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Review

CIRCULAR ECONOMY AND FUZZY SET THEORY: A BIBLIOMETRIC AND SYSTEMATIC REVIEW BASED ON INDUSTRY 4.0 TECHNOLOGIES PERSPECTIVE

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Abstract. The Circular Economy (CE) is receiving more attention, especially in Industry 4.0 (I4.0). In the face of several ambiguous and uncertain information, fuzzy techniques based on Fuzzy Set Theory (FST) are essential for developing CE strategies. This paper uses bibliometric methods to analyze the characteristics of the authors, nations/regions, institutions of the literature of FST and CE, and the collaborations relations between them, and then summarize the literature on fuzzy techniques in the CE and identify the specific role that FST can play in each stage of CE, its primary effects on the CE's pre-preparation stage, design and production stage, and recycling and reuse stage. Meanwhile, the paper explores the advantages of I4.0 technologies for CE and analyzes the research on the role of fuzzy techniques based on FST for CE and I4.0 technologies. Last but not least, this paper is concluded by summarizing the knowledge gained from the bibliometric and content analyses of the literature and suggesting further research directions of investigation. This research will draw attention to FST's contribution and encourage its advancement in CE and I4.0 technologies.

Keywords: circular economy, fuzzy set theory, Industry 4.0, I4.0 technology, Internet of Things.

JEL Classification: C60, O14, O32, Q56.

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1. Introduction

Rapid economic growth and industrialization have resulted in a misuse of planetary resources, environmental degradation, and resource depletion (Karuppiah et al., 2021). In the face of increasingly serious environmental challenges, sustainable development has emerged as a critical strategy for resolving the global resource and environmental crisis (Tang & Liao, 2021). To achieve sustainability, we urgently need to enhance our existing business model and move to a sustainable social and corporate ecosystem. The Circular Economy (CE), as an economic system as opposed to a linear open system, aims to enhance environmental and social quality and achieve sustainable development (Awan et al., 2021). CE's design and business model strategies that ensure the implementation of a business model with minimal environmental impact include design, maintenance, repair, reuse, remanufacture, refurbishment and recycling (Ingemarsdotter et al., 2020). Furthermore, focusing on the "resource-product-regenerated resource" cycle, the CE promotes an economic system that develops in harmony with the environment. As a result, all resources and energy are utilized sensibly and sustainably (Millar et al., 2019; Urbinati et al., 2017).

Simultaneously, as the I4.0 era evolves, I4.0 technologies are being integrated with traditional manufacturing and industrial practices. I4.0 technologies like the Internet of Things (IoT), Blockchain Technology (BCT) and Big Data Technology (BDT) offer technical support for the transition to the CE. The introduction of I4.0 technologies has also made CE theory more applicable to economic practice. With its capacity to handle real-time information flows, sense local constituent functioning states and communicate with users, the IoT has been drawing study interest for some time (Rymaszewska et al., 2017). Throughout the product lifecycle, businesses can use IoT to monitor and manage their products' status, usage and location in real-time. Manufacturing executives can learn more about the quality of their products and how customers use them, resulting in more productive interactions between manufacturers and their customers (Sun & Wang, 2022). There is a wealth of current research on the I4.0 technologies' enabling role in the development and application of CE strategies (Antikainen et al., 2018; Cetin et al., 2021; Chauhan et al., 2022a; Kerin & Pham Duc, 2020). All of these studies concur that the use of I4.0 technologies offers a new field for the development and change of CE.

The literature on CE is currently exploding with topics such as the definition of CE (Alhawari et al., 2021; Kirchherr et al., 2017; Lahti et al., 2018), drivers and barriers (Govindan & Hasanagic, 2018; Tan et al., 2022), opportunities and challenges (Bag & Pretorius, 2022; Tamasiga et al., 2022), digitalization (Agrawal et al., 2022; Burmaoglu et al., 2022; Chauhan et al., 2022a), waste management (Pan et al., 2022; Tanveer et al., 2022), linkages with small and medium-sized enterprises (SMEs) (Min et al., 2021), sustainable supply chain management (Gil-Lamata & Pilar Latorre-Martinez, 2022; Theeraworawit et al., 2022), and integration of I4.0 technologies (Ghobakhloo, 2020; Lopes de Sousa Jabbour et al., 2018; Rosa et al., 2020), etc. To address these issues, a variety of aspects must be taken into account, including a significant amount of data collection, numerous uncertainties, and randomness. To address the issue of data ambiguity, many researchers use fuzzy methodologies to address the problems with CE strategies, such as performance assessment, framework enhancement, and barrier measurement for CE and so on (Chen et al., 2022; Liang et al., 2018; Rehman et al., 2022). Zadeh (1965) first proposed the idea of FST in his article "Fuzzy Sets," in which he suggested that an affiliation function accepting any value on the closed interval [0, 1] can be used to define how much a member belongs to a set. Since the introduction of FST, several extension forms have been developed to suit various decision-making problems, such as intuitionistic fuzzy sets (Atanassov, 1986), type-2 fuzzy sets (Zadeh, 1975), hesitant fuzzy sets (Torra, 2010), and complex linguistic term sets (Gou et al., 2017, 2021a, 2021b, 2023), etc. The research on applying FST to CE practices is expanding, and FST can be used to various stages of the transformation to the CE. In the I4.0 digital transformation era, I4.0 technologies-enabled CE transformation requires FST for assessment and decision-making at each crucial stage. Therefore, to explore the specific role that FST can play and the untapped potential as a powerful tool in the CE transformation process, a systematic review of the prior literature is required in order to fully, adequately and deeply understand the prior research work that has been conducted. Based on this, the goal of this paper is to investigate, review and discuss the prior research on fuzzy techniques and CE and address the five research questions listed below:

(1) What are the characteristics of the publication trend, the keyword developments, the authors, the nations/regions, the institutions, as well as the collaborations between them, for papers of CE and FST?

(2) Which stages of CE can FST-based fuzzy techniques be specifically applied?

(3) How do I4.0 technologies affect CE?

(4) How do FST-based fuzzy techniques make I4.0 technologies easier to integrate with CE?

(5) What are the foreseeable directions for research?

The remainder of the paper is structured as follows: Section 2 describes the bibliometric visual analysis preparation in data acquisition and tool selection, followed by the bibliometric analysis results, including publication trends and analysis by authors, regions, institutions, categories, and keywords. In Section 3, we provide a systematic analysis of the literature, covering fuzzy techniques frequently applied in the field of CE and their particular applications, followed by a phased examination of the research on the use of fuzzy techniques under various stages of CE. In Section 4, we explore the advantages of I4.0 technologies for CE and analyze the research on the role of fuzzy techniques based on FST for CE and I4.0. Section 5 suggests further research directions. Finally, Section 6 summarizes the research presented in this paper.

2. Bibliometrics

2.1. Analysis tool and data acquisition

The bibliometric analysis employs mathematical and statistical methods to describe and analyze the current state of a discipline or research direction and to forecast its future development trend based on a large body of literature (Sun et al., 2022). Currently, many tools are available for bibliometric analysis, including VOSviewer, Bibliometrix R-package, CiteSpace, BibExcel, etc. One of the most popular bibliometric analysis tools is VOSviewer (Xu et al., 2023), and its ability to perform cluster analysis is beneficial in identifying similar research interests or study areas (van Eck & Waltman, 2010). The VOSviewer is used in this study to analyze the literature extensively on the application of FST to the CE and to pinpoint its potential future directions (Zhang et al., 2021b). Bibliometrix is programmed in R, the proposed tool is flexible and can be rapidly upgraded and integrated with other statistical R-packages (Aria & Cuccurullo, 2017). In this study, Bibliometrix and VOSviewer will serve as the primary tools for visualizing each topic's fundamental metrics and the network linkages that connect them from various angles to analyze the literature extensively on the application of FST to the CE and pinpoint its potential future directions.

The use of a single database could result in leaving out important material because of the coverage constraints of a single database (Mirzynska et al., 2021). Therefore, two databases, Scopus and Web of Science (WoS) Core Collection database, were specifically chosen in this study to ensur that high-quality journals can be searched. The following search strategy for searching the literature was used: "(((TS = (fuzzy set)) OR TS = (fuzzy))) AND (((TS = (circular economy))))" in the WoS Core Collection database, and "TITLE-ABS-KEY (circular AND economy) AND (TITLE-ABS-KEY (fuzzy AND set) OR TITLE-ABS-KEY (fuzzy))" in the Scopus database. As of March 26, 2023, we had located a total of 311 publications in the Scopus database and

322 publications in the WoS database. After merging and de-duplicating the publications in both databases, 408 publications were remained. The 408 articles were examined, and after removing irrelevant publications such as conference call papers, 399 publications were left for bibliometric analysis.

2.2. Results analysis

2.2.1. The publications and citations trends

Figure 1 depicts the development in the number and citations of publications examining FST and CE. The literature on FST and CE has grown rapidly in recent years, since the first publication appeared in 2006, going from 9 publications in 2018 to 135 in 2022. As of March 26, 2023, there were 35 publications in 2023. By the end of 2023, it is anticipated that there will be a new record for the number of publications. The number of citations of publications has also sharply increased recently and repeatedly surpassed new peaks. The first citation appeared in 2008, however, publications were cited 2458 times in 2022 alone, demonstrating the high regard the later researchers hold for earlier studies and the field is developing at a previously unheard-of rate. The main reasons for this include the promotion and support of the United Nations (UN) Sustainable Development Goals (SDGs), as well as the rising global agreement among nations to address environmental concerns including resource scarcity and climate change (Firoiu et al., 2022). The UN established the 2030 Agenda for SDCs in 2015, which included 17 sustainable development objectives. The CE has drawn attention to these objectives as a key component of sustainable patterns of consumption and production. Several countries, including the European Union, China, the UK, the US, and Japan, have implemented various policies and plans to promote CE and green development in recent years. Therefore, it is conceivable that the CE will give rise to more passionate debates and richer findings.

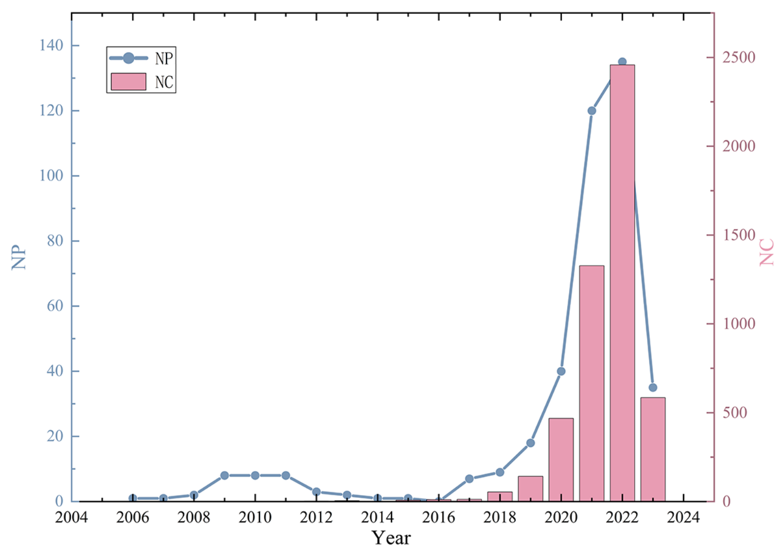


Figure 1. The number of publications and citations from 2006 to 2023 (by March 26, 2023)

This study examines the impact of publications in the field by analyzing highly cited publications. First, as shown in Table 1, the top 10 cited publications on CE and FST were listed. It can be seen that 5 of the top 10 cited publications are related to the application of FST for the study of barriers to CE, ranked 1, 2, 3, 5 and 7 (Farooque et al., 2019; Mahpour, 2018; Mangla et al., 2018; Ozkan-Ozen et al., 2020; Zhang et al., 2019), which demonstrates the superiority of FST in the study of barriers. Additionally, challenge analysis (Tseng et al., 2021b), methodological research (Shen & Wang, 2018), evaluation of benefit and role (Sadhukhan et al., 2018; Zhao et al., 2017), and selection of partners (Chen et al., 2021a) are the topics of concern for the remaining highly cited articles.

Table 1. Top 10 most cited publications

Rank	Title	Year	Source	Citations Numbers	Average Per Year
1	Barriers to effective circular supply chain management in a developing country context	2018	Production Planning & Control	230	38.33
2	Prioritizing barriers to adopting circular economy in construction and demolition waste management	2018	Resources Conservation and Recycling	168	28
3	Barriers to smart waste management for a circular economy in China	2019	Journal of Cleaner Production	140	28
4	Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: a data-driven analysis	2021	Journal of Industrial and Production Engineering	117	39
5	Synchronized barriers for circular supply chain in industry 3.5/industry 4.0 transition for sustainable resource management	2020	Resources Conservation and Recycling	95	23.75
6	Z-VIKOR method based on a new comprehensive weighted distance measure of Z-number and its application	2018	IEEE transactions on fuzzy systems	90	15
7	Barriers to circular food supply chains in China	2019	Supply Chain Management-An International Journal	89	17.8
8	Evaluating the comprehensive benefit of eco-industrial parks by employing a multi-criteria decision-making approach for circular economy	2017	Journal of Cleaner Production	85	12.14
9	Role of bioenergy, biorefinery, and bioeconomy in sustainable development: Strategic pathways for Malaysia	2018	Renewable & Sustainable Energy Reviews	81	13.5
10	Third-party reverse logistics provider selection: A computational semantic analysis-based multi-perspective multi-attribute decision-making approach	2021	Expert systems with applications	75	25

2.2.2. Characterization of the authors of the publications

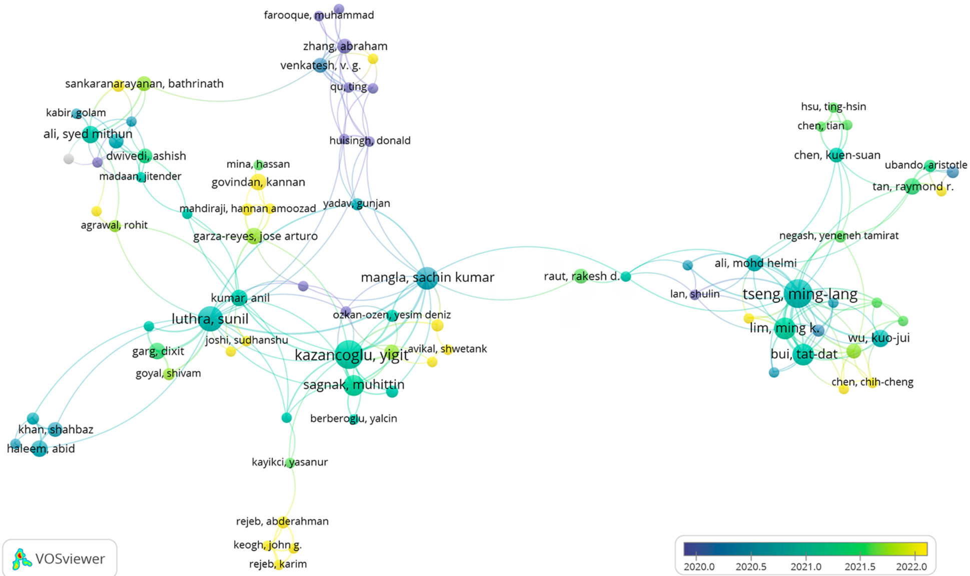
This subsection offers a systematic analysis of the publications' authors, regions/countries and institutions to identify the most prolific and significant authors, regions/countries and institutions. Evaluating the authors' cooperation and contributions to FST and the CE can give academics looking to collaborate in related fields some guidance (Sun et al., 2022). Table 2 lists the top 5 research scholars in terms of publications and information about their nations, educational institutions, number of publications and citations. According to Table 2, Tseng, Ming-Lang from the China Medical University Hospital have a remarkable number of publications and citations, have made significant contributions, and hold a key position in the field, next is Professor Kazancoglu, Yigit from Yasar University. TatDat Bui and Tseng, Ming-Lang, two of the top five researchers in terms of publications, have had a tight working relationship since 2020. They primarily employ fuzzy techniques for digital sustainable supply chain management (Tseng et al., 2021a, 2022b) and municipal solid refuse management (Bui et al., 2020; Tsai et al., 2020). Together, Yigit Kazancoglu and Sachin Kumar Mangla collaborate closely to assess barriers, evaluate risks (Kazancoglu et al., 2022), and develop frameworks for decision-making in the CE (Kazancoglu et al., 2021a). Professor Luthra, Sunil's research centers on developing nations like India in order to dismantle obstacles and offer methodologies for the development of CE in those nations (Goyal et al., 2022; Luthra et al., 2022).

Collaboration between researchers working in the same field will result in more beneficial literature results that will better support the field's growth. To investigate cooperation between researchers in this field, this subsection employs VOSviewer software to visualize and analyze collaboration among published authors. Larger corresponding nodes in the network indicate a more significant number of documents co-authored with other authors, and circles of the same color indicate that they belong to the same clusters, which can be used to identify groups of collaborating researchers. 84 authors with at least two publications and a collaborative relationship between them were used to conduct a collaborative network analysis, and the results are shown in Figure 2a and Figure 2b. We can see that many of the nodes in Figure 2a are tightly connected to one another, creating a more intricate network structure. We can find some researchers with significant impact by examining the size of the nodes, including the top three authors in terms of publications, Tseng, Ming-Lang, Kazancoglu, Yigit and Luthra, Sunil. According to the density plot in Figure 2b, we can find that the 84

Table 2. The top 5 most publications research scholars

Rank	Name	Region	Institution	Number of Publications	Number of Citations
1	Tseng, Ming-Lang	China, Taiwan	China Medical University, Taiwan	17	281
2	Kazancoglu, Yigit	Turkey	Yasar University	13	238
3	Luthra, Sunil	India	Ch. Ranbir Singh State Institute of Engineering & Technology	12	387
4	Mangla, Sachin Kumar	India	O. P. Jindal Global University	12	429
5	Tat-Dat Bui	China, Taiwan	Asia University Taiwan	10	227

a) Network visualization



b) Density visualization

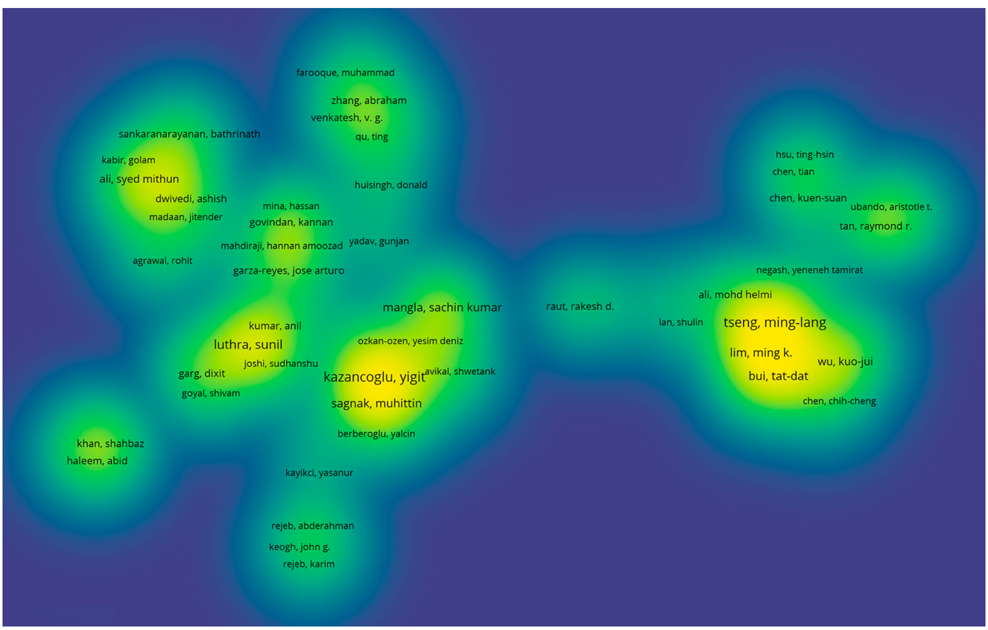


Figure 2. Authors cooperation network

authors who had collaborated were divided into 11 clusters based on their collaborative links, with Cluster 1 containing 13 authors, and Clusters 2 and 3 including 13 and 12 authors, respectively. The fact that there are crossover and overlap between the various clusters suggests that there are complementarity and crossover in the research directions of the various clusters. Although some clusters are less linked to one another and may include a few independent scholars or small teams, they still make a research contribution.

2.2.3. Characterization of the regions/countries of the publication

Studying national/regional collaborations in FST and CE and metrics like the impact of publications and citations are the main ways to comprehend the global distribution and evolution of research in the field. Table 3 shows the number of publications in the top 5 countries/regions. According to the number of papers and citations, China and India are the two main nations conducting research on the CE and FST. China, in particular, far outnumbers other nations with 126 papers, demonstrating that China has a high level of interest and development potential in the field of CE study. This is primarily because these two nations have more severe resource use and environmental protection issues, research on the CE is given high priority by the government and academics, and there is active policy support. Secondly, the UK is performing exceptionally well in this area. Although the number of papers is only ranked third, the citation volume and average citation frequency are both ranked first, indicating that the UK's research findings are widely recognized in the international academic community and have a significant academic impact. This might be connected to its pioneering work in sustainable growth and environmental protection. Turkey and China Taiwan also perform quite well in terms of study in CE and FST, and both the quantity and average frequency of citations indicate a high level.

Whether international cooperation between diverse nations/regions has a direct impact on the rapid future development of this field. We undertake a visual study of the collaboration and exchange between nations/regions to investigate this issue. The global interchange and cooperation in this area are depicted in Figure 3 for all nations and regions. We can see that among these nations, China is a more significant partner and collaborates with the UK (Frequency: 20), India (Frequency: 13), Malaysia (Frequency: 13), Australia (Frequency: 9), and Vietnam (Frequency: 9) more frequently. This demonstrates the potency and impact of Chinese study in the fields of FST and CE. China and India, the two biggest economies and populous nations in Asia, cooperate to some extent in the development of FST and CE, despite

Table 3. The top 5 Countries/Regions with the most publications

Rank	Countries/Regions	Number of Publications	Number of Citations	Citation frequency per article
1	China	126	1577	12.51
2	India	102	1430	14.01
3	United Kingdom	58	1645	28.36
4	Turkey	40	609	15.225
5	China Taiwan	36	498	13.83

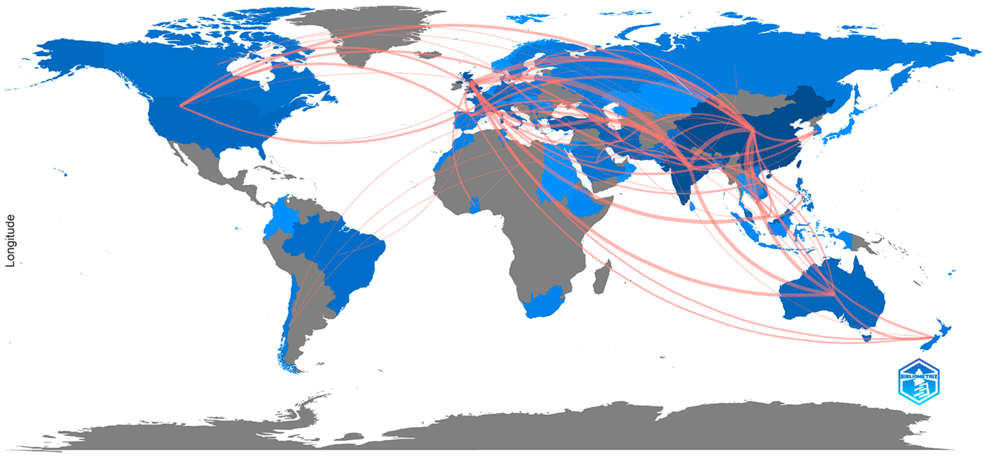


Figure 3. Countries cooperation network

some degrees of rivalry between them. Aside from that, the UK has established the most substantial ties with India. In contrast, Turkey, which ranks the fourth in publications, has only started research collaborations with a few Asian and European nations. Nations like the UK, Malaysia, Australia and Vietnam also have significant contributions to make in these areas.

2.2.4. Characterization of the institutions of the publication

This subsection analyzes the institutions of publications. The top 5 institutions with the most publications are shown in Table 4, the total number of publications, citations, rates of article citations, and the "h-index" index. From Table 4, the National Institute of Technology has the most publications, followed by Yasar University, Asia University Taiwan, China Medical University Taiwan, and China Medical University Hospital Taiwan. The National Institute of Technology ranks first with 22 publications and also has a good impact. One possible reason for three out of the top five institutions being from Taiwan is that Taiwan has been committed to environmental protection and sustainable development. Especially, China Medical University Taiwan (CMU Taiwan) and its affiliated hospitals, which have a significant number of articles released and citations, are the fourth and fifth-ranked institutions. This demonstrates that CMU Taiwan and its affiliated hospitals are also very significant in the study of FST and CE. The research of the medical university on the topics of CE and FST is related to the management of medical waste and the circular supply chain management in the healthcare industry (Tseng et al., 2022a). In the healthcare industry, there are problems with low production and consumption efficiency, as well as incomplete medical waste disposal, which results in environmental pollution. Fuzzy techniques based on FST can be used for waste management classification and evaluation, as well as for decision analysis of disposal options (Peng et al., 2021). FST can also be applied to the optimization of medical resources in the context of the CE, ensuring the rational allocation of medical resources, and conducting risk assessment and sensitivity analysis of the decision-making results (Bhalaji et al., 2019).

Table 4. The top 5 institutions with the most publications

Rank	Institutions	Number of Publications	Number of Citations	Citation frequency per article	h-index
1	National Institute of Technology	22	273	12.41	10
2	Asia University Taiwan	20	414	20.7	10
3	Yasar University	18	364	20.22	11
4	China Medical University Taiwan	16	407	25.44	10
5	China Medical University Hospital Taiwan	14	337	24.07	10

2.2.5. Keywords co-occurrence

The keywords of a publication are a condensed version of its main ideas, and keywords analysis can grasp important themes and areas of research that academics are currently concentrating on. Figure 4 depicts the co-occurrence network in the paper, with larger circles denoting keywords that occur more frequently and a network connection denoting the co-occurrence of two keywords. Table 5 shows the frequency of keywords in publications. Based on the analysis, several key observations can be made. Firstly, barriers and management emerge as the top two keywords with the highest co-occurrence frequency. This indicates that researchers primarily focus on identifying and addressing the challenges and obstacles that hinder the adoption and implementation of CE practices based on FST. This is a crucial aspect since identifying the barriers and developing effective management strategies are essential for ensuring the successful implementation of CE practices. Secondly, sustainability, framework and performance are also among the top five keywords with high co-occurrence frequency. This suggests that researchers are also exploring the potential of FST in developing sustainable frameworks and evaluating the performance of CE practices. Developing sustainable frameworks is crucial for promoting the long-term adoption of CE practices while evaluating performance can help identify areas of improvement and promote continuous improvement. Thirdly, supply chain management, decision-making and challenges also emerge as important keywords in this field. These keywords indicate that researchers are exploring how FST can be used to optimize the supply chain management process and improve decision-making in the CE context. The analysis suggests that researchers are focused on addressing the challenges and obstacles that hinder the adoption and implementation of CE practices, developing sustainable frameworks and evaluating the performance of CE practices.

Besides, emerging keywords, as the yellow keywords, represent the latest cutting-edge developments, such as "Industry 4.0", "big data", "technology," etc. Therefore, in the era of I4.0, an increasing number of academics are incorporating technology and digital techniques in the research of CE and FST, exploring the opportunities and challenges presented by I4.0 technologies. Additionally, the analysis indicates that researchers are exploring how FST can be used to optimize supply chain management processes and improve decision-making in the CE context. These findings can help guide future research and development in this field and promote the successful implementation of CE practices.

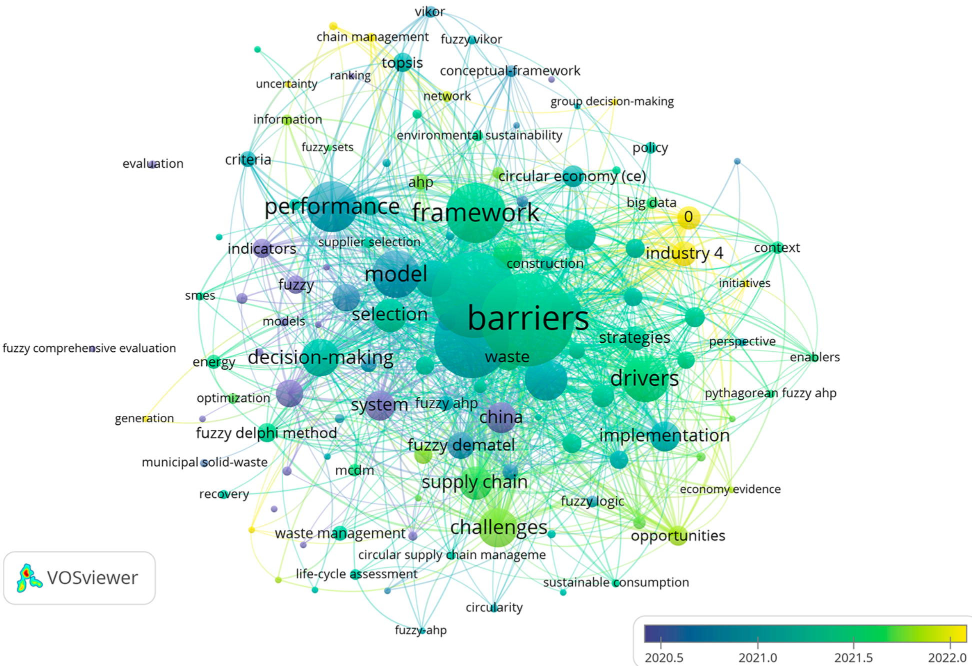


Figure 4. Keyword co-occurrence network

Table 5. The top 10 keywords on the occurrence

Rank	Keywords	Occurrences	Total link strength
1	Barriers	101	766
2	Management	91	665
3	Sustainability	78	628
4	Framework	60	471
5	Performance	52	365
6	Model	46	307
7	Drivers	45	403
8	Supply chain management	40	338
9	Challenges	36	312
10	Decision-making	35	250

3. Research on the application of FST in CE

3.1. Principal fuzzy techniques based on FST

Making decision is necessary for the efficient operation of all aspects of the CE. It involves processing a significant amount of linguistic information generated by imprecise and subjective judgments made by various decision-makers. FST stands out as the best method for handling this type of information. As a result, fuzzy multi-criteria decision-making (MCDM) techniques are frequently used in CE-related problems (Sassanelli et al., 2019). Fuzzy MCDM techniques include a variety of fuzzy methods, among which fuzzy Analytic Hierarchy Process (ANP) (Yadav et al., 2020), fuzzy Combined Compromise Solution (CoCoSo) (Wang et al., 2022), fuzzy Delphi (Tseng et al., 2021c), fuzzy TOPSIS (Toker & Gorener, 2023), fuzzy ANP (Chen et al., 2019), fuzzy Additive Ratio Assessment (ARAS) (Liu & Mishra, 2022), fuzzy Complex Proportional Assessment (COPRAS) (Omerali & Kaya, 2020), fuzzy VIKOR (Shen & Wang, 2018), fuzzy Preference Ranking Organization Method For Enrichment Evaluations (PROMETHEE) (Kaya et al., 2019), fuzzy Elimination et Choix Traduisant la Realite (ELECTRE) (Kaya et al., 2019), fuzzy Stepwise Weight Assessment Ratio Analysis (SWARA) (Mohammadian et al., 2021), fuzzy Best-Worst Method (BWM) (Govindan et al., 2022), fuzzy Decision-making Trial and Evaluation Laboratory (DEMATEL) (Thavi et al., 2021), fuzzy Inference System (FIS) (Alam et al., 2022), fuzzy COmprehensive distance Based RAnking (COBRA) (Krstic et al., 2022) and combinations of more than two (Luo et al., 2020), which are used to solve problems such as identifying barriers, performance evaluation and supplier selection to CE, etc. The articles that used the techniques above to study the CE are listed in Table 6, along with their research purposes, ideas, and results.

Table 6. Examples of fuzzy MCDM methods used to solve problems in the CE

Research Methodology used	Reference	Research purpose	Research idea	Research results
PF-AHP, PF-CoCoSo	(Lahane & Kant, 2021)	Ranking the necessary elements for using circular supply chains	PF-AHP is used to obtain the weights, PF-CoCoSo is used to rank the performance outcomes	"global climate pressure and ecological scarcity of resources" is the most significant CSCE
HFL-BWM-ANP, fuzzy TOPSIS	(Luo et al., 2020)	Selecting the optimal waste-to-energy incineration plant site	HFL-BWM-ANP is proposed to obtain criteria weights, the TOPSIS approach is employed to rank alternative sites	The plant is suitable for layout in a city with a complete law and policy system, a developed economy, and a dense population
Fuzzy PROMETHEE, TOPSIS, VIKOR, ARAS, COPRAS	(Simsek et al., 2022)	Contributing to the BAT decision process in industrial facilities	PROMETHEE, TOPSIS, VIKOR, ARAS, and COPRAS decision-making models were selected for use in the BAT decision-making process	In identifying the priority BAT for industrial cleaner production applications, the VIKOR and COPRAS models can produce better results
Fuzzy AHP, gery-based ELECTRE	(Agarwal et al., 2023)	Identifying barriers to the CE in developing countries from a supply chain perspective	A hybrid approach of AHP and the ELECTRE method had been employed to obtain the mutual rankings of the identified obstacles	"Lack of consumer knowledge and consciousness towards environmental sustainability" was found to be the top-ranked obstacle

End of Table 6

Research Methodology used	Reference	Research purpose	Research idea	Research results
Fuzzy DEMATEL	(Farooque et al., 2019)	Identifying barriers related to the integration of CE concepts into food supply chain management	The DEMATEL method was used to investigate the causal connections between the barriers	One major obstacle is a lack of market pressure and inclination
PF-SWARA, CoCoSo	(Cui et al., 2021)	Identifying the critical barriers to the adoption of IoT in the CE in the manufacturing sector	The SWARA and CoCoSo methods were proposed to estimate and rank the significance degree of the barriers	Sensor technology with a weight value of 0.0533 has become the most critical barrier
FIS	(Alavi et al., 2021)	Proposing a dynamic DSS for sustainable supplier selection in circular supply chains	Users to customize and weigh their criteria with a fuzzy BWM and select the most suitable supplier with the FIS	This integrated framework produces a robust and effective DSS applicable to many problems
Fuzzy Delphi	(Priyadarshini et al., 2022)	Examining the obstacles and priorities in adopting AM to accomplish CE goals	The fuzzy Delphi was used to identify barriers, the obstacles were ranked using the BWM	The top biggest obstacle is the "high cost of printing supplies"

Notes: Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP); Hesitant Fuzzy Linguistic Best-Worst Method-Analytic Network Process (HFL-BWM-ANP); Circular Supply Chain Enablers (CSCEs); Best Available Techniques (BAT); Decision Support System (DSS); Fuzzy Inference System (FIS); Additive Manufacturing (AM).

3.2. Application of fuzzy techniques to the stages of CE

According to its definition (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018), the CE is a regenerative system that reduces resource inputs, waste and energy emissions by reducing material and energy cycles, including sustainable design, production, upkeep, reuse and recycling processes. According to a review of the literature, the pertinent research focuses on evaluating barriers, risks and challenges, developing sustainable products, choosing and evaluating suppliers, and reversing logistics and performance assessment under various stages of the CE. The aforementioned research content is assigned to three stages: the pre-preparation stage, the design and production stage, and the recycling and reuse stage. To clearly explore how the fuzzy techniques-based FST is applied to various stages of CE, this section presents the application scenarios and usage of fuzzy techniques under three different stages.

3.2.1. Pre-preparation stage

The pre-preparation stage is critical in the implementation of the CE. Various studies and analyses are required at this stage to determine the suitability of the CE model, the feasibility and potential benefits of implementing a CE, the challenges, obstacles and risks that may be encountered. In the pre-preparation step, the application of fuzzy techniques based on FST focuses on 2 areas: barriers assessment, and risk and challenge assessment.

Barriers assessment: The assessment of barriers in the CE is an analysis and assessment of the barriers in the implementation of the CE in different sectors such as manufacturing, industry, agriculture, food industry, etc (Cao et al., 2022; Liu et al., 2021b). This aspect is covered in 120 papers out of 399, with the majority of them focusing on the barriers to transition in the CE process (Govindan et al., 2022; Vatansever et al., 2021), waste management (Ali et al., 2022; Kharola et al., 2022) and technology adoption (Cui et al., 2021; Percin, 2023; Rejeb et al., 2022). Circular supply chain management and waste management are the two fields of barrier evaluation that also have been the focus of the research. Circular supply chain management is an important step of the CE, a production model that enables recycling via the movement of resources, products and wastes through the supply chain, which can reduce the negative environmental impact of supply chain activities (Genovese et al., 2017). Waste management is an essential part of the circular supply chain and is strategically crucial for achieving CE (Bijos et al., 2022). However, the road to expediting the realization of the CE through waste management is challenging due to the lack of consensus on waste management among governments, corporations and individuals, as well as insufficient infrastructure, financial resources and technical experience (Kharola et al., 2022). Typically, the process of identifying obstacles starts with a literature review to find initial barriers, followed by categorizing the initially discovered barriers and gathering expert feedback, and finally, examining these barriers using a fuzzy decision-making strategy. Table 7 lists the primary decision-making techniques used to look for obstacles and the frequency, advantages and disadvantages, applicable scenarios of each technique. As we have seen, the fuzzy DEMATEL method is the most frequently used in this field, next is the fuzzy Delphi method as well as the fuzzy AHP method. The DEMATEL method is an MCDM method for identifying and prioritizing the causal relationships between system components (Chen et al., 2021b), Fuzzy DEMATEL is the most appropriate method for determining the interrelationship among the variables (Sharma et al., 2023). The Fuzzy Delphi approach can be used to gather recommendations and expert opinions, then integrate the opinions to determine the most significant obstacles and potential solutions. The Fuzzy AHP approach can be used to assess the importance of different barriers to the CE development. In real-world situations, the most appropriate fuzzy technique must be chosen depending on the unique barrier assessment problem and the existing circumstances, such as data collection.

Risk and challenges assessment: For CE projects to be implemented, risk management and challenge analysis are essential. A risk management and challenges assessment should be carried out prior to the start of a circular construction project, and a suitable risk management and mitigation plan should be developed to minimize the impact of risks on the project. In the CE, risk and challenges assessment usually involves the identification of potential environmental, social and economic risks, and the impact of these risks on various stakeholders.

Table 7. The primary decision-making techniques used to look for obstacles

Rank	Techniques	Frequency	Advantages	Disadvantages	Applications
1	Fuzzy DEMATEL	40	Be able to analyze the cause-effect relationships and interactions between barriers.	The results need to be supported by a substantial amount of data and expertise, and the dependability of the results is affected by the data and expert judgment.	Appropriate for more complicated barrier assessments where causation and interactions must be taken into account.
2	Fuzzy Delphi	27	It is simple to use, anonymous expert opinions may be gathered, and can work remotely together.	The choice of experts and the formulation of specific questions may cause subjectivity and bias in the outcomes.	Suitable for the initial assessment and identification of barriers, as well as when information regarding the barriers is limited or challenging to find.
3	Fuzzy AHP	26	The relative importance and priority of barriers can be determined.	For various decision makers, judgment criteria may carry varying weights.	For situations where determining the relative significance and priority of barriers is necessary.

There were 18 relevant articles found about the use of FST for risk and challenge assessment. The articles mainly focused on challenges in the context of the CE (Abdul-Hamid et al., 2020; Yıldızbaşı et al., 2022), investment risk assessment (Wan et al., 2023), supply chain risk assessment (Yang & Li, 2010), and among others (Rehman et al., 2022; Weglarz & Gilewski, 2021). The fuzzy SWARA, fuzzy VIKOR, fuzzy AHP and fuzzy Delphi methodologies were applied in these 18 publications. The most utilized one was fuzzy SWARA approach, with a cumulative total of 5 papers. To more effectively handle ambiguity and uncertainty, the fuzzy SWARA technique employs fuzzy values to reflect the decision maker's weights and scores for each assessment element (Hu et al., 2022). It uses a hierarchical framework to level-divide each aspect and calculate its weight within the total assessment. In particular, the fuzzy SWARA technique also takes into account how evaluation elements interact and are dependent upon one another for a more thorough assessment of risks and challenges (Liu & Mishra, 2022). Also, the fuzzy SWARA method can be used in combination with fuzzy VIKOR for determining the weight of the risk criteria and the final risk ranking, respectively (Hassan et al., 2023). After the risks and risk levels are identified, the optimal solution should also be evaluated and selected by decision-makers or experts for the purpose of risk avoidance and confronting challenges.

3.2.2. Design and production stage

The process of production and design is a crucial stage of the CE. The ultimate goal is to optimize product design and production processes to minimize resource consumption and waste generation while maximizing resource utilization and minimizing environmental pollution. In the design phase, there is a need to ensure that products are designed to meet sustainable development requirements. And in the production phase, it is necessary to ensure that the best quality suppliers are selected and continuously monitored and evaluated them.

Sustainable product development: Sustainable manufacturing, also known as circular manufacturing practices within the concept of the CE (Enyoghasi & Badurdeen, 2021), entails the development of more sustainable products using sustainable processes and systems. This involves producing products with minimal adverse environmental impact, conserving energy and natural resources, being harmless to humans and being profitable (Gholami et al., 2019). Existing studies aim to promote sustainable product development by evaluating key technologies (Gholami et al., 2022) and developing sustainable product production frameworks (Ahmed et al., 2022; Chauhan et al., 2022b). First of all, policymakers and decision-makers may gain a better understanding of these technologies and their relevance to the production of sustainable products by evaluating the extent to which key technologies are applicable in promoting product-level sustainability (Gholami et al., 2022). The precise procedures in technology evaluation are: (1) Choosing evaluation indicators. (2) Experts and stakeholders assess and rank technology using the developed criteria. (3) Conducting a sensitivity analysis of the choices made. During the technology evaluation process, fuzzy TOPSIS is regarded as a crucial tool, which can be used to distinguish the cost and benefit criteria of a technology and calculate how similar each is to scenarios of the best case and the worst cases to measure the distance between them (Nara et al., 2021). In addition, a research framework based on fuzzy techniques can be created to increase the life cycle of design products, satisfy the value standards for the design and development of industrial product service systems, and provide cyclic value. Firstly, value requirements are identified, and then they are prioritized using fuzzy techniques like the fuzzy AHP method to determine the most crucial value factors for creating cyclic products (Nag et al., 2022). The research mentioned above will assist policy and decision-makers in better understanding critical technologies and how they can be applied to the creation of sustainable products, which is crucial for sustainable development.

Supplier evaluation and selection: The CE requires us to use materials, components, and products that are easier to recycle, so a reasonable choice of suppliers is critical. There are 30 papers address aspects of supplier selection and evaluation in aggregate (Ecer & Torkayesh, 2022). The three steps involved in resolving the supplier selection and evaluation problems are: (1) Developing the selection criteria. (2) Determining the relative weights and ranking of the criteria. (3) Ranking the suppliers (Zhang et al., 2020). The supplier selection and evaluation can be seen as MCDM problems with unclear quantitative and qualitative information (Alimardani et al., 2013), and fuzzy MCDM tools are usually used to solve the problems (Chai & Ngai, 2020). The establishment of an appropriate system of assessment indicators has a significant impact on the choice of assessment and decision-making, a comprehensive system of evaluation indicators is needed to assess suppliers under the circular supply chain, including indicators for cost, product quality and delivery date, employment opportunities, product liability, air pollution, eco-friendly materials, clean technology in production and recycling processes, risk, etc. (Alavi et al., 2021; Kannan et al., 2020; Kartsonakis et al., 2017). It is important to note that these indicators that are taken into account involve not only the environmental factors of supplier selection but also the factors of economic and social issues, all of which significantly influence supplier selection. In the CE context, supplier selection decisions should include more innovative evaluation indicators to distinguish the supplier selection problem from that in the traditional environment. So far, the fuzzy MCDM approaches have significantly contributed to firms' circular supplier selection. Multiple frameworks have been developed to evaluate suitable suppliers in CE, and various fuzzy linguistic term sets, such as probabilistic linguistic term sets (Wei et al., 2021) and Pythagorean language (Blanco-Mesa et al., 2017), are utilized to convey subjective or ambiguous information in the decision-making process. Table 8 lists the primary fuzzy techniques, the frequency, advantages and disadvantages, applicable scenarios of each technique. As we can see, in studies on supplier selection and assessment in the context of CE, fuzzy TOPSIS is the most frequently utilized fuzzy technique, next is fuzzy BWM, followed by fuzzy VIKOR.

Table 8. The primary decision-making techniques used to supplier evaluation and selection

Rank	Techniques	Frequency	Advantages	Disadvantages	Applications
1	Fuzzy TOPSIS	8	Data distribution, sample size and the number of indicators are not strictly constrained	No valid results can be obtained if the index values of two evaluation objects are symmetrical about the line linking the best and worst solutions	Scenarios where there are multiple evaluation metrics to consider and the relative importance of the metrics to each other needs to be taken into account
2	Fuzzy BWM	7	It has the ability to handle inconsistencies	Huge calculations when there is a lot of data involved	It is the preferred MCDM method for comparing two criteria side by side and figuring out the best weights for each (Liu et al., 2021a)
3	Fuzzy VIKOR	6	It can incorporate the subjective preferences of decision makers while simultaneously taking into account both group utility maximization and individual regret minimization	The findings can be affected by the weights of the criteria and the standardization process	Appropriate for circumstances where decision-makers cannot or do not know how to express their preferences precisely and where there is a dispute between evaluation criteria

3.2.3. Recycling and reuse stage

Reverse logistics and performance evaluation are two key aspects of the recycling and reuse stage in CE. Fuzzy techniques can be applied to enhance the efficiency and effectiveness of the recycling and reuse stage in CE, by optimizing reverse logistics processes, evaluating performance, and identifying the best strategies for managing waste streams.

Reverse logistics: The importance of reverse logistics has increased with the development of the CE. Reverse logistics is the process of obtaining used, outdated and damaged products and packaging from the consumer and collecting, inspecting, classifying and reprocessing them until their disposal (Keshavarz Ghorabaee et al., 2017; Kovacic & Bogataj, 2017). Research on the use of fuzzy techniques in reverse logistics is also shown an increase in popularity, which is mainly related to the evaluation of reverse logistics under uncertain environments (Zhao et al., 2012; Zhou, 2012), service supplier selection (Fu & Liao, 2023; Wang & Liao, 2023), logistics facility network design, etc. (Dehshiri et al., 2022; Torgul & Paksoy, 2022). Fuzzy techniques can be used to evaluate the sustainability of different reverse logistics options, taking into account a range of criteria, such as environmental impact, cost and efficiency. By fuzzy techniques, decision-makers can more effectively weigh up the pros and cons of different options and make more informed decisions (Lu et al., 2021). Fuzzy AHP, fuzzy TOPSIS, fuzzy ANP and fuzzy COBRA methods are the commonly used fuzzy techniques for decision-making and evaluation in reverse logistics. The COBRA method was established by Krstic et al. (2022) and it is a type of distance-based MCDM method. It ranks the alternatives by integrating two types of distances of the alternatives, namely Euclidian and taxicab, from three types of solutions, namely ideal, nadir and average. The COBRA approach can distinguish between the distances of the alternatives with great precision, increasing the accuracy of the results. Additionally, the development of a MCDM model that combines multiple fuzzy techniques, like COBRA, ANP and other fuzzy techniques, as well as the application of the developed model to future scenario studies, will enable more accurate results in all facets of reverse logistics research (Krstic et al., 2022).

Performance evaluation: Nowadays, the performance evaluation of CE has attracted significant attention from researchers in several fields. Fuzzy techniques can be used to evaluate the performance of different recycling and reuse options and identify the most sustainable and cost-effective solutions. However, the lack of a comprehensive and complete methodology for analyzing the performance of the CE is a substantial difficulty for CE in evaluating its application and implementation at various levels in various industries. The performance evaluation of CE is a complicated system that includes economic, technical, environmental and management factors. A total of 13 publications out of 399 publications examined performance evaluation in the context of the CE, with a focus on evaluating urban CE performance (Wang et al., 2021), enterprise performance evaluation (Ren, 2009; Zheng, 2010) and green supply chain performance evaluation (Dolatabad et al., 2022; Jun & Soc, 2009). There are numerous indicators in its assessment, and to overcome the problems, a mature and viable decision-making method must be adopted. Several fuzzy modeling methods are being applied in this field, including fuzzy VIKOR, fuzzy Data Envelopment Analysis (DEA), fuzzy AHP, fuzzy DEMATEL method and fuzzy Delphi method, etc. Wang et al. (2021) developed a comprehensive fuzzy DEA for evaluating urban CE utilizing substantial data sets, which can quickly solve the urban CE efficiency problem under uncertain conditions and large data sets. In performance evaluation, fuzzy techniques can help analysts and decision-makers better handle ambiguous and uncertain information, improve the accuracy and reliability of evaluations, and play an important role in promoting the sustainable development of the CE. More decision-making techniques can be created in the future to cope with complicated decision-making problems in CE performance evaluation and promote CE use globally.

4. Application of FST to the CE and I4.0 technologies

4.1. I4.0 technologies-enabled CE

According to our analysis of the related content, two terms, namely "Industry 4.0" and "sustainability", frequently recur in the literature on FST and CE. The CE has been adopted on a global scale to achieve environmental and economic sustainability, and the emergence of I4.0 presents new chances to boost the effectiveness of the CE adoption, whether in waste management or recycling (Zhang et al., 2020). I4.0 depends on I4.0 technologies like sensors, the IoT, BCT, BDT, cloud computing, and cloud storage. All things can be connected, and their real-time data can be gathered, processed, and made visible, allowing users to see products throughout their entire life cycle. Numerous research on the CE and I4.0 technologies have been published in recent years, and an increasing number of academics have emphasized the crucial role that I4.0 technologies play in overcoming the obstacles and difficulties associated with the CE (D'Amico et al., 2022; Rusch et al., 2022). This subsection provides an overview of how prominent I4.0 technologies affect the CE.

IoT-enabled CE: IoT provides a set of practices that can help realize CE. In the first place, IoT devices can be used in the CE process of remanufacturing, recycling, and reuse by transmitting real-time data about product condition, predicting product maintenance plans, and designing parts ahead of time to extend product life cycle (Akbari & Hopkins, 2022; Akram et al., 2022; Alcayaga et al., 2019). Furthermore, IoT can assist businesses in planning their decisions better. Based on the information sent from sensors, decision-makers can track and monitor products to determine when maintenance follow-up is necessary, which aids businesses in making wise design choices (Cheah et al., 2022). Moreover, the effectiveness of CE measures performance can be evaluated by IoT through real-time metrics and early warning systems (Chauhan et al., 2022a). The IoT is becoming increasingly important, and many businesses are starting to incorporate it to increase and maintain operational efficiency.

BCT-enabled CE: BCT is a technology that involves many parties and uses cryptographic mechanisms to verify the data-sharing process. It represents an open, distributed ledger that makes it easier to share data on peer-to-peer networks (Kayikci et al., 2022). BCT offers enormous potential to promote CE from various viewpoints due to its verifiable, transparent, and automated nature (Kouhizadeh et al., 2020). In global supply networks, BCT offers the benefits of traceability, transparency, and sustainability (Kuo et al., 2018). It can also facilitate intricate interactions between supply chain network stakeholders and address data inconsistencies (Tsolakis et al., 2021). Thereupon, the oversight, visibility, and lack of transparency in circular supply chains can be effectively addressed by BCT (Erol et al., 2022). Additionally, it is argued that BCT enables access to more reliable data at every stage, which can help better manage green product data and recycled products by improving lifecycle assessment, product tracking, and product shelf life accuracy (Khan et al., 2022). In summary, the CE benefits from the use of BCT in every way, especially in the area of data reliability.

BDT-enabled CE: BDT has gotten much attention in the business world over the last decade because of its immense potential to solve corporate problems and open up new possibilities (Raut et al., 2019). The CE is starting to benefit from the widespread adoption of big data analytics infrastructure and computer technology. Using the Internet and big data, we can create a unified and open big data information platform to remove obstacles to the slow flow of product quality and other information, thus avoiding the problem of inefficiency caused by too many circulation links. At the same time, we can use the big data information gathered during production to understand the current quality features of products, reduce rework and waste products, and enhance product usage and recycling efficiency. In addition, Stakeholders play an essential part in business decisions and CE activities, and gaining consensus on traditional decisions is difficult owing to the involvement of several stakeholders (Kunz et al., 2018). Big data-driven intelligent decision-making can assure the authenticity of the information. It may swiftly examine the perspectives of many stakeholders to establish consensus in the shortest amount of time, which will help business decisions be made more successfully (Modgil et al., 2021).

4.2. Specific application studies

As mentioned in Subsection 2.3, the CE has the potential to use emerging I4.0 technologies to breathe new life into the CE and provide solutions to difficulties associated with its transformation. However, the scope of application of CE and I4.0 technologies is still limited, and several studies have used FST to investigate the barriers and challenges associated with their integration and provided solutions. Among the 305 publications retrieved, 32 were related to FST, CE, and I4.0 technologies, all of which were published in 2020 or later, demonstrating that recent advances in science and technology have contributed to the formation and advancement of this cross-cutting field. These studies used various fuzzy approaches to address the content of different research themes, 20 of these publications were about barrier research (Agarwal et al., 2022; Luthra et al., 2022; Shang et al., 2022), with others about driver analysis (Zhang et al., 2021a), supplier selection (Kusi-Sarpong et al., 2021; Zhang et al., 2020), relationship analysis (Belhadi et al., 2021), and performance evaluation (Agarwal et al., 2022; Karuppiah et al., 2022). Table 9 covers some critical studies that have significantly contributed to integrating CE and I4.0 technologies, along with their research themes, background, methodologies, and outcomes.

Meanwhile, MCDM methods like fuzzy SWARA, fuzzy BWM, fuzzy VIKOR, and fuzzy COPRAS are more often employed techniques. Most of the literature uses a hybrid strategy that combines more than two strategies. Additionally, the case study contexts are primarily centered on the manufacturing industries in developing nations, demonstrating that the digitization of the CE in developing countries is moving more slowly but has caught the interest of many academics.

5. Future research opportunities

The CE, which aims to improve business models and mitigate environmental impacts, has grown and enhanced gradually amidst the explosive growth of the literature. However, there is a vast and complicated body of knowledge at its junction with I4.0 and FST, and there are far too many problems to explore and resolve. This paper gives the following discussions to indicate some expectations for future research based on what has been discussed.

Table 9. FST to facilitate the integration of CE and I4.0 technologies

Research subjects	Research topic	Research case background	Reference	Research methods	Research results
IoT and CE	Barriers	Manufacturing Industry	(Cui et al., 2021)	Fuzzy SWARA-CoCoSo	Sensor technology was found the most critical barrier
		Smart waste management in underdevel-oped countries	(Yadav et al., 2021)	Fuzzy DEMATEL	The most significant causal factors were the "lack of strict government regulatory policies."
	A framework for smart waste management	Environmental engineering in Pakistan	(Khan & Ali, 2022)	Fuzzy SWARA-VIKOR	Pakistan should prioritize policy and law
	Evaluating CE-IoT-EBP	Food processing industry	(Persis et al., 2021)	Fuzzy ANN	CE-IoT-EBP has a positive impact on the organization
BCT and CE	Barriers	BCT adoption in the CE	(Rejeb et al., 2022)	Fuzzy Delphi and BWM	"Lack of knowledge and management support" is the most significant barriers
		Indian electronic MSMEs	(Mukherjee et al.)	ISM, MICMAC, Fuzzy TOPSIS	"Lack of support from distribution channels" is the most critical barrier.
	Evaluating the potential of BCT	CE adoption barriers	(Erol et al., 2022)	MCDM-based QFD method with HFLTS	"Enhanced supply chain traceability management" is the most significant function
	Evaluating critical success factors	Solar photovoltaic energy systems in Turkey	(Erol et al., 2021)	Intuitionistic Fuzzy DEMATEL	Effective government incentive programs and regulations are significant
BDT and CE	Barriers and Solutions	The dairy supply chain in the CE	(Kazanco-glu et al., 2021b)	Fuzzy ANP and Fuzzy VIKOR	"Economy" is the most severe barrier, and "optimization" is the most solution
		Digital supply chains in the CE	(Dwivedi & Paul, 2022)	Fuzzy BWM	"Lack of skills and facilities" is the most influential barrier, and "financial and regulatory supports" are the primary steps
	Evaluating the impact	Agricultural supply chain in developing countries	(Percin, 2022)	Three-Stage Multi-Criteria Decision Model	Big data analytics has the most significant impact on productivity improvements

End of Table 9

Research subjects	Research topic	Research case background	Reference	Research methods	Research results
I4.0 and CE	Barriers	The food industry in India	(Krishankumar et al.,2022)	Fuzzy CRITIC and fuzzy COPRAS	The proposed model is better than the existing model, with a 30% increase in variability
	Challenges	Manufacturing supply chains	(Xin et al., 2022)	SWARA-COPRAS	"Lack of vision and strategy" (0.0489) had the first rank
	The potential risks	A logistics company in Turkey	(Kazancoglu et al.,2021a)	Fuzzy AHP	The most critical responses are the integrated business processes for cross-functional collaboration
	Supplier selection	Textile manufacturing in Pakistan	(Kusi-Sarpong et al., 2021)	Fuzzy BWM, VIKOR	Technology and Infrastructure are the most valued criteria

Notes: Ethical Business Practices (EBP); Artificial Neural Network (ANN); Quality Function Deployment (QFD); Hesitant Fuzzy Linguistic Term Sets (HFLTS).

5.1. Establishment and optimization of comment index system

From earlier research into the literature on FST, CE, and I4.0 technologies, we may find that whether employing numerous fuzzy approaches for supplier selection, framework creation, or performance evaluation, the study issue necessitates the development of appropriate criteria and metrics systems. However, the above research themes are inseparable from a specific application context, and there are differences not only among different manufacturing enterprises but even among different industries and countries, which leads to the singularity and limitation of the index system (Wang et al., 2017). Coupled with the fact that the CE is still a developing research field, there is currently no uniform indicators system and principles that provide vital indicators that can be referenced.

Particularly in the context of I4.0, many intersecting fields of I4.0 technologies and CE are gradually forming, which contain numerous I4.0 technologies components and require consideration of multiple influencing factors. In particular, decision-making and evaluation consider the rise in indicators related to the "adoption of digital technology" and "plans for digital transformation". As a result, it is critical to have a standard indicator system that incorporates necessary indicators and enables the flexible mobilization of relevant indicators for varied practice situations. Its advancement can serve as a strong foundation for improving this cross-cutting topic, making the function of FST in this field more precise and dazzling. We eagerly anticipate researchers to comprehend the similarities across indicators that are valid enough to serve as guiding principles for constructing metrics in various case studies and applications that account for variances in practice.

5.2. Extension of research background and themes

SMEs are more likely to be significant implementers of CE globally since they are responsible for about 70% of employment and more than 70% of industrial pollution (Dey et al., 2022). However, CE digitalization has been particularly sluggish among SMEs in non-developed nations (Pappas et al., 2021). Therefore, to achieve global economic transformation and tackle global social and environmental concerns, it is vital to understand each SME's corporate attitudes and decision-making and propose solutions based on them. Unfortunately, little research currently investigates and suggests solutions to the hurdles to CE adoption in SMEs. As a result, we may employ the fuzzy technique for identifying and analyzing limitations and drivers of CE adoption in SMEs. At the same time, the supply chain's core firms limit and assess their partner-enterprises based on rules, which will aid in implementing the CE in SMEs.

Furthermore, in addition to the extensively mentioned adoption of CE in manufacturing, the implementation of CE in the textile sector is progressively becoming visible. As one of the most polluting industries in the world, the textile industry should pay greater attention to the requirement to adopt the circular concept at crucial phases of design, production, retailing, and recycling throughout the textile supply chain (Cao et al., 2022). Additionally, future studies should broaden the application of the circular idea to businesses and scenarios, such as the service and food industries, to provide a sound theoretical and practical framework for implementing CE in various industries.

While applying FST to implement CE in diverse sectors, it is critical to note that more significant consideration should be given to stakeholders' perspectives in the supply chain. The adoption process of CE practices is heavily impacted by stakeholders' interests (Kannan, 2018), particularly in the era of I4.0, which necessitates the rapid development of advanced I4.0 technologies. Any realization might not occur in the absence of the stakeholders' expectations. As a result, businesses must enlist external stakeholders' assistance, input, and information (e.g., customers, suppliers, and government). To accomplish this, researchers must thoroughly understand the significance of stakeholders while making crucial choices, investigating hurdles, and designing and producing goods following stakeholder demands.

5.3. AI and CE

With the expansion of the Internet, research utilizing Artificial Intelligence (AI)-related techniques has gained popularity. By integrating real-time and historical data on users and goods, AI may assist in the optimization of product turnover and develop intelligent inventory management through pricing and demand forecasts (Nikseresht et al., 2022). AI also improves the capacity to evaluate the enormous quantity of data created during manufacturing and can forecast uncertainties in various processes, monitor those processes in real-time, and identify cycle system flaws (Fraga-Lamas et al., 2021).

The use of FST to study AI and the CE is still a relatively new field, so there aren't as many studies on it. Tang and Liao (2021) developed an effective multi-attribute large-scale group decision-making model to undertake the selection of pilot parks or cities under the CE, where their information of attributes was obtained by mining public preference data using natural language processing techniques from a particular data mining application domain. This application provides a new perspective on the information-gathering and decision-making process combined with data techniques such as data mining. With AI, CE will move toward automation, so examining the causes, effects, and ramifications of automated process safety systems for CE may be another fruitful area of research for future studies. In the future, FST, CE, and AI will collide to create more sparks. Prospective researchers are anticipated to develop fuzzy AI techniques to apply AI more effectively to CE.

5.4. The CE in a global context

After witnessing the unsustainable use of the earth's resources and paying a heavy price for the industrial development stage, humankind realized the flaws in the prior economic development model and the irreversible adverse effects. Therefore, they started to consider and propose a new development model of CE based on contemporary scientific and technological advancement (Gebhardt et al., 2022).

Along with economic globalization, developed and developing nations have gained growth opportunities and environments (Shen et al., 2020). The distinctive industries of each nation, particularly developing countries, have steadily become more robust, resulting in an increasingly visible divide between economic and industrial labor among countries globally (Gedam et al., 2021). It is important to note that the quick expansion of some industries that consume a lot of resources and damage the environment in some developing countries has not only depleted their already scarce resources but also severely harmed their already fragile ecology. They have sacrificed resources and the environment for today's progress while breaking the back of their long-term development. Clearly, in the face of economic globalization, developing nations should plan their future scientifically from a strategic vantage point, effectively implement appropriate science and technology, seek to transform the pattern of economic growth, and develop the CE aggressively.

However, no country can fulfill its demands with its natural resources, necessitating the economic, reasonable, and practical distribution of essential resources through investment, development, or global commerce. Therefore, in the worldwide context, scholars in the field of CE should pay attention to the progress of international cooperation, explore potential barriers to national and corporate collaboration, and promote global economic transformation and win-win cooperation while focusing on the development of their own country or a specific country.

6. Conclusions

The goal of reviewing journal papers on CE and FST is to identify aspects of the issue that have not yet been investigated or might be examined more deeply. As a result, this paper first used bibliometric tools to visualize and analyze the literature on FST and CE, then conducted a systematic content analysis of that literature about FST and CE and identify the specific role that FST can play in each stage of CE, concerning cutting-edge technologies like IoT and big data under I4.0, laying the groundwork for future research.

Based on 399 publications obtained in Scopus and WoS Core Collection database, we have examined it from various angles using visualization tools, the information has been obtained about the trends of publication for CE and FST publications, the development of keywords, the authors, the nations/regions, the institutions, and the features of their collaboration. Firstly, the number of publications and citations of CE and FST has shown an explosive growth trend since 2018, for hot research content, publications on barrier assessment obtained the most citations among the highly cited papers, followed by topics like challenge analysis, methodological research, assessment, and supplier selection. Tseng, Ming-Lang from China Medical University, Taiwan, have had the highest number of publications, next is Professor Kazancoglu, Yigit from Yasar University, followed by Luthra, Sunil, Mangla, Sachin Kumar, and Tat-Dat Bui. Tat-Dat Bui and Tseng, Ming-Lang, have a tight working relationship since 2020, and Yigit Kazancoglu and Sachin Kumar Mangla collaborate closely. The authors' collaborative network has been forming since 2020. 84 authors with at least two publications were divided into 11 clusters based on their collaborative links. Secondly, according to the number of papers and citations, China and India are the two main nations researching the CE and FST, next are UK, Turkey, and China, Taiwan. According to the global cooperation network, China is a more significant partner and collaborates with other countries. Besides, for high-contribution research institutions, the National Institute of Technology has the most publications, followed by Yasar University, Asia University Taiwan, China Medical University Taiwan, and China Medical University Hospital Taiwan. The research of the medical university on the topics of CE and FST is related to the management of medical waste and circular supply chain management in the healthcare industry. Thirdly, the results of the keyword analysis show that "management" and "barriers" are the top two keywords with the highest coexistence frequency, indicating that researchers are mainly interested in identifying and addressing difficulties and barriers that prevent the adoption and application of FST-based CE practices. "Sustainability", "framework", and "performance" are also among the top five keywords with the highest frequency of co-occurrence. This suggests that researchers are also investigating the role that FST could play in creating sustainable frameworks and evaluating the effectiveness of CE practices. "Supply chain management", "decision making" and "challenges" have also emerged as important keywords in the field. These keywords indicate that researchers are exploring how to use FST to optimize supply chain management processes and improve decision-making in the context of a CE. Finally, With the advent of the I4.0 era, I4.0 technologies such as big data, the Internet of Things, and BCT steadily developed, and critical terms in publications such as "big data", "technology", "facilitator" and "opportunity" rapidly surfaced in people's minds. These technologies and the CE represent a new field of study, opening up new potential for the CE.

Additionally, through a systematic analysis of the literature, we discovered that fuzzy techniques can be applied to several key stages of CE, including barriers assessment, risk and challenge assessment in the pre-preparation stage; sustainable product development, supplier evaluation and selection in the design and production stage; and reverse logistics and performance assessment in the recycling and reuse stage. The most commonly used fuzzy techniques for each link are analyzed in this study, along with the unique application procedures. For important links of the study, such as barrier assessment and supplier evaluation, the top three tools are given. The advantages and disadvantages of each technique are also listed, along with examples from actually applied scenarios, to aid in the selection of research methods. Among the fuzzy methods used to address issues with the CE, the fuzzy

AHP, fuzzy TOPSIS, fuzzy Delphi and fuzzy DEMATEL methods have been the most widely utilized. In the interim, several researchers have employed hybrid approaches to address the challenges, including the fuzzy BWM-ANP technique and the fuzzy SWARA-CoCoSo method, each of which has shown promising outcomes. Meanwhile, it is worth noting that numerous approaches have been taken to handle the same problem in various publications. Most research backgrounds are from developing country manufacturing industries, with approximately half of the studies focusing on supply chains and suppliers. This is because that the CE has altered the traditional economic model and businesses are now required to engage in pro-environment and pro-social initiatives. A number of these projects rely heavily on the supply chain for their success, and supply chain management is inseparable from the CE. I4.0 can enable the integration of industrialized production with the digital world and make digitally connected production a reality, paving the way for the technological requirements of the CE (Mastrocinque et al., 2022). However, there are still many challenges and barriers in the course of its effective deployment. The fuzzy MCDM technique has shown to be a successful strategy for SMEs' uncertainty issues with technology selection, framework design and performance enhancement.

We examined how I4.0 technologies, i.e., IoT, BCT and BDT, affect CE. The findings demonstrate that the advantages of IoT in CE include real-time data transmission for product monitoring and maintenance, predictive planning for extended product lifecycle, improved decision-making through sensor-based information, and evaluation of CE performance through real-time metrics and early warning systems, etc. Secondly, the use of BCT in CE enables verifiable data-sharing, transparency, and traceability, addressing challenges related to oversight, visibility, and data reliability in circular supply chains. What's more, the implementation of BDT in CE allows for the creation of a unified and open information platform, leveraging big data analytics and stakeholder consensus to enhance product quality, efficiency and decision-making. Then, we discuss how fuzzy techniques based on FST can facilitate the integration of CE with I4.0 technologies, the findings demonstrate that barrier identification, impact and performance assessment, and innovation of a digital framework are significant tasks that fuzzy methods can address. Suppose that we want to create a sustainable circular supply chain within I4.0, in that case, it is necessary to consider more fuzzy optimization models to resolve the decisions of site selection, supplier selection, technology selection, logistics model, etc. Finally, we suggest further research directions of investigation. Given the lack of literature discussing FST's significance in the CE, we believe that this research will draw attention to FST's good contribution and encourage its advancement in CE and I4.0 technologies.

This article still has several limitations. Firstly, keyword searches might not turn up all relevant and significant papers. Additionally, the search strategy and selection criteria are subjective, which could have an impact on the analysis's outcomes. This paper primarily focuses on fuzzy decision-making methods in CE. However, there are still some FST combined with neural network and deep learning methods applied in this field, and fuzzy theory will continue to shine if fuzzy deep learning and other methods are thoroughly and extensively researched.

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Author contributions

Marinko Škare conceived the study. Xunjie Gou and Xinru Xu wrote the first draft of the article. Zeshui Xu was responsible for supervision and funding acquisition.

Disclosure statement

The authors have no competing financial, professional, or personal interests from other parties that are related to this paper.

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