Progress in Circular Economy
https://www.sciltp.com/journals/pce

Article

Progress in Circular Economy Future Perspectives and Supply Chain Management Challenges: A Hybrid Approach

Yi-Chun Chen [1], Ching-Hsin Wang [2], Taufik Kurrahman [3], Feng Ming Tsai [3] and Ming-Lang Tseng [4,5,6,7,8,*]

1 Department of Business Administration, College of Management, Asia University, Taichung 41354, Taiwan
2 Department of Healthcare Industry Technology Development and Management, National Chin-Yi University of Technology, Taichung 411030, Taiwan
3 Department of Shipping and Transportation Management, National Taiwan Ocean University, Keelung 202301, Taiwan
4 Institute of Innovation and Circular Economy, Asia University, Taichung 41354, Taiwan
5 The University of Economics and Human Sciences in Warsaw, 01-043 Warsaw, Poland
6 Department of Medical Research, China Medical University Hospital, China Medical University, Taichung 404328, Taiwan
7 Department of Industrial Engineering, Khon Kaen University, Khon Kaen 40002, Thailand
8 UKM-Graduate School of Business, Universiti Kebangsaan Malaysia, Bangi 43000, Malaysia
* Correspondence: tsengminglang@gmail.com or tsengminglang@asia.edu.tw

How To Cite: Chen, Y.-C.; Wang, C.-H.; Kurrahman, T.; et al. Progress in Circular Economy Future Perspectives and Supply Chain Management Challenges: A Hybrid Approach. *Progress in Circular Economy* **2025**, *1*(1), 1.

Received: 21 April 2025
Revised: 9 September 2025
Accepted: 15 September 2025
Published: 17 September 2025

Abstract: This study contributes to the progress of circular economy future perspectives and supply chain management challenges using a hybrid approach. In recent decades, numerous studies have addressed the circular economy in terms of supply chain management benefits; however, few studies have explored the future perspectives and key challenges encountered. In this study, content, bibliographic and cluster analyses are used to extract attributes of challenges to circular economy practices in supply chain management from the Scopus database. The entropy weighted method is subsequently employed to convert the derived attributes' co-occurrence values into comparable scales, facilitating further fuzzy Delphi method analysis. These processes are applied to identify valid key challenges that can inform future progress in the circular economy. The results reveal that waste and energy management, circular business design and strategy, circular resource management, and digital technology utilization and transformation are issues that need to be addressed in future studies.

Keywords: circular economy; supply chain management; entropy weighted method; fuzzy Delphi method; bibliographic analysis; content analysis

1. Introduction

The circular economy (CE) has been advocated and implemented over the past two decades as a strategy to address climate change and environmental degradation by providing novel perspectives on overall industrial production and operations [1–3]. The CE promotes product and process design, production and end-of-life management for improved reuse, recycling and remanufacturing across industries to facilitate more sustainable and efficient production and consumption, which benefits supply chain management (SCM) [4–6]. However, despite the increasing concern for the use of CE practices to enhance SCM, their adoption throughout industries remains inadequate due to various challenges; this stems predominantly from the involvement of numerous stakeholders, which complicates process design and resource management; technological requirements; and intricate practices pertaining to waste and energy management [7–9]. To address these concerns, it is essential to initially determine the challenges associated with redesigning the present supply chain and develop future perspectives and approaches to ensure the gradual and seamless development of CE practices in SCM [10,11].

This study identifies the key challenges associated with the adoption of CE practices in SCM and offers potential guidelines for future development and approaches.

In the literature, CE practices in SCM address the challenge of promoting circularity in the supply chain through the establishment of closed-loop processes along with the pursuit of potential open-loop methods to increase resource efficiency, reduce waste, and enable the reuse and recycling of materials and products, with the aim to reduce energy consumption and environmental impacts [2,4,12,13]. For example, Zheng et al. [14] and Kharayat et al. [11] argued that CE practices in SCM entail the challenges of redesigning all tiers of the manufacturing system to optimize value creation, ensuring that value is preserved in a closed loop over the product's lifespan and dynamically recovering value from diverse forms and volumes of products returned over time. In addition, Meier et al. [15] and Al-Swidi et al. [16] emphasized the difficulties associated with digital technology utilization and transformation to advance and maintain circular material flows and thereby optimize the use of materials for enhanced circular resource management. Wu et al. [6] reported that CE practices in SCM face the challenge of transcending conventional limits of the supply chain and encompass waste and energy management throughout the end-of-life phase, with the aims to minimize waste production and the need for new raw materials, reuse byproducts as inputs for other processes, effectively recycle at the most localized level feasible, and improve reverse logistics processes for a more effective closed-loop system. Therefore, the extensive perspectives to the progress of the CE in SCM that integrates challenges related to circular business design and strategy, waste and energy management, digital technologies utilization and transformation, and circular resource management must be considered. This study argues that these perspectives and associated challenges are needed to be comprehensively understood for enhancing future development.

CE practices in SCM are considered necessary for industries to attain improved operations and reduced environmental consequences [9.14,17]. However, the identification of major difficulties that might provide insights and serve as guidance for future development efforts and approaches remains inadequate [10,11,18]. Prior studies predominantly emphasize the advantages of CE practices in SCM for mitigating environmental impacts. However, limited studies address the key challenges encountered across complex industrial practices, which must be addressed in order to achieve enhanced performance. Consequently, an in-depth assessment of key challenges can contribute to the literature and provide recommendations for future development and research. To address these issues and thoroughly describe the key challenges for CE practices in SCM, this study presents a systematic review to identify relevant keywords and co-occurring themes.

Many studies have employed qualitative and quantitative methods to explore CE practices in SCM [13,14,19]. However, these studies have failed to identify and thoroughly validate the key challenges of CE practices in SCM. To address these issues, in this study, a systematic review that employs content, bibliographic and cluster analyses, the entropy weighted method (EWM) and the fuzzy Delphi method (FDM) is presented. Content, bibliographic and cluster analyses are utilized to identify and cluster challenges associated with CE practices in SCM on the basis of co-occurrence data from Scopus database publications [20–22]. The EWM is used to transform the co-occurrence data obtained from the Scopus database into corresponding weights for further FDM analysis [23–25]. The FDM is subsequently used to validate and remove less important attributes or challenges under perception preferences [26–28]. Hence, the objectives of this study are to identify valid, key challenges for CE practices in SCM and to offer potential future perspectives for progress in the CE.

The subsequent sections are structured as follows. Section 2 contains the literature review. Section 3 describes the proposed systematic review designed to achieve the study objectives. The results are presented in Section 4. In Section 5, future perspectives of progress in the CE and challenges for CE practices in SCM identified. Finally, the conclusions, study limitations, and recommendations for further research are highlighted in Section 6.

2. Literature Review

This section provides an in-depth review of the literature pertaining to the challenges to CE practices in SCM associated with the circular business design and strategy, waste and energy management, digital technology utilization and transformation, and circular resource management.

2.1. Circular Business Design and Strategy

The circular design and strategy are a fundamental CE perspective in SCM that aims to redesign all tiers of business processes and production systems and ensure that value remains preserved within a closed-loop system throughout the lifespan of materials and products [12,29,30]. These endeavors include product and process design focused on waste minimization and product lifespan extension through the development of materials that can be easily disassembled for improved reuse, recovery, and remanufacturing [2,5,13]. Saccani et al. [8] and Bals et al. [31]

emphasized that circular design and strategies are capable of enhancing the durability, reparability and recyclability of products, facilitating better end-of-life management and contributing to CE practices in SCM. Additionally, Zheng et al. [14] and Wu et al. [6] argued that the circular design and strategy can provide economic advantages to firms by minimizing the demand for raw materials and lowering waste disposal expenses, which can be reinvested to enhance the CE in SCM. By prioritizing the circular design of products that are repairable, recyclable, and remanufacturable, firms may diminish their environmental footprint while enhancing their circularity and business competitiveness; however, the circular design and strategy present various challenges that must be addressed.

The circular design and strategy for improved CE practices in SCM is limited by the intricate nature of supply chain processes, including production, distribution and consumption, which involve numerous stakeholders [10,29]. For instance, Roy et al. [10] and Rentizelas and Trivyza [32] argued that a firm's circular design and strategy implementation, which facilitates repair and maintenance activities while developing products intended for extended lifespans beyond those in a linear economy, is challenging due to its potential to undermine the sales of new products, restrict future revenue streams, and thereby present financial challenges that discourage manufacturers and supply chain partners. Salehi et al. [29] emphasized that the circular design and strategy for enhanced CE practices in SCM encounter further difficulties owing to the focus on the need for infrastructure for product returns after each use cycle, in accordance with designated recovery procedures, such as reuse, refurbishment, or remanufacturing. Strategies regarding collection, inspection, and recovery processes, which are essential for addressing the diverse conditions of products, such as multiple cycles of use and recovery, are often neglected. In addition, Tajik et al. [33] and Singh et al. [34] highlighted that the circular design and strategy are challenged by inadequate digital technologies, which restrict the capacity to monitor and control the movement of items throughout the reverse supply chain. In the absence of appropriate technologies, it is challenging to ensure the effective and efficient recovery of products for reuse or recycling. Therefore, a circular design and strategy must incorporate digital technologies to enhance product or waste collection, inspection, and recovery processes, improve resource and end-of-life management, and promote economic performance and CE practices in SCM.

Proposition 1. *The circular business design and strategy in SCM faces challenges*.

2.2. Waste and Energy Management Challenges

Waste and energy management significantly contribute to mitigating the severe consequences of climate change by reducing waste and carbon emissions [17,35,36]. Wu et al. [6] emphasized that effective waste and energy management can reduce waste, emission and energy loss by decelerating, closing and narrowing materials and energy loops. Waste and energy management can enhance byproduct recovery, hazardous waste control, energy conservation and efficiency in alignment with the zero-waste vision [2,37,38]. In addition, Dehshiri et al. [19] argued that a focus on waste and energy management can enhance reuse and recycling, minimize resource waste, and optimize energy consumption, thereby diminishing costs and reducing environmental impacts. Waste and energy management is essential for attaining the zero-waste objective in SCM by applying the CE principles; nevertheless, various challenges must be addressed.

The challenges in waste and energy management encompass the needs for the adoption of circular practices and technologies and the establishment of relationships with suppliers and other stakeholders [17,30,39]. Zhang et al. [30] argued that insufficient stakeholder relationships and collaboration deter firm decision makers from implementing waste and energy management practices. In this context, stakeholder collaboration must include not only technical integration but also the alignment of joint responsibilities and incentives that promote effective waste and energy management. Fernando et al. [17] highlighted that the adoption of technologies is another substantial barrier that constrains waste and energy management, as firms incur expenses related to technical costs. Moreover, Moktadir et al. [39] emphasized that the performance and transparency of waste and energy management products, in conjunction with the recyclability of waste feedstock, are the major challenges that must be addressed. The effectiveness and reliability of waste and energy management are contingent upon the performance and transparency of products, whereas the recycling of waste feedstock is necessary to close the loop in SCM and reduce the dependency on scarce resources. Hence, waste and energy management must be integrated with technologies that can facilitate collaboration among stakeholders and improve waste and energy management product performance and transparency for improved economic benefits.

Proposition 2. *Manufacturing firms face waste and energy management challenges*.

2.3. Utilization and Transformation of Digital Technologies

The utilization and transformation of digital technologies is a perspective that focuses on the application of diverse digital tools, platforms, and systems in specific business processes to enhance efficiency, improve waste management and develop the business model in a supply chain network [3,16,40]. Within this context, Li et al. [37] and Yuan and Pan [1] argued that digital technology utilization and transformation assist firms in tracking and controlling pollutant emissions, precisely forecasting patterns and fluctuations in energy usage, overseeing resource recovery procedures, and thereby reducing environmental impacts and increasing economic benefits. Liu et al. [4] and Moktadir et al. [39] emphasized that digital technology adoption can enhance efficiency and optimize waste and energy management through the use of data analytics and intelligent technologies to upgrade operational processes. In addition, Huang et al. [3] highlighted that digital technologies are capable of optimizing the efficiency, security, transparency, and reliability of information flow and thereby maximizing the capacity of the supply chain network. These studies provide compelling evidence regarding the significance of digital technology utilization and transformation for supporting the transparency of information in the application of CE principles; however, the utilization and transformation of digital technologies continue to face obstacles in numerous domains.

Saccani et al. [8] and Massari et al. [41] argued that digital technology utilization and transformation designed to rectify inefficiencies in the recovery process face obstacles in improving waste sorting and the recycling of complex material compositions, which results disharmony between waste collection, transport, and sorting costs and reduces the subsequent value throughout recycling. Dehshiri et al. [19] and Jaouhari et al. [2] emphasized that transparency is another major challenge for digital technology utilization and transformation in the promotion of a CE. The lack of definitive standards and protocols for sharing information and project implementation results in insufficient knowledge or diverse interpretations, which eventually diminishes trust and limits CE practices in SCM. Furthermore, Fernando et al. [17] and Kharayat et al. [11] highlighted that the adoption and transformation of digital technologies face challenges due to substantial investment costs, which can be particularly burdensome for SMEs. Consequently, efforts to promote digital technology utilization and transformation in the context of CE practices in SCM must address these challenges to increase trust and facilitate information exchange.

Proposition 3. *Digital technology utilization and transformation faces challenges in terms of the SCM network.*

2.4. Circular Resource Management

Circular resource management is another indispensable perspective for improved CE practices in SCM; this concept emphasizes the recirculation of materials, products and energy back into the economy through reverse supply chains [10,13,38]. In circular resource management, resources are recirculated and maintain their value through the reevaluation of conventional reverse supply chains to include CE procedures, including reusing, repairing, remanufacturing, refurbishing, and recycling. These steps are completed in collaboration with one or more supply chain partners to minimize environmental impacts in SCM. For example, Vegter et al. [38] and Chien et al. [42] highlighted that circular resource management directs the reduction, maintenance and recovery of natural resources through regenerative and restorative cycles, which involve stakeholders within the entire supply chain. Lee et al. [13] and Mahmoudi et al. [43] argued that circular resource management accurately assesses the efficiency of energy and material utilization; promotes the design of products for prolonged durability to minimize material waste and raw material extraction; and enhances operational efficiencies, including collection, recycling, and product recyclability efficiencies, within the supply chain. Circular resource management has proven effective in reducing greenhouse gas emissions and overall environmental impacts. The incorporation of a circular resource management perspective into firms' operations is vital for fostering a more sustainable economy throughout the supply chain; nevertheless, various problems must be addressed.

Circular resource management aimed at enhancing CE practices in SCM is challenging because of the interlinked activities of CE practices across production, distribution, and consumption processes [7,17,44]. In this context, Ozkan-Ozen et al. [45] and Agrawal et al. [7] argued that circular resource management is impeded by the insufficient eco-efficiency of technology processes designed to enhance flexibility and interoperability, as well as the difficulty of integrating all CE practices into SCM processes. Pongpunpurt et al. [36] highlighted that circular resource management faces challenges due to insufficient collaboration among businesses across the upstream-to-downstream spectrum, along with increased logistical costs, workforce difficulties, inadequate capital accessibility, insufficient knowledge and technology, and imbalances in supply and demand. In addition, Rashied et al. [44] emphasized that insufficient knowledge and governmental regulations on resource management, which restrict the impetus for internal leadership to embrace circularity, are seen as significant challenges that necessitate urgent resolution. Hence, circular resource management regulations must be strengthened to support the deployment of technologies that can link all stakeholders, facilitate collaboration, and integrate processes to improve CE practices in SCM.

Proposition 4. *Circular resource management poses challenges in SCM.*

3. Method

This section delineates the data collection process and provides comprehensive explanations of all the methodologies employed, including bibliographic analysis, content analysis, the EWM, and the FDM.

3.1. Data Collection

The literature has extensively investigated the importance of the circular economy, together with its challenges and future outlook, with the aim to improve industrial operations and sustainability [19,44,46]. Thus, in this study, a data-driven investigation of the challenges and future prospects of the circular economy is undertaken. The Scopus database was employed for this data-driven search, as it is regarded as a comprehensive bibliographic source that provides access to a significant amount of scholarly research and extensive pertinent data and outperforms other existing sources with respect to both quantity and quality [21,22,47]. Identifiers such as abstracts, titles, and keywords were used in this data-driven examination of the Scopus database.

The following search terms were employed in this investigation: ((“circular” OR “circularity” OR “circular economy”) AND (“challenge” OR “challenges”) AND (“future” OR “future perspective” OR “future prospect”)). These terms served as the basis for the search that was initiated on 23 February 2025. The search results were based on keywords, abstracts, and titles, regardless of chronological order. A total of 2852 articles and reviews were obtained.

3.2. Content, Bibliographic and Cluster Analyses

For the content, bibliographic and cluster analyses, VOSviewer version 1.6.19 software was employed. VOSviewer arranges data into clusters or perspectives according to related meanings, which facilitates the visualization of associations and the creation of scientific topographies [21,22,48]. Furthermore, VOSviewer was used to discover major challenges and future perspectives in the circular economy and to reveal the distribution of keyword or attribute co-occurrence. This process was undertaken to provide relevant insights that could assist in understanding challenges and future prospects of the circular economy that are closely associated with industrial practices [20,49]. Therefore, VOSviewer is an adequate tool for discerning attributes relevant to the challenges and future perspectives of the circular economy.

3.3. Entropy Weighting Method

The EWM was applied to data derived from the Scopus database via multiple procedures. In this method, the degree of variability in a system is quantified, and weights are objectively distributed among different attributes, thereby reducing the influence of human subjectivity [23–25]. The entropy level in this investigation exhibited an inverse correlation with the allocated weight. A correlation existed between a decline in encoded information and an increase in entropy. The equation below denotes the search frequency, represented as b, for a certain attribute at a designated time, given as c.

$$F_b = \sum_{c=1}^{\ell} f_b(c) \tag{1}$$

The equations below were further utilized to calculate the entropy for each attribute.

$$\varepsilon = \frac{1}{[(e^{0.5} - 1) \times b]} \tag{2}$$

$$E_b = \varepsilon \times \sum_{c=1}^{\ell} f\left(\frac{f_b(c)}{F_b}\right) \tag{3}$$

The following equations were then used to further determine the normalized entropy weight ω_b:

$$\bar{E} = \sum_{b=1}^{k} E_b \tag{4}$$

$$\theta_b = \frac{1}{(b - \bar{E})} \times (1 - E_b) \tag{5}$$

$$\omega_b = \frac{\theta_b}{\sum_{b=1}^{k} \theta_b} \tag{6}$$

3.4. Fuzzy Delphi Method

The FDM combines fuzzy logic and the Delphi method and is intended to address imprecision and ambiguity, which are often inherent in qualitative data. This integrated methodology is essential for the assessment and elimination of attributes that are deemed invalid and of little significance [27,28,50]. Within this method, the calculated entropy weight value is used to validate attributes. The following equation is applied by dividing the entropy weight value ω_b by the total number of attributes n to obtain the convex combination value D_b for the validation of the attributes [26,27].

$$D_b = \omega_{bn}/n \tag{7}$$

The threshold γ is further calculated using the following equation:

$$\gamma = \sum_{a=1}^{n} (D_b /n) \tag{8}$$

The attribute is considered valid if the D_b value exceeds γ. In contrast, the attribute is considered invalid if the D_b value is less than γ. The accepted attributes from the first-round FDM analysis were subsequently employed in the second-round EWM and FDM analyses to achieve the final valid structure comprising valid clusters or perspectives and attributes or challenges, utilizing the same equations.

3.5. Analytical Procedures

The analytical steps, as depicted in Figure 1, are outlined below:

(1) The content and bibliographic analyses are conducted by employing the Scopus database and VOSviewer to identify the keywords or attributes pertinent to CE challenges along with their co-occurrences. These keywords or attributes are subsequently clustered using VOSviewer to obtain a future perspective.

(2) The first-round EWM is then implemented to transform the attribute co-occurrence entropy into comparable scales. This process requires the completed computation of Equations (1)–(6).

(3) The first-round FDM is subsequently performed by employing the EWM results to validate and discard any keywords or attributes deemed less important through the application of Equations (7)–(8). Next, the second-round EWM and FDM are carried out utilizing the exact same equations to form the final valid structure comprising valid clusters and attributes associated with key progress in future CE perspectives and challenges in SCM.

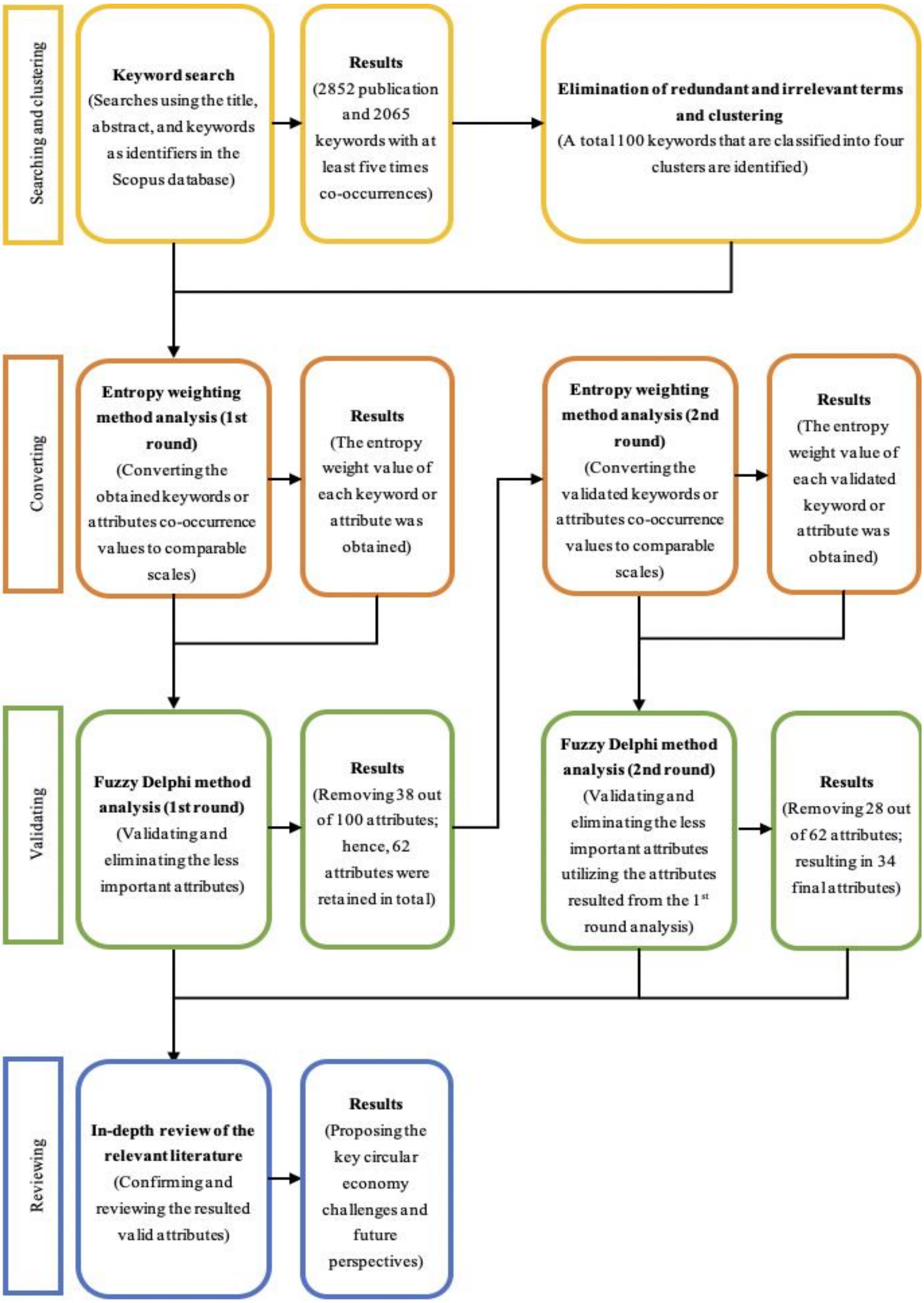

Figure 1. Analytical procedures.

4. Results

This section describes the findings of the content and bibliographic analyses, in addition to the EWM and FDM analyses.

(1) Content, bibliographic and cluster analyses

Based on the findings of the content, bibliographic and cluster analyses, the search in the Scopus database identified a total of 2852 journal publications. VOSviewer was employed to visually represent the distribution of keywords in the co-occurrence bibliographic coupling form. A total of 2065 keywords or attributes that occurred a minimum of five times were identified. Furthermore, 100 keywords or attributes were obtained following the removal of identical terms, acronyms, methodological terminology, industrial keywords, and all redundant entries. Cluster analysis via VOSviewer was subsequently applied to the derived keywords or attributes. Four clusters were identified from the 100 keywords or attributes, and the network visualization is displayed in Figure 2. The identified clusters were then redefined following an in-depth literature review of circular business design and strategy, waste and energy management, digital technology utilization and transformation and circular resource management. Table 1 presents the clustered list of attributes along with their co-occurrences.

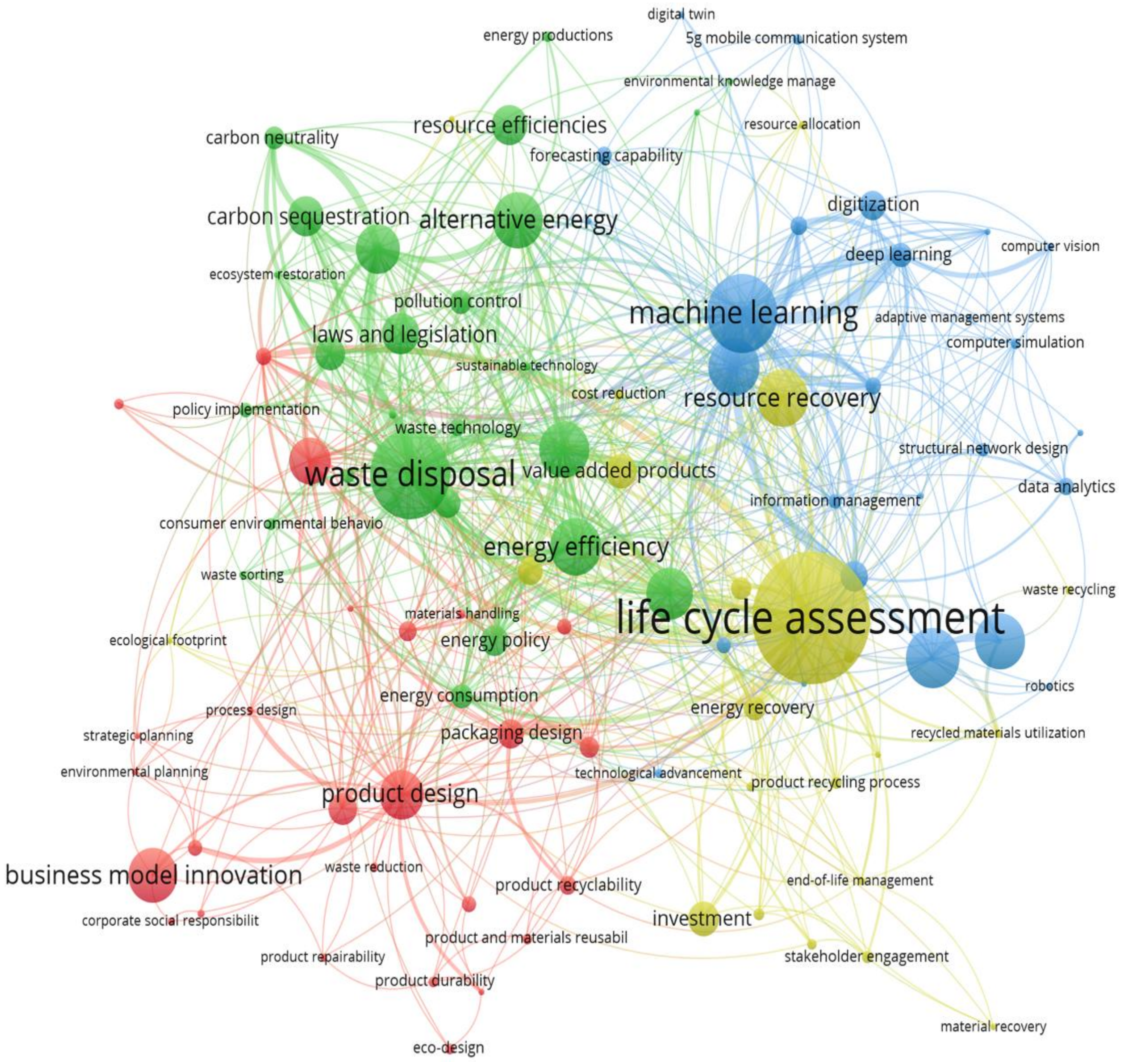

Figure 2. Network visualization.

(2) Entropy weighting method

The EWM was employed to properly quantify the information associated with each keyword or attribute retrieved from the content and bibliographic analyses. This method is used to examine inadequate information while producing precise weights and assessing the utility value of the attributes. By employing keyword co-occurrences, the entropy value, which serves as a metric to assess the degree of disorder in a system while attributing weights to a specific attribute, is obtained. Equations (1)–(5) were employed to determine the entropy value. A high entropy value signifies that an attribute has a substantial impact on the system, whereas a high weight indicates a significant concentration of information. The entropy weights for the attributes were computed via Equation (6). The first-round EWM results are presented in Table 2. The entropy weights resulting from this analysis were further utilized for the first-round FDM analysis.

Table 1. List of identified keywords or attributes.

Clusters	Keywords or Attributes	Co-Occurrences	Clusters	Keywords or Attributes	Co-Occurrences
Circular business design and strategy (Perspective 1)	Business model innovation	49	Digital technologies utilization and transformation (Perspective 3)	3D printing	54
	Circular design	14		5G mobile communication systems	9
	Corporate social responsibility	7		Accident prevention systems	14
	Eco-design	9		Adaptive management systems	5
	Environmental awareness	5		Additive manufacturing	50
	Environmental monitoring	17		Artificial intelligence	51
	Environmental planning	5		Automation	15
	Extended producer responsibility	9		Big data analytics	5
	Manufacturing process	14		Computer simulation	9
	Material flow analysis	41		Computer vision	6
	Materials handling	8		Data acquisition	5
	Network analysis	7		Data analytics	15
	Packaging design	26		Decision support systems	6
	Packaging materials	18		Deep learning	20
	Process design	6		Digital twin	6
	Process optimization	15		Digitization	25
	Product design	44		Forecasting capability	15
	Product durability	9		Information management	12
	Product recyclability	16		Internet of things	27
	Product reparability	7		Machine design	6
	Product and materials reusability	9		Machine learning	72
	Risk assessment	28		Process control	5
	Strategic planning	6		Robotics	5
	Sustainable design	5		Structural network design	11
	Sustainable materials	13		Technological advancement	8
	Waste reduction	8		Technology benchmarking	16
Waste and energy management (Perspective 2)	Alternative energy	50	Circular resource management (Perspective 4)	Cost benefit analysis	19
	Carbon emission	44		Cost reduction	9
	Carbon neutrality	19		Ecological footprint	6
	Carbon sequestration	35		End-of-life management	7
	Consumer environmental behavior	10		Energy conservation	24
	Cost effectiveness	50		Energy recovery	21
	Ecosystem restoration	6		Investment	30
	Emission control	26		Life cycle assessment	125
	Energy consumption	20		Material recovery	6
	Energy efficiency	52		Product and materials repurposing	8
	Energy policy	27		Product recovery	5
	Energy productions	9		Product recycling process	10
	Environmental policy	29		Profitability	9

Table 1. *Cont.*

Clusters	Keywords or Attributes	Co-Occurrences	Clusters	Keywords or Attributes	Co-Occurrences
	Environmental technology	46		Recycled materials utilization	7
	Environmental knowledge management	5		Recycling technologies	5
	Laws and legislation	36		Resource allocation	7
	Policy implementation	12		Resource recovery	52
	Pollution control	21		Reverse logistics	10
Waste and energy management (Perspective 2)	Resource efficiencies	35	Circular resource management (Perspective 4)	Stakeholder engagement	10
	Sustainable consumption	12		Value added products	30
	Sustainable resource management	5		Waste recycling	7
	Sustainable technology	7			
	Waste disposal	83			
	Waste management systems	7		Water recycling	10
	Waste sorting	6			
	Waste technology	15			

Table 2. First-round EWM.

Clusters		Keywords or Attributes	Ratio	Normalize	Entropy	Entropy Weight
	1	Business model innovation	0.12405	0.07946	0.92054	0.03670
	2	Circular design	0.03544	0.03633	0.96367	0.03842
	3	Corporate social responsibility	0.01772	0.02194	0.97806	0.03900
	4	Eco-design	0.02278	0.02645	0.97355	0.03882
	5	Environmental awareness	0.01266	0.01698	0.98302	0.03919
	6	Environmental monitoring	0.04304	0.04155	0.95845	0.03821
	7	Environmental planning	0.01266	0.01698	0.98302	0.03919
	8	Extended producer responsibility	0.02278	0.02645	0.97355	0.03882
	9	Manufacturing process	0.03544	0.03633	0.96367	0.03842
Circular business design and strategy (Perspective 1)	10	Material flow analysis	0.10380	0.07217	0.92783	0.03699
	11	Materials handling	0.02025	0.02424	0.97576	0.03890
	12	Network analysis	0.01772	0.02194	0.97806	0.03900
	13	Packaging design	0.06582	0.05497	0.94503	0.03768
	14	Packaging materials	0.04557	0.04320	0.95680	0.03815
	15	Process design	0.01519	0.01952	0.98048	0.03909
	16	Process optimization	0.03797	0.03812	0.96188	0.03835
	17	Product design	0.11139	0.07504	0.92496	0.03688
	18	Product durability	0.02278	0.02645	0.97355	0.03882
	19	Product recyclability	0.04051	0.03986	0.96014	0.03828
	20	Product reparability	0.01772	0.02194	0.97806	0.03900

Table 2. *Cont.*

Clusters		Keywords or Attributes	Ratio	Normalize	Entropy	Entropy Weight
Circular business design and strategy (Perspective 1)	21	Product and materials reusability	0.02278	0.02645	0.97355	0.03882
	22	Risk assessment	0.07089	0.05758	0.94242	0.03758
	23	Strategic planning	0.01519	0.01952	0.98048	0.03909
	24	Sustainable design	0.01266	0.01698	0.98302	0.03919
	25	Sustainable materials	0.03291	0.03449	0.96551	0.03850
	26	Waste reduction	0.02025	0.02424	0.97576	0.03890
			1.00000	0.91915	25.08085	1.00000
Waste and energy management (Perspective 2)	27	Alternative energy	0.07496	0.05961	0.94039	0.03749
	28	Carbon emission	0.06597	0.05504	0.94496	0.03767
	29	Carbon neutrality	0.02849	0.03111	0.96889	0.03863
	30	Carbon sequestration	0.05247	0.04747	0.95253	0.03798
	31	Consumer environmental behavior	0.01499	0.01933	0.98067	0.03910
	32	Cost effectiveness	0.07496	0.05961	0.94039	0.03749
	33	Ecosystem restoration	0.00900	0.01301	0.98699	0.03935
	34	Emission control	0.03898	0.03882	0.96118	0.03832
	35	Energy consumption	0.02999	0.03228	0.96772	0.03858
	36	Energy efficiency	0.07796	0.06105	0.93895	0.03743
	37	Energy policy	0.04048	0.03984	0.96016	0.03828
	38	Energy productions	0.01349	0.01783	0.98217	0.03916
	39	Environmental policy	0.04348	0.04184	0.95816	0.03820
	40	Environmental technology	0.06897	0.05660	0.94340	0.03761
	41	Environmental knowledge management	0.00750	0.01126	0.98874	0.03942
	42	Laws and legislation	0.05397	0.04836	0.95164	0.03794
	43	Policy implementation	0.01799	0.02219	0.97781	0.03898
	44	Pollution control	0.03148	0.03342	0.96658	0.03854
	45	Resource efficiencies	0.05247	0.04747	0.95253	0.03798
	46	Sustainable consumption	0.01799	0.02219	0.97781	0.03898
	47	Sustainable resource management	0.00750	0.01126	0.98874	0.03942
	48	Sustainable technology	0.01049	0.01468	0.98532	0.03928
	49	Waste disposal	0.12444	0.07959	0.92041	0.03670
	50	Waste management systems	0.01049	0.01468	0.98532	0.03928
	51	Waste sorting	0.00900	0.01301	0.98699	0.03935
	52	Waste technology	0.02249	0.02619	0.97381	0.03882
			1.00000	0.91774	25.08226	1.00000
Digital technologies utilization and transformation (Perspective 3)	53	3D printing	0.11441	0.07613	0.92387	0.03678
	54	5G mobile communication systems	0.01907	0.02317	0.97683	0.03889
	55	Accident prevention systems	0.02966	0.03203	0.96797	0.03854
	56	Adaptive management systems	0.01059	0.01479	0.98521	0.03923

Table 2. *Cont.*

Clusters		Keywords or Attributes	Ratio	Normalize	Entropy	Entropy Weight
Digital technologies utilization and transformation (Perspective 3)	57	Additive manufacturing	0.10593	0.07299	0.92701	0.03691
	58	Artificial intelligence	0.10805	0.07379	0.92621	0.03688
	59	Automation	0.03178	0.03364	0.96636	0.03847
	60	Big data analytics	0.01059	0.01479	0.98521	0.03923
	61	Computer simulation	0.01907	0.02317	0.97683	0.03889
	62	Computer vision	0.01271	0.01703	0.98297	0.03914
	63	Data acquisition	0.01059	0.01479	0.98521	0.03923
	64	Data analytics	0.03178	0.03364	0.96636	0.03847
	65	Decision support systems	0.01271	0.01703	0.98297	0.03914
	66	Deep learning	0.04237	0.04111	0.95889	0.03818
	67	Digital twin	0.01271	0.01703	0.98297	0.03914
	68	Digitization	0.05297	0.04776	0.95224	0.03791
	69	Forecasting capability	0.03178	0.03364	0.96636	0.03847
	70	Information management	0.02542	0.02865	0.97135	0.03867
	71	Internet of things	0.05720	0.05023	0.94977	0.03781
	72	Machine design	0.01271	0.01703	0.98297	0.03914
	73	Machine learning	0.15254	0.08804	0.91196	0.03631
	74	Process control	0.01059	0.01479	0.98521	0.03923
	75	Robotics	0.01059	0.01479	0.98521	0.03923
	76	Structural network design	0.02331	0.02689	0.97311	0.03874
	77	Technological advancement	0.01695	0.02121	0.97879	0.03897
	78	Technology benchmarking	0.03390	0.03521	0.96479	0.03841
Circular resource management (Perspective 4)	79	Cost benefit analysis	0.04556	0.04553	0.95447	0.04508
	80	Cost reduction	0.02158	0.02678	0.97322	0.04597
	81	Ecological footprint	0.01439	0.01974	0.98026	0.04630
	82	End-of-life management	0.01679	0.02220	0.97780	0.04618
	83	Energy conservation	0.05755	0.05316	0.94684	0.04472
	84	Energy recovery	0.05036	0.04869	0.95131	0.04493
	85	Investment	0.07194	0.06126	0.93874	0.04434
	86	Life cycle assessment	0.29976	0.11684	0.88316	0.04171
	87	Material recovery	0.01439	0.01974	0.98026	0.04630
	88	Product and materials repurposing	0.01918	0.02454	0.97546	0.04607
	89	Product recovery	0.01199	0.01716	0.98284	0.04642
	90	Product recycling process	0.02398	0.02894	0.97106	0.04586
	91	Profitability	0.02158	0.02678	0.97322	0.04597
	92	Recycled materials utilization	0.01679	0.02220	0.97780	0.04618
	93	Recycling technologies	0.01199	0.01716	0.98284	0.04642
	94	Resource allocation	0.01679	0.02220	0.97780	0.04618
	95	Resource recovery	0.12470	0.08399	0.91601	0.04326

Table 2. *Cont.*

Clusters		Keywords or Attributes	Ratio	Normalize	Entropy	Entropy Weight
Circular resource management (Perspective 4)	96	Reverse logistics	0.02398	0.02894	0.97106	0.04586
	97	Stakeholder engagement	0.02398	0.02894	0.97106	0.04586
	98	Value added products	0.07194	0.06126	0.93874	0.04434
	99	Waste recycling	0.01679	0.02220	0.97780	0.04618
	100	Water recycling	0.02398	0.02894	0.97106	0.04586
			1.00000	0.82717	21.17283	1.00000

(3) Fuzzy Delphi method

The FDM analysis was conducted using an extensive list of the 100 attributes in four clusters or perspectives established through content and bibliographic analyses and according to the results of the EWM analysis. This method was employed to ascertain the key attributes deemed valid in the context of circular economy challenges and future perspectives. To achieve these goals, the FDM analysis calculates the convex combination value utilizing the entropy value of each attribute obtained from the EWM through Equation (7). The value of the convex combination must surpass the predetermined threshold derived from Equation (8) for the attribute to be deemed acceptable. The first-round FDM analysis resulted in the removal of 38 out of the 100 assessed attributes, as shown in Table A1. Hence, this analysis yielded a set of four clusters and 62 attributes. Furthermore, the second-round EWM and FDM analyses were performed on the set of four clusters and 62 attributes that resulted from the first-round FDM analysis. Table A2 presents the results of the second-round EWM and FDM analyses, which led to the elimination of 28 out of 62 attributes. The resulting final valid structure comprised four clusters or perspectives and 34 attributes or challenges; these results and their FDM values are presented in Table 3. The results indicated that waste and energy management are the primary perspectives that must be considered and prioritized to achieve greater progress in the CE. Additionally, circular business design and strategy, circular resource management and digital technology utilization and transformation are sequentially the perspectives with the next highest importance. In addition, the following valid key challenges must be addressed to attain improved CE practices in SCM: environmental awareness (A2), environmental planning (A3), and sustainable design (A8) from a circular business design and strategy perspective; environmental knowledge management (A12) and sustainable resource management (A13) from a waste and energy management perspective; adaptive management systems (A17), big data analytics (A18), data acquisition (A20), process control (A24) and robotics (A25) from a digital technology utilization and transformation perspective; and product recovery (A30) and recycling technologies (A32) from a circular resource management perspective.

Table 3. Final valid structure.

Clusters		Attributes	FDM
Circular business design and strategy (Perspective 1)	A1	Corporate social responsibility	0.00445
	A2	Environmental awareness	0.00452
	A3	Environmental planning	0.00452
	A4	Network analysis	0.00445
	A5	Process design	0.00448
	A6	Product reparability	0.00445
	A7	Strategic planning	0.00448
	A8	Sustainable design	0.00452
Average: 0.00448(#2)			
Waste and energy management (Perspective 2)	A9	Consumer environmental behavior	0.00511
	A10	Ecosystem restoration	0.00521
	A11	Energy productions	0.00513
	A12	Environmental knowledge management	0.00524
	A13	Sustainable resource management	0.00524
	A14	Sustainable technology	0.00518
	A15	Waste management systems	0.00518
	A16	Waste sorting	0.00521
Average: 0.00519 (#1)			
Digital technologies utilization and transformation (Perspective 3)	A17	Adaptive management systems	0.00314
	A18	Big data analytics	0.00314
	A19	Computer vision	0.00312
	A20	Data acquisition	0.00314
	A21	Decision support systems	0.00312
	A22	Digital twin	0.00312
	A23	Machine design	0.00312
	A24	Process control	0.00314
	A25	Robotics	0.00314
	A26	Technological advancement	0.00309
Average: 0.00313 (#4)			
Circular resource management (Perspective 4)	A27	Ecological footprint	0.00449
	A28	End-of-life management	0.00446
	A29	Material recovery	0.00449
	A30	Product recovery	0.00452
	A31	Recycled materials utilization	0.00446
	A32	Recycling technologies	0.00452
	A33	Resource allocation	0.00446
	A34	Waste recycling	0.00446
Average: 0.00448 (#3)			

5. Discussion

This section discusses progress in the future of the CE, with a focus on circular business design and strategy, waste and energy management, digital technology utilization and transformation, and circular resource management. Additionally, the challenges of CE practices in SCM are described.

5.1. Progress in Future Perspectives of the CE

The progress of the CE includes a comprehensive array of perspectives, such as circular business design and strategy, waste and energy management, digital technology utilization and transformation, and circular resource management.

First, the progress of CE requires the design of manufacturing systems that can close the loop and enable the continuous utilization of products, parts and components over their life cycles according to the circular business design and strategy perspective [10,29,47]. To achieve these goals, a circular business design and strategy must provide a closed-loop system design that enables consumers to return their obsolete products for reintegration into the initial supply chain for repair, remanufacturing, or recycling [18,31,32]. In the recovery process, a system design that is capable of reducing and recycling waste to generate products with added value, optimizing resource utilization, and decreasing adverse environmental consequences throughout every stage of the product cycle is necessary. Circular business design and strategy must not only focus on reuse and recycling processes but also prioritize the reusability and recyclability of the product itself to enhance these processes to achieve improved closed-loop systems [13,33,39].

In addition to the closed-loop design, the open loop design that facilitates the market-based procurement of waste from different supply chains for use as input in the primary supply chain must also be considered to enhance CE practices in SCM.

From the perspective of waste and energy management for enhanced CE, firms must effectively manage waste, convert it into profit and maximize energy efficiency, which leads to minimized greenhouse gas emissions and addresses the implications of climate change [17,36]. To attain these targets, waste and energy management practices must be designed to prevent waste and energy waste generation across all production phases through measures to reduce energy consumption [19,35]. Waste and energy management must prioritize the collection of postconsumer waste, which is currently insufficient to transition the linear supply chain network toward a circular system and mitigate environmental degradation [31,39]. This postconsumer waste collection may include diverse entities, including nongovernmental organizations that incorporate waste material gathering into their primary operations or commercial partners that market recyclable products. In addition, stringent rules and regulations, together with financial assistance from governmental agencies, are essential for the effective management of waste and byproducts, as well as for the mitigation of pollution stemming from diverse industrial operations for improving CE [9,43].

The utilization and transformation of digital technologies reflect an important perspective for enhancing CE practices in SCM. Firms must be adept at adopting and advancing disruptive digital technologies that enhance flexibility, traceability, visibility, and information sharing throughout the entire supply chain, which are fundamental for reconceptualizing value chains into circular ecosystems [4,15,41]. These requirements strengthen and facilitate the planning and management of resources, manufacturing, and logistics across all stages of the closed-loop process with consideration of the social and environmental implications. The deployment and transformation of digital technology must extend beyond the improvement in internal operational efficiency to the enhancement of organizational performance. Moreover, firms must be proficient in adopting and creating technologies that enhance resource efficiency, minimize waste, and foster cooperation and innovation throughout the supply chain [2,40]. Digital technology utilization and transformation entail the effective leveraging of modern technology to create new markets or business opportunities, reinvent operations and improve value delivery to achieve improved CE practices in SCM [16,34].

The achievement of improved CE further requires circular resource management in SCM. This perspective must be refined to optimize resource consumption and reduce waste formation [38,45]. Circular resource management must be adopted to effectively reintegrate resources and energy into the economy via a reverse supply chain [10,42]. This method is necessary to augment resource productivity owing to its capacity to improve recycling, reuse, and regeneration practices [7,13]. A firm adopting circular resource management must forge alliances with suppliers to recuperate, repurpose, and recycle materials from products at the end of their life cycle. These recovered materials can potentially be reintegrated into the manufacturing process to minimize the demand for new raw materials, decrease waste, and enhance resource productivity. In addition, circular resource management necessitates the total closure of all resource loops and the disregard of the exploration of virgin resources [44].

5.2. Challenges to CE Practices in SCM

Challenges to CE practices in SCM are found in circular business design and strategy, waste and energy management, digital technology utilization and transformation, and circular resource management perspectives. These challenges encompass environmental awareness (A2), environmental planning (A3), and sustainable design (A8) from a circular business design and strategy perspective; environmental knowledge management (A12) and sustainable resource management (A13) from a waste and energy management perspective; adaptive management systems (A17), big data analytics (A18), data acquisition (A20), process control (A24) and robotics (A25) from a digital technology utilization and transformation perspective; and product recovery (A30) and recycling technologies (A32) from a circular resource management perspective.

From the circular business design and strategy perspective, environmental awareness and planning among all stakeholders, in conjunction with the sustainable design of products and processes, poses significant challenges to the effective design and execution of circular business models and strategies across industrial sectors. In this context, poor environmental awareness and interest from industry's stakeholders impede the implementation of CE practices in SCM, since these challenges diminish demand for circular and sustainable alternatives, restrict the implementation of potential autonomous systems in labor-oriented circularity practices, as well as obstruct the collaborative efforts necessary to close material loops [8,45]. Without strong environmental awareness, a widespread lack of in-depth comprehension and engagement with environmental concerns among consumers, firms, and legislators, hinder the development of products, procedures, and technologies that could facilitate firms' progress toward the adoption of CE practices in the supply chain. Moreover, environmental planning challenges hinder the development of a thorough, expansive, and collaborative strategies, impeding the execution of CE practices in SCM by causing deficiencies in strategic alignment, resource distribution, and process design essential for effective circularity [35,42]. Inadequate environmental planning that failed to address the intricacies of resource flows, technological advancements, unpredictability, laws and regulations, financial feasibility, and stakeholder involvement obstruct the design of products and processes that support improved CE practices in SCM. Additionally, challenges in sustainable design that restrict the selection and utilization of sustainable materials, as well as challenges regarding the design for disassembly, reparability, recyclability, remanufacturing, and waste management, must be addressed to improve the circular design and strategies for CE practices in SCM [37,44]. To address such challenges, industries must embrace a multifaceted strategy that encompasses development in materials and design processes, infrastructure investment, supporting legislation, stakeholders' knowledge, and robust cooperation across the value chain is needed.

From the perspective of waste and energy management, the challenges presented by environmental knowledge management hinder industries' improvements in environmental decision-making for supply chain reengineering, which could limit preparedness and effective recovery strategies for enhanced CE practices in SCM [34,48]. In this context, this study argues that environmental knowledge management faces challenges due to data dispersion concerning waste substances, production and management technologies, energy usage, and renewable energy sources, which hinder the comprehensive accessibility, integration, and analysis of data for refined waste and energy management. A firm culture that neglects information sharing or lacks efficient collaboration practices obstructs the transfer of environmental understanding and constrains environmental knowledge management across the industries value chain. The continuous development of waste and energy concerns makes it difficult to maintain up-to-date environmental information, which necessitates ongoing learning and adaptation. In addition, the challenges of sustainable resource management obstruct resource efficiency, leading to significant environmental consequences and limiting long-term sustainability [45]. This study argues that sustainable resource management is impeded by the intricacy of contemporary waste streams, which often include a mixture of components, notably hazardous compounds and composite substances, and thereby complicate recycling and resource recovery processes for better waste management. To address these difficulties, a systematic strategy that combines technology innovation, governmental initiatives, and financial support is essential for advancing waste and energy systems to improve CE practices in SCM.

The advancement of CE practices in SCM is limited by the inadequate adoption of digital technology utilization and transformation perspectives, including adaptive management systems, big data analytics, data acquisition, process control, and robotics, which are essential for improving circularity, resilience, and transparency across various industries. In this context, adaptive management systems and big data analytics face challenges owing to the need for effective data acquisition and the combining of data sources, modeling programs, and feedback systems, which are intricate and necessitate advanced data administration and interoperability. In the process control for digital transformation, issues arise in real-time data processing and semi- or fully autonomous decision-making, which necessitate the use of advanced algorithms and credible streams of data. Prior studies argued that challenges in these attributes cause industrial failure to improve the robustness and quality of business decisions, resulting in restricted visibility and suboptimal planning, thereby causing supply chain operations to remain fragmented and susceptible to inefficiencies [1,7,30]. Additionally, the substantial initial expenditure associated with the implementation of advanced robotic systems remains a significant barrier to the adoption and transformation of digital technologies [2]. The difficulty of establishing an evident and prompt return on investment constrains the development of CE practices in SCM. Engaging in skills development and establishing prominent regulatory standards to foster technology utilization and transformation are essential for implementing managerial changes inside firms.

From the perspective of circular resource management, product recovery and recycling technologies designed to minimize waste, preserve natural resources, and mitigate environmental consequences face challenges that impede their successful adoption. In many instances by prior studies, industries' product recovery is hindered by designs that complicate disassembly, rendering intricate and expensive repair, refurbishing, or recycling practices for better CE in SCM [2,8,47]. The erratic pattern in the quantity and timing of product returns to the reverse supply chain that facilitates circular resource management complicates the planning and optimization of product recovery operations. Furthermore, given the products' insufficient traceability, the monitoring of products and their parts over their lifespans is typically complex and arduous, which complicates the management of end-of-life products for recovery. In addition, recycling technologies aimed at enhancing product recovery often have limited efficiency or cost-effectiveness given the existence of various materials and intricate product designs, which constrains optimal resource management for improved CE practices in SCM [9]. Hence, This study argues that supporting regulations and fostering cooperation across the entire supply chain is needed to promote the development of innovative product designs that are capable of facilitating effective product recovery and recycling technology processes.

6. Conclusions

This study strives to identify valid progress in future CE perspectives and challenges for the adoption of CE practices in SCM. The progress of CE practices in SCM has received significant attention and scrutiny in recent years because of the capacity of such practices to mitigate climate change and adverse environmental impacts through the enhanced design, manufacturing, and waste management of materials and products, which can facilitate improved reuse, recycling, and remanufacturing within the industry. Nonetheless, the advancement of CE practices in SCM is insufficient, and its implementation across industries remains markedly deficient due to numerous challenges, which arise primarily from intricate process designs, resource management, technological prerequisites, and waste and energy management. The systematic review approach adopted in this study advances CE future perspectives and highlights key challenges for CE practices in SCM.

The findings highlight the importance of the perspectives of waste and energy management, circular business design and strategy, circular resource management, and digital technology utilization and transformation. These identified perspectives and the related attributes or challenges must be addressed to promote the advancement of CE practices in SCM. The challenges include environmental awareness, environmental planning, and sustainable design from a circular business design and strategy perspective; environmental knowledge management and sustainable resource management from a waste and energy management perspective; adaptive management systems, big data analytics, data acquisition, process control, and robotics from a digital technology utilization and transformation perspective; and product recovery and recycling technologies from a circular resource management perspective. These challenges must be addressed in initiatives to improve the adoption of CE practices in SCM.

This study substantially contributes to the literature on CE practices in SCM by establishing the progress in the CE and highlighting the future perspectives that need to be considered. This study further offers insights into the pertinent and valid challenges that need to be addressed to promote CE practices in SCM. The importance of addressing the perspectives of waste and energy management, circular business design and strategy, circular resource management, and digital technology utilization and transformation is highlighted to foster progress in the CE. In addition, environmental awareness, environmental planning, and sustainable design from a circular business design and strategy perspective; environmental knowledge management and sustainable resource management from a waste and energy management perspective; adaptive management systems, big data analytics, data acquisition, process control, and robotics from a digital technology utilization and transformation perspective; and product recovery and recycling technologies from a circular resource management perspective are the valid, key challenges for CE practices in SCM that need to be addressed.

This study has certain limitations that future studies may address. First, it is essential to acknowledge the possible limitations of this study regarding its structural depth, since the attributes or challenges employed were sourced from the current literature within a single database utilizing a particular set of search terms. Future studies may expand and enhance this structure by discovering and employing extended search terms. Moreover, future studies may include other credible data sources to achieve an expanded structure. Furthermore, this study does not focus on any specific industry or country. Notwithstanding this study's wide generalizability, future research may explore progress in CE future perspectives and key challenges to CE practices in SCM across various industries or countries to extend the literature and achieve a greater understanding of the subject. Future research may also develop comparisons across geographical locations. Finally, the methods used in this research may be applied to other fields to expand the literature.

Author Contributions

C.Y.-C.: conceptualization, methodology; T.F.M., K.T., W.C.-H. and T.M.-L.: data curation, writing—original draft preparation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

Given the role as Editor-in-Chief, Ming Lang Tseng had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Appendix

Table A1. First-round FDM analysis results.

Clusters		Keywords or attributes	Entropy Weight	FDM	Decision
Circular business design and strategy (Perspective 1)	1	Business model innovation	0.03670	0.00141	Unaccepted
	2	Circular design	0.03842	0.00148	Unaccepted
	3	Corporate social responsibility	0.03900	0.00150	Accepted
	4	Eco-design	0.03882	0.00149	Accepted
	5	Environmental awareness	0.03919	0.00151	Accepted
	6	Environmental monitoring	0.03821	0.00147	Unaccepted
	7	Environmental planning	0.03919	0.00151	Accepted
	8	Extended producer responsibility	0.03882	0.00149	Accepted
	9	Manufacturing process	0.03842	0.00148	Unaccepted
	10	Material flow analysis	0.03699	0.00142	Unaccepted
	11	Materials handling	0.03890	0.00150	Accepted
	12	Network analysis	0.03900	0.00150	Accepted
	13	Packaging design	0.03768	0.00145	Unaccepted
	14	Packaging materials	0.03815	0.00147	Unaccepted
	15	Process design	0.03909	0.00150	Accepted
	16	Process optimization	0.03835	0.00148	Unaccepted
	17	Product design	0.03688	0.00142	Unaccepted
	18	Product durability	0.03882	0.00149	Accepted
	19	Product recyclability	0.03828	0.00147	Unaccepted
	20	Product reparability	0.03900	0.00150	Accepted
	21	Product and materials reusability	0.03882	0.00149	Accepted
	22	Risk assessment	0.03758	0.00145	Unaccepted
	23	Strategic planning	0.03909	0.00150	Accepted
	24	Sustainable design	0.03919	0.00151	Accepted
	25	Sustainable materials	0.03850	0.00148	Accepted
	26	Waste reduction	0.03890	0.00150	Accepted
				Threshold: 0.00148	
Waste and energy management (Perspective 2)	27	Alternative energy	0.03749	0.00144	Unaccepted
	28	Carbon emission	0.03767	0.00145	Unaccepted
	29	Carbon neutrality	0.03863	0.00149	Accepted
	30	Carbon sequestration	0.03798	0.00146	Unaccepted
	31	Consumer environmental behavior	0.03910	0.00150	Accepted
	32	Cost effectiveness	0.03749	0.00144	Unaccepted
	33	Ecosystem restoration	0.03935	0.00151	Accepted
	34	Emission control	0.03832	0.00147	Unaccepted
	35	Energy consumption	0.03858	0.00148	Accepted
	36	Energy efficiency	0.03743	0.00144	Unaccepted
	37	Energy policy	0.03828	0.00147	Unaccepted
	38	Energy productions	0.03916	0.00151	Accepted
	39	Environmental policy	0.03820	0.00147	Unaccepted
	40	Environmental technology	0.03761	0.00145	Unaccepted
	41	Environmental knowledge management	0.03942	0.00152	Accepted
	42	Laws and legislation	0.03794	0.00146	Unaccepted
	43	Policy implementation	0.03898	0.00150	Accepted
	44	Pollution control	0.03854	0.00148	Accepted
	45	Resource efficiencies	0.03798	0.00146	Unaccepted
	46	Sustainable consumption	0.03898	0.00150	Accepted
	47	Sustainable resource management	0.03942	0.00152	Accepted
	48	Sustainable technology	0.03928	0.00151	Accepted
	49	Waste disposal	0.03670	0.00141	Unaccepted
	50	Waste management systems	0.03928	0.00151	Accepted
	51	Waste sorting	0.03935	0.00151	Accepted
	52	Waste technology	0.03882	0.00149	Accepted
			1.00000	**Threshold: 0.00148**	
Digital technologies utilization and	53	3D printing	0.03678	0.00141	Unaccepted
	54	5G mobile communication systems	0.03889	0.00150	Accepted

transformation (Perspective 3)	55	Accident prevention systems	0.03854	0.00148	Accepted
	56	Adaptive management systems	0.03923	0.00151	Accepted
	57	Additive manufacturing	0.03691	0.00142	Unaccepted
	58	Artificial intelligence	0.03688	0.00142	Unaccepted
	59	Automation	0.03847	0.00148	Accepted

Table A1. *Cont.*

Clusters		Keywords or attributes	Entropy Weight	FDM	Decision
Digital technologies utilization and transformation (Perspective 3)	60	Big data analytics	0.03923	0.00151	Accepted
	61	Computer simulation	0.03889	0.00150	Accepted
	62	Computer vision	0.03914	0.00151	Accepted
	63	Data acquisition	0.03923	0.00151	Accepted
	64	Data analytics	0.03847	0.00148	Accepted
	65	Decision support systems	0.03914	0.00151	Accepted
	66	Deep learning	0.03818	0.00147	Unaccepted
	67	Digital twin	0.03914	0.00151	Accepted
	68	Digitization	0.03791	0.00146	Unaccepted
	69	Forecasting capability	0.03847	0.00148	Accepted
	70	Information management	0.03867	0.00149	Accepted
	71	Internet of things	0.03781	0.00145	Unaccepted
	72	Machine design	0.03914	0.00151	Accepted
	73	Machine learning	0.03631	0.00140	Unaccepted
	74	Process control	0.03923	0.00151	Accepted
	75	Robotics	0.03923	0.00151	Accepted
	76	Structural network design	0.03874	0.00149	Accepted
	77	Technological advancement	0.03897	0.00150	Accepted
	78	Technology benchmarking	0.03841	0.00148	Unaccepted
				Threshold: 0.00148	
Circular resource management (Perspective 4)	79	Cost benefit analysis	0.04508	0.00205	Unaccepted
	80	Cost reduction	0.04597	0.00209	Accepted
	81	Ecological footprint	0.04630	0.00210	Accepted
	82	End-of-life management	0.04618	0.00210	Accepted
	83	Energy conservation	0.04472	0.00203	Unaccepted
	84	Energy recovery	0.04493	0.00204	Unaccepted
	85	Investment	0.04434	0.00202	Unaccepted
	86	Life cycle assessment	0.04171	0.00190	Unaccepted
	87	Material recovery	0.04630	0.00210	Accepted
	88	Product and materials repurposing	0.04607	0.00209	Accepted
	89	Product recovery	0.04642	0.00211	Accepted
	90	Product recycling process	0.04586	0.00208	Accepted
	91	Profitability	0.04597	0.00209	Accepted
	92	Recycled materials utilization	0.04618	0.00210	Accepted
	93	Recycling technologies	0.04642	0.00211	Accepted
	94	Resource allocation	0.04618	0.00210	Accepted
	95	Resource recovery	0.04326	0.00197	Unaccepted
	96	Reverse logistics	0.04586	0.00208	Accepted
	97	Stakeholder engagement	0.04586	0.00208	Accepted
	98	Value added products	0.04434	0.00202	Unaccepted
	99	Waste recycling	0.04618	0.00210	Accepted
	100	Water recycling	0.04586	0.00208	Accepted
			1.00000	**Threshold: 0.00207**	

Table A2. Second-round EWM and FDM analyses.

Clusters		Keywords or Attributes	Ratio	Normalize	Entropy	Entropy Weight	FDM	Decision
Circular business design and strategy (Perspective 1)	1	Corporate social responsibility	0.06195	0.06363	0.93637	0.06682	0.00445	Accepted
	2	Eco-design	0.07965	0.07441	0.92559	0.06605	0.00440	Unaccepted
	3	Environmental awareness	0.04425	0.05095	0.94905	0.06773	0.00452	Accepted
	4	Environmental planning	0.04425	0.05095	0.94905	0.06773	0.00452	Accepted
	5	Extended producer responsibility	0.07965	0.07441	0.92559	0.06605	0.00440	Unaccepted
	6	Materials handling	0.07080	0.06923	0.93077	0.06642	0.00443	Unaccepted
	7	Network analysis	0.06195	0.06363	0.93637	0.06682	0.00445	Accepted
	8	Process design	0.05310	0.05756	0.94244	0.06725	0.00448	Accepted
	9	Product durability	0.07965	0.07441	0.92559	0.06605	0.00440	Unaccepted
	10	Product reparability	0.06195	0.06363	0.93637	0.06682	0.00445	Accepted
	11	Product and materials reusability	0.07965	0.07441	0.92559	0.06605	0.00440	Unaccepted
	12	Strategic planning	0.05310	0.05756	0.94244	0.06725	0.00448	Accepted
	13	Sustainable design	0.04425	0.05095	0.94905	0.06773	0.00452	Accepted

	14	Sustainable materials	0.11504	0.09187	0.90813	0.06481	0.00432	Unaccepted
	15	Waste reduction	0.07080	0.06923	0.93077	0.06642	0.00443	Unaccepted
			1.00000	0.98681	14.01319	1.00000	**Threshold:** 0.00444	

Table A2. *Cont.*

Clusters		Keywords or Attributes	Ratio	Normalize	Entropy	Entropy Weight	FDM	Decision
Waste and energy management (Perspective 2)	16	Carbon neutrality	0.12338	0.09783	0.90217	0.06916	0.00494	Unaccepted
	17	Consumer environmental behavior	0.06494	0.06728	0.93272	0.07150	0.00511	Accepted
	18	Ecosystem restoration	0.03896	0.04791	0.95209	0.07298	0.00521	Accepted
	19	Energy consumption	0.12987	0.10045	0.89955	0.06896	0.00493	Unaccepted
	20	Energy productions	0.05844	0.06289	0.93711	0.07184	0.00513	Accepted
	21	Environmental knowledge management	0.03247	0.04217	0.95783	0.07342	0.00524	Accepted
	22	Policy implementation	0.07792	0.07535	0.92465	0.07088	0.00506	Unaccepted
	23	Pollution control	0.13636	0.10295	0.89705	0.06876	0.00491	Unaccepted
	24	Sustainable consumption	0.07792	0.07535	0.92465	0.07088	0.00506	Unaccepted
	25	Sustainable resource management	0.03247	0.04217	0.95783	0.07342	0.00524	Accepted
	26	Sustainable technology	0.04545	0.05324	0.94676	0.07257	0.00518	Accepted
	27	Waste management systems	0.04545	0.05324	0.94676	0.07257	0.00518	Accepted
	28	Waste sorting	0.03896	0.04791	0.95209	0.07298	0.00521	Accepted
	29	Waste technology	0.09740	0.08596	0.91404	0.07007	0.00500	Unaccepted
			1.00000	0.95469	13.04531	1.00000	0.00510	
Digital technologies utilization and transformation (Perspective 3)	30	5G mobile communication systems	0.05732	0.05670	0.94330	0.05538	0.00308	Unaccepted
	31	Accident prevention systems	0.08917	0.07457	0.92543	0.05434	0.00302	Unaccepted
	32	Adaptive management systems	0.03185	0.03798	0.96202	0.05648	0.00314	Accepted
	33	Automation	0.09554	0.07762	0.92238	0.05416	0.00301	Unaccepted
	34	Big data analytics	0.03185	0.03798	0.96202	0.05648	0.00314	Accepted
	35	Computer simulation	0.05732	0.05670	0.94330	0.05538	0.00308	Unaccepted
	36	Computer vision	0.03822	0.04316	0.95684	0.05618	0.00312	Accepted
	37	Data acquisition	0.03185	0.03798	0.96202	0.05648	0.00314	Accepted
	38	Data analytics	0.09554	0.07762	0.92238	0.05416	0.00301	Unaccepted
	39	Decision support systems	0.03822	0.04316	0.95684	0.05618	0.00312	Accepted
	40	Digital twin	0.03822	0.04316	0.95684	0.05618	0.00312	Accepted
	41	Forecasting capability	0.09554	0.07762	0.92238	0.05416	0.00301	Unaccepted
	42	Information management	0.07643	0.06800	0.93200	0.05472	0.00304	Unaccepted
	43	Machine design	0.03822	0.04316	0.95684	0.05618	0.00312	Accepted
	44	Process control	0.03185	0.03798	0.96202	0.05648	0.00314	Accepted
	45	Robotics	0.03185	0.03798	0.96202	0.05648	0.00314	Accepted
	46	Structural network design	0.07006	0.06444	0.93556	0.05493	0.00305	Unaccepted
	47	Technological advancement	0.05096	0.05248	0.94752	0.05563	0.00309	Accepted
			1.00000	0.96830	17.03170	1.00000	0.00309	
Circular resource management (Perspective 4)	48	Cost reduction	0.07759	0.07324	0.92676	0.06615	0.00441	Unaccepted
	49	Ecological footprint	0.05172	0.05657	0.94343	0.06734	0.00449	Accepted
	50	End-of-life management	0.06034	0.06256	0.93744	0.06691	0.00446	Accepted
	51	Material recovery	0.05172	0.05657	0.94343	0.06734	0.00449	Accepted
	52	Product and materials repurposing	0.06897	0.06810	0.93190	0.06652	0.00443	Unaccepted
	53	Product recovery	0.04310	0.05004	0.94996	0.06781	0.00452	Accepted
	54	Product recycling process	0.08621	0.07802	0.92198	0.06581	0.00439	Unaccepted
	55	Profitability	0.07759	0.07324	0.92676	0.06615	0.00441	Unaccepted
	56	Recycled materials utilization	0.06034	0.06256	0.93744	0.06691	0.00446	Accepted
	57	Recycling technologies	0.04310	0.05004	0.94996	0.06781	0.00452	Accepted
	58	Resource allocation	0.06034	0.06256	0.93744	0.06691	0.00446	Accepted
	59	Reverse logistics	0.08621	0.07802	0.92198	0.06581	0.00439	Unaccepted
	60	Stakeholder engagement	0.08621	0.07802	0.92198	0.06581	0.00439	Unaccepted
	61	Waste recycling	0.06034	0.06256	0.93744	0.06691	0.00446	Accepted
	62	Water recycling	0.08621	0.07802	0.92198	0.06581	0.00439	Unaccepted
			1.00000	0.99017	14.00983	1.00000	0.00444	

References

1. Yuan, S.; Pan, X. The effects of digital technology application and supply chain management on corporate circular economy: A dynamic capability view. *J. Environ. Manag.* **2023**, *341*, 118082.

2. El Jaouhari, A.; Samadhiya, A.; Benbrahim, F.Z.; et al. Forging a green future: Synergizing industry 4.0 technologies and circular economy tactics to achieve net-zero in sustainable supply chains. *Comput. Ind. Eng.* **2025**, *201*, 110691.
3. Huang, C.; Nan, G.; Qiu, H.; et al. Launching smart circular supply chain practices toward sociotechnological synergy: An integrative influential fast fashion model.*Resour. Conserv. Recycl.* **2025**, *212*, 107935.
4. Liu, L.; Song, W.; Liu, Y. Leveraging digital capabilities toward a circular economy: Reinforcing sustainable supply chain management with Industry 4.0 technologies. *Comput. Ind. Eng.* **2023**, *178*, 109113.
5. Lan, S.; Jiang, Y.; Guo, T.; et al. Personalized product design and user review and experience analysis: A data-driven hybrid novel approach. *Comput. Ind. Eng.* **2025**, *202*, 110939.
6. Wu, Z.; Oger, R.; Lauras, M.; et al. A guiding framework for hyperconnected circular supply chain implementation. *J. Clean. Prod.* **2025**, *501*, 145229.
7. Agrawal, R.; Yadav, V.S.; Majumdar, A.; et al. Opportunities for disruptive digital technologies to ensure circularity in supply Chain: A critical review of drivers, barriers and challenges. *Comput. Ind. Eng.* **2023**, *178*, 109140.
8. Saccani, N.; Bressanelli, G.; Visintin, F. Circular supply chain orchestration to overcome Circular Economy challenges: An empirical investigation in the textile and fashion industries. *Sustain. Prod. Consum.* **2023**, *35*, 469–482.
9. Chen, J.R.; Bang, S.H.; Ha, M.H.; et al. A structural analysis of the influential factors affecting the implementation of circular supply chain management in South Korea. *J. Clean. Prod.* **2025**, *494*, 145005.
10. Roy, T.; Garza-Reyes, J.A.; Kumar, V.; et al. Redesigning traditional linear supply chains into circular supply chains–A study into its challenges. *Sustain. Prod. Consum.* **2022**, *31*, 113–126.
11. Kharayat, T.S.; Gupta, H. A Multi-Criteria Assessment of Barriers to Low-Carbon Technology adoption for Sustainable Circular Supply Chain Management: A Pathway to Sustainability Achievement in the Carbon Trading Era. *J. Clean. Prod.* **2025**, *490*, 144722.
12. Tseng, M.L.; Lim, K.M.; Wong, W.P. Sustainable supply chain management: A closed-loop network approach. *Ind. Manag. Data Syst.* **2015**, *115*, 436–461.
13. Lee, Y.; Hu, J.; Lim, M.K. Revisiting circular economy indicators: A circular supply chain perspective. *J. Purch. Supply Manag.* **2024**, *30*, 100941.
14. Zheng, G.; Haq MZ, U.; Huo, B.; et al. Leveraging intellectual capital for building a supply chain circular economy system: A knowledge-based view. *Int. J. Prod. Econ.* **2024**, *272*, 109225.
15. Meier, O.; Gruchmann, T.; Ivanov, D. Circular supply chain management with blockchain technology: A dynamic capabilities view. *Transp. Res. Part E Logist. Transp. Rev.* **2023**, *176*, 103177.
16. Al-Swidi, A.K.; Al-Hakimi, M.A.; Gelaidan, H.M.; et al. Harnessing Digital Technologies in Circular Supply Chains: The role of Technological Opportunism Capability and Technological Turbulence. *Sustain. Futures* **2025**, *9*, 100492.
17. Fernando, Y.; Tseng, M.L.; Aziz, N.; et al. Waste-to-energy supply chain management on circular economy capability: An empirical study. *Sustain. Prod. Consum.* **2022**, *31*, 26–38.
18. Bag, S.; Dhamija, P.; Bryde, D.J.; et al. Effect of eco-innovation on green supply chain management, circular economy capability, and performance of small and medium enterprises. *J. Bus. Res.* **2022**, *141*, 60–72.
19. Dehshiri SJ, H.; Mostafaeipour, A.; Amiri, M. Evaluating challenges of circular economy and Internet of Things in renewable energy supply chain through a hybrid decision-making framework. *J. Environ. Manag.* **2024**, *370*, 122785.
20. Rabbi, M.F.; Amin, M.B. Circular economy and sustainable practices in the food industry: A comprehensive bibliometric analysis. *Clean. Responsible Consum.* **2024**, *14*, 100206.
21. Abdirahman, A.A.; Asif, M.; Mohsen, O. Circular Economy in the Renewable Energy sector: A review of growth trends, gaps and future directions. *Energy Nexus* **2025**, *17*, 100395. https://doi.org/10.1016/j.nexus.2025.100395.
22. Cerchione, R.; Morelli, M.; Passaro, R.; et al. Balancing sustainability and circular justice: The challenge of the energy transition. *J. Clean. Prod.* **2025**, *494*, 144942.
23. Liu, J.; Zhang, Q.; Xie, M.; et al. A blockchain platform selection method with heterogeneous multi-attributes Decision-Making based on hybrid distance measures and an AHP-EWM weight method. *Expert Syst. Appl.* **2024**, *256*, 124910.
24. Luo, Z.; Tian, J.; Zeng, J.; et al. Flood risk evaluation of the coastal city by the EWM-TOPSIS and machine learning hybrid method. *Int. J. Disaster Risk Reduct.* **2024**, *106*, 104435.
25. Tsai, F.M.; Kurrahman, T.; Chiu, A.S.F.; et al. Optimization techniques for green supply chain practice challenges: A systematic hybrid approach. *Eng. Optim.* **2024**, *57*, 1–25.
26. Tseng, M.L.; Tran TP, T.; Ha, H.M.; et al. Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: A data driven analysis. *J. Ind. Prod. Eng.* **2021**, *38*, 581–598.
27. Kurrahman, T.; Tsai, F.M.; Sethanan, K.; et al. Data-driven natural capital accounting model in Indonesia: Impacts of environmentally related economic activities on ecological processes and services. *J. Clean. Prod.* **2024**, *469*, 143213.
28. Thompson, E.A.; Alimo, P.K.; Abudu, R.; et al. Towards sustainable freight transportation in Africa: Complementarity of the fuzzy Delphi and best-worst Methods. *Sustain. Futures* **2024**, *8*, 100371.

29. Salehi, N.; Amir, S.; Roci, M.; et al. Towards circular manufacturing systems implementation: An integrated analysis framework for circular supply chains. *Sustain. Prod. Consum.* **2024**, *51*, 169–198.
30. Zhang, A.; Venkatesh, V.G.; Liu, Y.; et al. Barriers to smart waste management for a circular economy in China. *J. Clean. Prod.* **2019**, *240*, 118198.
31. Bals, L.; Taylor, K.M.; Rosca, E.; et al. Toward a circular supply chain: The enabling role of information and financial flows in open and closed loop designs. *Resour. Conserv. Recycl.* **2024**, *209*, 107781.
32. Rentizelas, A.; Trivyza, N.L. Enhancing circularity in the car sharing industry: Reverse supply chain network design optimisation for reusable car frames. *Sustain. Prod. Consum.* **2022**, *32*, 863–879.
33. Tajik, M.; Yousefi, S.; Tosarkani, B.M.; et al. Digitalization-driven circular economy in battery Closed-Loop supply chain network design. *J. Clean. Prod.* **2025**, *496*, 145054.
34. Singh, K.; Chaudhuri, R.; Chatterjee, S. Assessing the impact of digital transformation on green supply chain for achieving carbon neutrality and accelerating circular economy initiatives. *Comput. Ind. Eng.* **2025**, *201*, 110943.
35. Mahmoud, H.A.; Essam, S.; Hassan, M.H.; et al. Modeling circular supply chains as an approach for waste management: A systematic review and a conceptual framework. *J. Eng. Res.* **2024**, *In Press*. https://doi.org/10.1016/j.jer.2024.05.004.
36. Pongpunpurt, P.; Chawaloesphonsiya, N.; Poyai, T.; et al. Exploring the circular business model for sustainable plastic waste management in shopping malls: Challenges, opportunities, and impacts in Thailand. *Case Stud. Chem. Environ. Eng.* **2024**, *10*, 100872.
37. Li, M.; Cao, G.; Cui, L.; et al. Examining how government subsidies influence firms' circular supply chain management: The role of eco-innovation and top management team. *Int. J. Prod. Econ.* **2023**, *261*, 108893.
38. Vegter, D.; Van Hillegersberg, J.; Olthaar, M. Performance measurement system for circular supply chain management. *Sustain. Prod. Consum.* **2023**, *36*, 171–183.
39. Moktadir, M.A.; Zhou, J.; Ren, J.; et al. A decision support framework for safe and sustainable by-design practices promoting circularity in waste-to-energy supply chains. *Sustain. Prod. Consum.* **2025**, *51*, 487–501.
40. Tanveer, U.; Kremantzis, M.D.; Roussinos, N.; et al. A fuzzy TOPSIS model for selecting digital technologies in circular supply chains. *Supply Chain. Anal.* **2023**, *4*, 100038.
41. Massari, G.F.; Nacchiero, R.; Giannoccaro, I. Digital technologies for resource loop redesign in circular supply chains: A systematic literature review. *Resour. Conserv. Recycl. Adv.* **2023**, *20*, 200189.
42. Chien, C.F.; Kuo, P.C.; Sun, P.C.; et al. Green production planning for circular supply chain and resource management: An empirical study for high-tech textile dyeing. *Resour. Conserv. Recycl.* **2024**, *204*, 107499.
43. Mahmoudi, M.; Shojaei, P.; Javanmardi, E.; et al. A grey-based multiple attribute decision making model for implementing circular supply chain in copper industries. *Clean. Logist. Supply Chain.* **2025**, *15*, 100212.
44. Rashid KH, O.; Al Aziz, R.; Karmaker, C.L.; et al. Evaluating the challenges to circular economy implementation in the apparel accessories industry: Implications for sustainable development. *Green Technol. Sustain.* **2025**, *3*, 100140.
45. Ozkan-Ozen, Y.D.; Kazancoglu, Y.; Mangla, S.K. Synchronized barriers for circular supply chains in industry 3.5/industry 4.0 transition for sustainable resource management. *Resour. Conserv. Recycl.* **2020**, *161*, 104986.
46. Ravikumar, D.; Keoleian, G.A.; Walzberg, J.; et al. Advancing environmental assessment of the circular economy: Challenges and opportunities. *Resour. Conserv. Recycl. Adv.* **2024**, *21*, 200203.
47. MahmoumGonbadi, A.; Genovese, A.; Sgalambro, A. Closed-loop supply chain design for the transition towards a circular economy: A systematic literature review of methods, applications and current gaps. *J. Clean. Prod.* **2021**, *323*, 129101.
48. Kurrahman, T.; Tsai, F.M.; Sethanan, K.; et al. Assessing a hierarchical structure for circular supply chain management performance: Improving firms' Eco-Innovation and technological performance. *Bus. Strategy Environ.* **2024**, *32*, 2035–2064.
49. Cotrina-Teatino, M.A.; Marquina-Araujo, J.J. Circular economy in the mining industry: A bibliometric and systematic literature review. *Resour. Policy* **2025**, *102*, 105513.
50. Lee, Y.C.; Leite, F.; Lieberknecht, K. Prioritizing selection attributes of distributed circular water systems: A fuzzy based multi-attributes decision-making approach. *J. Clean. Prod.* **2023**, *417*, 138073.