support of circular practices and to discover new SD potential.

Regardless of these challenges, the shift to Industry 5.0 presents a key opportunity for manufacturers who intend not just to adapt but to pioneer eco-friendly innovation in the coming years. However, the European Commission has stated that the fifth industrial revolution is already underway. Industry 4.0 was primarily focused on developing advanced manufacturing technologies to boost profitability and productivity, whereas Industry 5.0 recognises the global manufacturing sector's significant social impact and leverages it to drive meaningful societal change. The study points to a lack of research grounded in management theory, given the interdisciplinary nature of the DTs and CE fields. Most research centres on creating exploratory conceptual frameworks. Only a few studies seek to improve the understanding of DTs, CE and SD implementation through management theories, such as institutional theory or stakeholder theory (Awan *et al.*, 2021; Dhamija and Bag, 2020; Nazir and Doni, 2024).

4.1 Practical implications

The SLR identifies clear types of connections and subset relationships between these areas. It also illustrates how these links lead to practical uses and provides specific information for supervisors, policymakers and stakeholders. DTs and CE provide tools for immediate monitoring and data collection, helping companies use resources more efficiently and operate more smoothly (Sánchez Garcia *et al.*, 2024). Financially, it is important for CE practices to be viable to gain support from businesses and investors in implementing DTs for sustainability (Nazir *et al.*, 2024). The research stresses that more funding and investment are needed in DTs and CE activities aimed at sustainability. The transition to combining DTs and CE is complex, as it involves many parties and factors that affect both financial and non-financial strategies. Overcoming these challenges requires targeted action focused on a firm's behaviour, culture and finances.

4.2 Limitations

The study has several limitations. The DTs analysed mainly include AI, the Internet of Things (IoT), blockchain, cloud computing and big data. In contrast, DTs such as 3D printing and virtual reality were not explored. Including additional technologies for the CE could yield greater insights. Another limitation is the focus on literature from only the business economy field. Exploring other disciplines, like physics or chemistry, could provide a better understanding of the effects of DT and CE on SD. Additionally, the analysis did not include documents such as annual reports, company records, or funding institution reports.

4.3 Future research

Additional research should deal with these gaps by using diverse methods to validate findings and clarify where they may not apply. This call for investigation invites the audience to contribute to ongoing academic discussion and to influence how organisations, governments, NGOs and stakeholders perceive the relationships under discussion. Connections between DTs, CE and SD – regarding the performance economy, the sharing economy, new business frameworks, strategies and value-driven enterprises – could also be explored. Researchers should analyse the concrete effects of DTs and CE activities on financial and non-financial (ESG) performance and their role in "solid sustainability", defined as consistent sustainable practices that reduce resource consumption. The study suggests testing its framework with quantitative methods. Sector-specific case studies and interview approaches could be used. Future agendas should include topics on AI governance and ethics for CE transition and implementation. Additionally, new human-centric metrics should be developed to assess Industry 5.0's impact on CE and SD.

Appendix

Search string and screening criteria

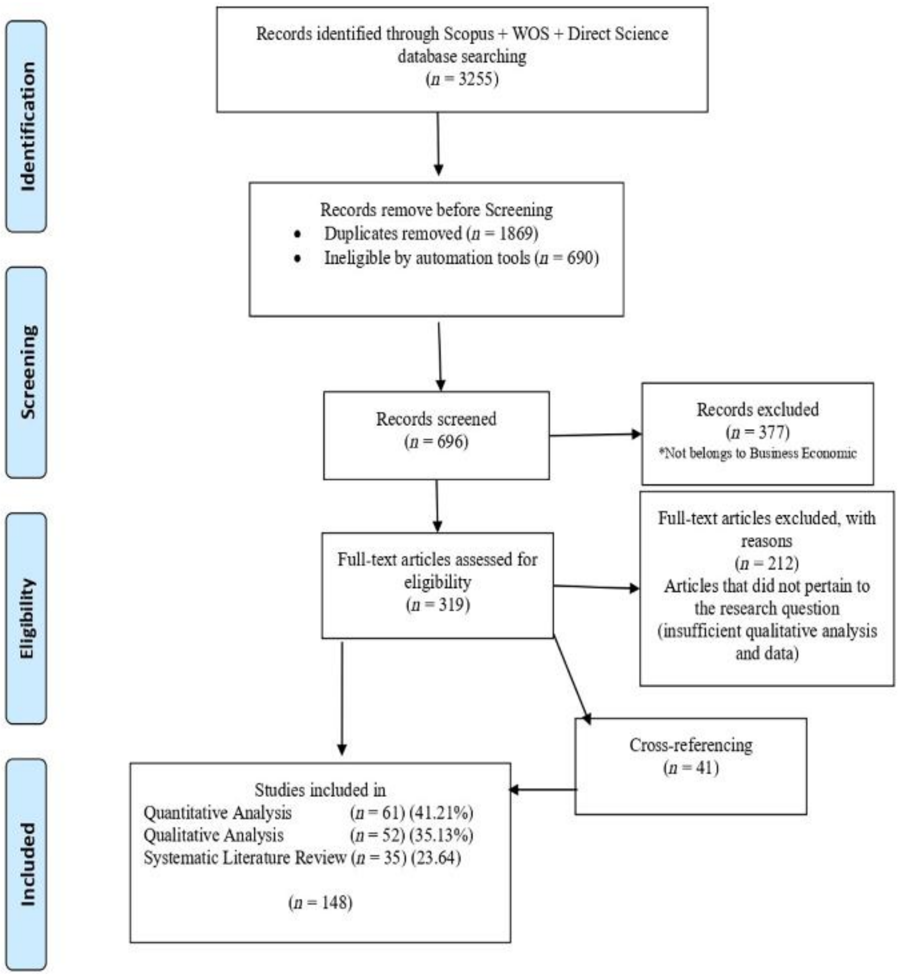

Figure A1. PRISMA diagram. Source: The SLR process adheres to the methodology proposed by Denyer and Tranfield (2009)

Appendix illustrates the PRISMA diagram, which visually represents the SLR process and provides a clear overview of the steps taken and decisions made, thereby enhancing the study's transparency and reproducibility. These steps provide a comprehensive understanding of the coverage of our research topic. This review began with a selection of relevant papers published in highly cited journals and authored by leading academics. Articles were retrieved from Scopus, Direct Science, and the Web of Science (WOS), focusing on digital technologies, the circular economy, and sustainable development, were published in journals from 2014 to 2025. A second round of article selection, including 41 cross-referenced articles, was conducted to gain a more in-depth understanding of the breadth of the future research agenda.

The researchers first examined the full content of 3,255 articles retrieved from a search for "digital technologies", "circular economy", and "sustainable development", limiting the analysis to English-language articles. The PRISMA Diagram reflects the increasing interest among businesses and the economy in a DTs and CE approach to SD, as evidenced by the keywords "Digital Technologies", "Circular Economy", and "Sustainable Development". This research identified 148 articles, including quantitative (61), qualitative (52), and literature review studies (35), focusing on various sectors of the economy such as ecology, supply chain management, marketing, circular business models, barriers, challenges, evidence, rethinking the circular economy, technology transfer, low carbon, sustainable technology, and the economic performance of remanufacturing plastics, among others. The aim is to explore the gaps among DTs, CE, and SD issues in business economics. The main purpose of including business economics is to create a multidisciplinary framework for tackling complex real-world challenges related to sustainability and efficiency. The review also supports linking technical feasibility (engineering), environmental impact (natural sciences), and economic viability (business) to identify research gaps, develop a theoretical foundation, and ensure comprehensive analysis. This approach also blends financial strategy with technical innovation and environmental considerations, fostering proactive business models, optimised resource management, and informed decision-making to generate long-term value.

After reviewing our initial sample, we identified and scanned articles referenced by the reviewed articles, along with other relevant works in our sample. The inclusion/exclusion process depended on whether the publications could provide new insights into the phenomena under investigation, and decisions were made after analysing their titles, contents, and abstracts. SLR analysis evaluates the contributions of research components, including authors, countries, institutions, and journals, to a specific field of study. This type of investigation is often carried out in reviews, and commonly used analysis metrics are also employed. Articles were retrieved from Direct Science, WOS/Scopus for SLR analysis and large enough to warrant SLR analysis (Donthu *et al.*, 2021).

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