Sustainable Production and Consumption 43 (2023) 94–112

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Do industry 5.0 advantages address the sustainable development challenges of the renewable energy supply chain?

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ARTICLE INFO

Editor: Dr. Sachin K. Mangla

Keywords:
Industry 5.0
Sustainable development
Renewable energy supply chain
Fuzzy set theory

ABSTRACT

Scholars assert that the fifth industrial revolution has the potential to go beyond Industry 4.0's efficiency and advance supply chain objectives for sustainable development, including adaptability, a human-centered orientation, and the durability of social and environmental issues. According to Industry 5.0-based solution methodologies, sustainable development challenges (SDCs) can be addressed in the renewable energy supply chain (solar energy). This study provides a distinct set of 23 SDCs and 19 Industry 5.0 advantages. Moreover, A hybrid fuzzy best worst method and fuzzy weighted aggregated sum product assessment technique are utilized in the renewable energy supply chain context. To determine the weight of SDCs, preliminary data are gathered based on experts' opinions. The outcomes indicate that the most significant SDCs in the renewable energy supply chain are “non-consideration of human factors,” “Inadequate regulation and implementation of environmental standards,” “Commitment of inadequate management for adopting sustainability,” “non-uniform alignment of sustainability, organization,” and “goal and customer expectation.” For overcoming the SDCs, “supply chain modularity,” “research and innovation in social and human problems,” and “building safer and more complicated hyper-connected networks” are the most prominent Industry 5.0 advantages. The study findings will give the most critical advantages for creating sustainability in the continued industry expansion–society engagement and more sustainable renewable energy supply chain, as well as creating a more resilient energy industry and society.

1. Introduction

Energy sustainability is probably the essential socio-environmental issue among the numerous components of sustainable development (SD) (Li et al., 2023; Marti and Puertas, 2022). Utilizing conventional energy sources on a wide scale increases environmental pollution and economic deficits (Bazmi and Zahedi, 2011). Renewable energy sources can replace fossil fuels and offer a cleaner and even more reliable energy source (Ghasemian Sahebi et al., 2023). Consequently, using them strategically to address environmental issues and ensure a clean energy source will lead to a more sustainable future (X. Li et al., 2023; Qazi et al., 2019). The transformation is predicted to significantly impact the welfare and well-being of the community and accelerate industrial development (Sahebi et al., 2022; Wee et al., 2012). The term “renewable energy supply chain” (RESC) refers to the overall process, commencing with the purchase of energy resources and ending with their consumption, that is involved in the transformation of raw energy into useable energy (Bazmi and Zahedi, 2011; Masoomi et al., 2022).

To achieve the SD, Industry 5.0 proponents contend that Industry 4.0 is inadequate (Golovianko et al., 2023). According to the literature, Industry 4.0 is primarily concerned with productivity that is driven by technology (Ghobakhloo and Fathi, 2021). Production efficiency and emission reduction are two micro-environmental sustainability indicators boosted by Industry 4.0's internal productivity mechanism (Garay-Rondero et al., 2020). It does not address the profit-driven foundation of modern production and consumer economic structures (Ma et al., 2021). Relying on the progress made in Industry 4.0 (L. Li, 2020) and the changes brought about by Covid-19, the term “Industry 5.0” has been coined to describe the creation of a hyperconnected, data-driven industrial environment with an emphasis on sustainable development (Javaid and Haleem, 2020). Sustainable development in

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https://doi.org/10.1016/j.spc.2023.10.018
Received 26 April 2023; Received in revised form 24 October 2023; Accepted 24 October 2023
Available online 3 November 2023
2352-5509/

Nomenclature

Abbreviations

CAI	Cognitive Artificial Intelligence
FBWM	Fuzzy Best Worst Method
FWASPAS	Fuzzy Weighted Aggregated Sum Product Assessment
GR	Global Rank
GW	Global Weight
I5.0 - I4.0	Industry 5.0 - Industry 4.0
IA	Industry 5.0 Advantage
MCDM	Multi-Criteria Decision-Making
RE	Renewable Energy
RESC	Renewable Energy Supply Chain
SD	Sustainable Development
SDC	Sustainable Development Challenge
SSC	Sustainable Supply Chain
SSCM	Sustainable Supply Chain Management
TFNs	Triangular Fuzzy Numbers
WPM	Weighted- Product Model
WSM	Weighted-Sum Model

Symbols

CI	Consistency index
C_n	Criteria index
$\tilde{A}$	Fuzzy BWM decision matrix
OW	Fuzzy comparison for other criteria over the worst
BO	Fuzzy comparison for the best to other criteria
$\widetilde{A}B_n$	Fuzzy matrix of best to other criteria
$\widetilde{A}_nW$	Fuzzy matrix of other to best criteria
$\widetilde{y}$	Fuzzy WASPAS decision matrix
$\widetilde{W}_B$	Fuzzy weight of the best criterion's
$\widetilde{W}_j$	Fuzzy weight of the criteria
$\widetilde{W}_w$	Fuzzy weight of the worst criterion's
(l_j, m_j, u_j)	Lower, Medium and upper bound of fuzzy numbers
$R^{\sim}$	Normalized Fuzzy WASPAS Decision Matrix
k^*	Optimum value of objective function
ב	Preference order value
Ai	Total substitute scores
$\widetilde{aij}$	Triangular fuzzy number
k_i	Value of the integrated utility function
$\xi^{\sim}$	Value of the objective function
$\widetilde{\widetilde{P}}$	Value of the weighted product model
$\widetilde{\widetilde{q}}$	Value of the weighted sum model
$\widetilde{x}_q$	Weighted decision matrix
$\widehat{x}_p$	Weighted normalized fuzzy decision matrix

Industry 5.0 aims to improve all aspects of sustainability, from the economy to the environment and society (Kasinathan et al., 2022). Industry 5.0, according to (Carayannis and Morawska-Jancelewicz, 2022; Kasinathan et al., 2022), is focused on manufacturing that seems to be human-centric. Technological developments in social smart factories must enhance people's quality of life (Alves et al., 2023). The idea of Industry 5.0, as described by (Huang et al., 2022), centers on human-robot interaction within a "smart business ecosystem" that prioritizes ecological economy and effectiveness in the use of limited resources (Xu et al., 2021). The scope of Industry 5.0, according to (Dutta et al., 2020), includes a range of industries, including manufacturing, healthcare, renewable energy, and agriculture (Akundi et al., 2022; Masoomi et al., 2022; Park and Li, 2021).

Industry 5.0 emphasizes the harmonious collaboration between humans and machines. In renewable energy, skilled workers should work alongside advanced robotics and automation systems to maintain renewable energy technologies like solar panels. Also, Industry 5.0 strongly emphasizes sustainability and environmental responsibility (Alves et al., 2023). In RESCs, this translates into eco-friendly materials, reduced energy consumption in production processes, and a commitment to producing sustainable energy solutions. Industry 5.0 brings about a paradigm shift in sustainable production, strongly focusing on sustainability, human-machine collaboration, customization, and flexibility (Dwivedi et al., 2023). In the context of renewable energy supply chains, these features lead to more efficient, eco-friendly, and sustainable energy solutions that contribute to sustainable development goals.

The effectiveness of the RESC has a considerable impact on organizational performance; thus, it is crucial to evaluate the current challenges facing RESC's sustainable development and potential research solutions (Sharma et al., 2021). The key measures relying on Industry 5.0 will assist companies in remaining current with updated technologies and penetrating the RESC sustainability (Dwivedi et al., 2023). According to experts, Industry 5.0 might substantially influence various sustainable development challenges (SDCs) (Fraga-Lamas et al., 2021; Xu et al., 2021). Industry 5.0 advantages are poorly understood, and it is unclear how sustainability objectives relate to transformative events like Industry 5.0. Therefore, it is vital to emphasize that the benefits needed to overcome the SDCs related to the RESC adoption must match the current business environment, which includes Industry 5.0. The following research objectives (RO) were developed for the present research relying on the previously addressed issues:

RO1: To identify the advantages of Industry 5.0 toward attaining sustainable development in the renewable energy supply chain.
RO2: To prioritize the advantages of Industry 5.0 for addressing sustainability challenges in the renewable energy supply chain.

The framework is examined using a case-based approach to meet the research goals. The fuzzy best worst method (FBWM) is used to determine weights, which is the main issue with sustainability adoption. Industry 5.0 adoption rate-increasing options are now accessible to the industry and are then examined utilizing the fuzzy weighted aggregated sum product assessment (FWASPAS) methodology. There are many potential characteristics of Industry 5.0 as a new paradigm for attaining sustainability, but before it can be fully implemented, two critical problems must be resolved (Aheleroff et al., 2023; Golovianko et al., 2023; Grabowska et al., 2022). First, preliminary research has been conducted on the functioning, limits, and fundamental principles of Industry 5.0. Second, how Industry 5.0 advantages will tackle sustainable supply chain issues remains ambiguous.

The paper is organized as follows: The introduction is the first of the article's eight sections. Section 2 summarizes the literature review conducted to investigate SDCs in RESC and Industry 5.0-based advantages, followed by a discussion of the literature gaps. Section 3 describes the research approach employed in this study. Section 4 examines the created framework for case organization. Section 5 discusses the case study, research results, and study implications, while Section 6 discusses the conclusion and future scope.

2. Literature review

2.1. Sustainable development challenges in RESC

The potential contribution of renewable energy (RE) to alleviating global environmental issues has attracted the attention of several academics in these areas. Sustainable development in RESC seems to be a critical component for enterprises to retain global competitiveness, which, if executed improperly, would lead to the loss of significant investment costs (Ghasemian Sahebi et al., 2023). Identifying the primary challenges to implementing SD operations is essential.

Consequently, it must be realized that every organization has a distinct environment and mode of process execution and that adoption advantages must be developed appropriately (Ozturk et al., 2016). In addition, understanding sustainability standards and regulations facilitates sustainability management implementation (Jouzdani and Govindan, 2021). Therefore, after studying papers on sustainable challenges in the RESC industry, Table 1 lists all the identified SDCs.

For this purpose, a comprehensive literature review was used to identify relevant studies and publications on SDCs in the renewable energy sector. This step ensures the review process is extensive, transparent, and based on diverse sources. The experts involved in the extraction process enhance the validity of the extracted SDCs. This approach allows for cross-validation. The challenges were shared with the three experts, allowing them to review and validate the relevance, significance, and applicability of the identified SDCs.

2.2. Industry 5.0 concept

Industry 5.0 has inspired numerous academic and industrial discussions (Demir et al., 2019). Researchers have postulated a variety of explanations for Industry 5.0's success. (Özdemir and Hekim, 2018), For example, characterize Industry 5.0 as a logical evolution. In short, where Industry 4.0 will improve the operations of a business, Industry 5.0 will help to build a human-centered, sustainable, and resilient manufacturing sector. Among others, (Kumar et al., 2021; Nahavandi, 2019) have argued that the rise of disruptive technologies is driving the evolution of human-centric industrial operations, which will ultimately lead to better working conditions, more jobs, and more productivity in the workplace (Ghobakhloo et al., 2022; L. Li, 2020). Earlier studies indicated a range of perspectives on this issue; nevertheless, they agreed on two critical aspects of Industry 5.0. Previous studies have linked the industrial transformation that forms the basis for Industry 4.0 to problems, including the digital divide and focusing on technology rather than people (Ghadge et al., 2022). (Matthess et al., 2022) have shown that Industry 4.0 has limited or harmed sustainability. Second, Industry 5.0 is predicted to build upon the technical foundations of Industry 4.0. Nevertheless, it is anticipated that cognitive artificial intelligence (CAI), energy transition technologies, and intelligent materials will play a key role (Lu et al., 2019; Park and Li, 2021). Table 2 lists the difference between Industry 4.0 and Industry 5.0.

Early in 2022, the European Commission strengthened its resistance to Industry 4.0, asserting that this paradigm is necessary for addressing the existing social and environmental crises (Mukherjee et al., 2023). Industry 5.0, according to the policy statement, gives a novel viewpoint on the industry by explaining the responsibilities and objectives of value chains (Patera et al., 2022), business models, and digital transformation in a hyperconnected corporate environment (Ivanov, 2022). Industry 5.0, according to the agreement, is a socio-technological phenomenon driven by stakeholders that gradually replaces conventional profit and consumption-driven economic models with circular (Xu et al., 2021), regenerative, sustainable, and resilient value-creating economic models (Fraga-Lamas et al., 2021).

2.3. Industry 5.0 advantages

The supporting elements of Industry 4.0 substantially influence supply chain operations. The presumption that robots will rule the industrial environment gave Industry 5.0 (Fraga-Lamas et al., 2021). The Industry 5.0 concept's main objective is to emphasize the value of people in the manufacturing environment (Javaid and Haleem, 2020).

Adopting Industry 5.0 ideas will help us use resources more efficiently and move us toward a better future. Renewable and green energy will significantly reduce carbon emissions and relieve the global strain on fossil fuel reserves across the globe (Ghasemian Sahebi et al., 2023). Since these resources can be carried into rural regions and areas with insufficient electricity, they can address the world's energy crisis. As a result, some level of sustainable development may be expected (Demir and Cicibaş, 2019). There is significant scope for research and improvement in logistics and supply chains for various operations. This sector incorporates several advances to enhance SC sustainability, including RESC sustainability (Masoomi et al., 2022). Developing a resilient economy necessitates the integration of these areas, which are placed on distinct platforms. In this manner, humanity will advance toward the global sustainability of civilization and our planet (Dwivedi et al., 2023). When properly implemented, Industry 5.0 principles aid in promoting the RESC's functions for sustainable development. In addition, conditions are established for the efficient utilization of new and enabling technologies to achieve sustainable development goals. After reading the required publications, Table 3 presents the Industry 5.0 advantages (IAs) that different investigators have described in the literature.

Numerous researchers argue the enabling technologies, applications, and challenges of previous industrial revolution standards (Industry 4.0) and the supporting industrial technologies (De Giovanni and Cariola, 2021; Ghadge et al., 2022). But concerning Industry 5.0, despite a growing trend in this industry, we are unaware of any paper that concurrently concentrates on Industry 5.0, SD, and RESC. Motivated by this observation, we propose to present a very first study on Industry 5.0 and sustainable development in RESC. Several forms of research (Caiado et al., 2022; Umar et al., 2022; Yadav et al., 2020) investigate the underlying industry standard and the associated industrial technologies, including their enabling technologies, applications, and obstacles. Despite the growing interest in Industry 5.0, we don't observe any publications that concurrently address the sustainable development challenges of the renewable energy supply chain in the context of Industry 5.0.

2.4. Research gap

Numerous researchers have examined and described the many challenges that companies in the manufacturing, service, healthcare, and various industries have when trying to establish their SSC (Ansari and Kant, 2017; Carter and Easton, 2011). The majority of researchers said that the critical barriers to SSC adoption are the “inappropriate execution of sustainability principles” and the “high cost of sustainability adoption” (Yadav et al., 2020). “Resistance to culture change,” “Lack of effective employee engagement and empowerment,” “Ineffective employee training for sustainability,” “Non-consideration of human factors,” and “Lack of effective interdepartmental communication” as certain sociocultural variables have a significant potential to prevent the adoption of sustainability(de Godoy Tominaga et al., 2020; Yadav et al., 2020). In their research, (Sajjad et al., 2015) also noted that several organizations have failed to implement SSC because of imitating the sustainability adoption tactics of other organizations. (Fraga-Lamas et al., 2021) Evaluated the effect of the role of Industry 5.0 in attaining sustainability and emphasized the importance of sustainable resource management due to its direct influence on the sustainability of the supply chain. The ranking of problem-solving metrics will help practitioners create compelling, sustainable development adoption advantages for the supply chain. If they expect to avoid or lessen the effects of SDCs on the supply chain, decision-makers must prioritize their methods. In the context of the industry 5.0 advantage for overcoming sustainable development challenges in the renewable energy sector, here is a detailed explanation of research gaps:

- ❖ Limited focus on I5.0: One research is the little attention given to the concept of Industry 5.0, specifically within the context of the renewable energy sector. Industry 5.0, characterized by human-

Table 1
List of sustainable development challenges in the renewable energy supply chain.

Challenges	Description	Literature support
Economic- SDC1		
strong sense of poor economic returns (SDC11)	The decision-makers perceive low economic returns from implementing the sustainable supply chain.	(Liu, 2022; Yadav et al., 2020)
High disposal costs (SDC12)	High disposal costs hamper the company's inability to develop a sustainable supply chain.	(Jouzdani and Govindan, 2021)
The high amount of infrastructure (SDC13)	Industry 5.0 has enormous business potential but requires high precision and accuracy. This research is still in its early phases and will need substantial money and infrastructure. Startups and entrepreneurs face challenges since Industry 5.0 needs vast investments in infrastructure and cutting-edge technology.	(Ansari and Kant, 2017)
Lack of availability of resources (financial, technical, human, etc.) (SDC14)	The lack of financial, technical, and human resources necessitates the business to find an appropriate supplier to accomplish the desired results.	(Abbaspour et al., 2022)
Environmental- SDC2		
Inadequate regulation and implementation of environmental standards (SDC21)	There is no substantial law or government support for adopting sustainable measures.	(de Godoy Tominaga et al., 2020; Shahin et al., 2019)
Insufficient attention to research and development sustainability (SDC22)	Research and development lack concerning recycling manners, product reusability, and less polluting manners. Support for energy and resource conservation via research and development.	(Abbaspour et al., 2022)
Inappropriate system of reverse logistics (SDC23)	Recycling becomes challenging and deviates from sustainability without an adequate reverse logistics system.	(de Godoy Tominaga et al., 2020)
Organizational- SDC3		
Collaborative robotics with human co-workers (SDC31)	When combined with human employees, collaborative robots seem to be an automation approach that represents a severe risk on the shop floor.	(Walker et al., 2008)
The threat posed by cyber security (SDC32)	Because of increasing connection and the usage of standard communications protocols, there is an enhanced cyber security threat in critical industrial systems and production lines at Industry 5.0.	(de Godoy Tominaga et al., 2020)
Ineffective integration of sustainability with available processes (SDC33)	Management often finds connecting sustainability within the current supply chain process challenging.	(Batista et al., 2018)
The commitment of inadequate management for adopting sustainability (SDC34)	Sustainable supply chain implementation failures are caused by senior management authorities' insufficient participation in promoting sustainability adoption.	(Irani et al., 2017)
Unavailability of sustainability standards and regulations (SDC35)	Exposure to sustainability standards and laws is vital since it ensures generated item benchmarking. Furthermore, the lack of advanced data auditing standards impacts renewable energy supply chain implementation.	(Jouzdani and Govindan, 2021)
Process- SDC4		
Overproduction phenomenon (SDC41)	Overproduction may occur because of rapid and efficient manufacturing. Transparency in implementation should also be considered.	(Schumacher et al., 2016)
Absence of autonomy in the current systems (SDC42)	As fundamental components of self-organized systems, smart manufacturing systems need more sociality. The shift from the current setting to Industry 5.0 is challenging owing to the systems' lack of autonomy, including integrated decision-making.	(Reche et al., 2020)
The challenge of acquiring high quality and integration (SDC43)	It also seems challenging to save high-quality and reliable data from manufacturing systems, and combining diverse data sources is difficult.	(Romero et al., 2020)
Challenging to draw regulatory mechanisms (SDC44)	Industry 5.0's high degree of automation makes it hard to create effective regulatory frameworks.	(Wan et al., 2021)
Design complexity for RE consumption reduction (SDC45)	To produce sustainable products while minimizing energy usage, many firms modify their design methods, which increases complexity.	(Paul et al., 2022; Singh and Trivedi, 2016)
Complexity within supply chain configuration (SDC46)	The existence of supply chain complexity limits the adoption of sustainability in traditional supply chains. The best way to keep production on schedule is to be in constant contact with the supplier via the monitoring of organizational operations.	(Singh and Trivedi, 2016)
Social- SDC5		
Adaption with the new industrial revolution (SDC51)	The next industrial revolution will be complex for older citizens and other significant groups to adapt to.	(Qin et al., 2016)
Inadequate employee training and culture (SDC52)	Training individuals for the new positions incur additional expenditures. Certain companies may find it difficult to modify their distribution networks to support Industry 5.0. In addition, the personnel must get training on sustainable adoption tactics to improve supply chain performance.	(Liu, 2022; Winter and Knemeyer, 2013)
Work polarization (SDC53)	Two communities are highly skilled and qualified professionals and low-wage, unskilled laborers. This can potentially decrease the societal divide between talented and untrained individuals.	(Schumacher et al., 2016)
Non-uniform alignment of sustainability, organization, goal, and customer expectation (SDC54)	To remain competitive in a global market, finding a balance between sustainability, organizational objectives, and consumer needs is crucial. In addition, the current firm advantage and business models must be modified and adapted to meet the requirements of Industry 5.0 for the sake of rising levels of automation in various companies.	(Winter and Knemeyer, 2013)
Non-consideration of human factors (SDC55)	Numerous firms disregard the human factors that ultimately impact organizational success and misalign supply chain operations.	(Winter and Knemeyer, 2013)

Table 2
Difference between Industry 4.0 and Industry 5.0.

No.	Industry 4.0	Industry 5.0
1	Industry 4.0 prioritized widespread product customization.	The goal of Industry 5.0 was to personalize products on a mass scale.
2	Data utilization in digital form	Utilizing data intelligently
3	Offer a distinctive experience	Provide innovative experience
4	improved integration of information technology and machines	A close partnership between humans and machines.
5	Establish digital manufactories	Develop intelligent manufactories looking ahead
6	Conduct all specialized duties in less time and for less cost.	Carry out an accurate and innovative duty in less time and with fewer resources.
7	Utilizing information technology creates digitalization and automation.	Utilizing innovative technology to globalize the manufacturing system

Table 3
Industry 5.0 advantages identified through literature.

Industry 5.0 advantage		Description	Reference
*IA*1	Building safer and more complicated hyper-connected networks	An intelligent information and communication system is created via coordination among supply chain components.	(Maddikunta et al., 2021)
*IA*2	Supply chain modularity	Modularization in the supply chain is an advantage of collaborating with suppliers to expedite the delivery of items. Modular supply chain management enables suppliers to build fundamental components rapidly.	(Ozkeser, 2018)
*IA*3	Use of lean innovation approach	The new technology expedites the process by allowing robots to do traditional repetitive tasks and human brains to be used for innovation.	(Østergaard, 2018)
*IA*4	Rewards and incentives for greener activities	Predefined incentives for greener operational implementation foster sustainability.	(Demir and Cicibas, 2017)
*IA*5	Audit	Industry 5.0 log management must match the scalability needs of massively connected future Industry 5.0 systems.	(Demir and Cicibas, 2017)
*IA*6	Sustainable thinking	An ability to successfully interact with challenges and social, environmental, and economic change in the modern world.	(Paschek et al., 2022)
*IA*7	Circular intelligent products	Lean/eco-design and industry 4.0 work together to improve product life cycle sustainability.	(Dwivedi et al., 2023)
*IA*8	Integrity	Control directives and monitoring information will be provided over third-party networks in Industry 5.0. The integrity validation, however, must not interfere with the system's performance capabilities.	(Serpa and Ferreira, 2018)
*IA*9	Employee technical assistance	Providing employees with opportunities to acquire necessary information and abilities and creating systems to facilitate continuous learning.	(Dautaj and Rossi, 2021)
*IA*10	Supplier commitment and involvement in sustainability adoption	Suppliers must be educated on the advantages of sustainability to reinforce their commitment.	(Nayeri et al., 2023)
*IA*11	Smart production processes	Industry 5.0 allows intelligent manufacturing via intelligent data and modern technologies to produce more customized goods. Utilizing smart industrial components will increase the likelihood of success for the renewable energy supply chain.	(Paschek et al., 2022)
*IA*12	Workers' appropriate skills to interact with technologies	Standards and regulatory guidelines must be implemented to solve technical, social, and managerial issues since skilled workers in Industry 5.0 are expected to undertake high-value activities.	(Demir et al., 2019)
*IA*13	Distributed and responsive supply chain	Organizations and facilities that are highly flexible and responsive to altering market/customer needs must deliver a cost-effective solution in a dynamic and competitive economy. Any environmental issues should be the responsibility of the supply chain.	(Fukuda, 2020)
*IA*14	Focus on customer and employee experience.	Experience management is gaining knowledge of customers and employees and applying strategic plans that allow cross-functional activities and a customer-centric culture to increase customer satisfaction, loyalty, and advocacy.	(Fraga-Lamas et al., 2021)
*IA*15	Sustainable resource management	Management of the sustainable source will aid in lowering energy use, leading to the realization of sustainability.	(Paschek et al., 2022)
*IA*16	Adoption of cloud technology among the RESC activity	Advanced cloud technology will increase the adaptability of the renewable energy supply chain.	(Serpa and Ferreira, 2018)
*IA*17	Green purchasing	Green purchasing programs can help identify and reduce hidden costs and develop cost-reduction strategies for the renewable energy supply chain.	(Demir and Cicibaş, 2019)
*IA*18	Supply chain adaptability	Capacity to adapt a supply chain's design to structural adjustments, disturbances, and changing consumer behavior and to alter every supply network to reflect these alterations.	(Atwell, 2017)
*IA*19	Research and innovation in social and human problems	To incorporate social and Human challenges into research and innovation more effectively. This method is required to solve challenges involving social and technical factors.	(Xu et al., 2021)

robot collaboration and intelligent automation, has the potential to enhance efficiency, productivity, and sustainability in renewable energy production and distribution. Exploring how Industry 5.0 can specifically address sustainable development challenges in this sector was an underexplored area.

❖ Lack of Comprehensive Frameworks: Another gap is the lack of comprehensive frameworks that effectively integrate sustainability principles and Industry 5.0. While both concepts are individually well-studied, there is a need to develop cohesive frameworks that explicitly address sustainability challenges, such as resource efficiency, circularity, and social and environmental impacts, within the context of Industry 5.0.
❖ Smart Grid and Energy Management Systems: Sustainable development challenges in the renewable energy sector often involve grid integration, demand-response management, and efficient utilization of resources. Exploring the role of Industry 5.0 in developing smart grid infrastructure, intelligent energy management systems and decentralized energy networks is a significant problem.
❖ Limited Implementation Studies: While there is theoretical research on the potential advantages of Industry 5.0 for sustainability, there is a shortage of empirical studies that examine its practical implementation in real-world settings.

Identifying and addressing these research gaps contribute to a better understanding of the potential of Industry 5.0 in overcoming sustainable development challenges in the renewable energy sector. Through our efforts, the following contributions have been made:

- ❖ The research indicates that in Industry 5.0, the renewable energy industry's focus on sustainability is centered. Industry 4.0 and 5.0 significantly focus on the growth of supply chain conceptual models.
- ❖ Recent multi-criteria decision-making (MCDM) techniques like the FBWM may be compatible with SDCs. FBWM utilizes subjective data throughout the selection process to describe the judgments of individuals. Unlike AHP, BWM permits consistent pairwise comparisons of evaluation criteria.
- ❖ FWASPAS may be used as linguistic variables. This advantage might be pretty practical if competing criteria are considered in the decision. Therefore, the suggested integrated technique may apply more to real-world decision-making issues. This integration with multifaceted decision analysis systems enables complicated decision-making processes to be handled more quickly and efficiently.
- ❖ The study's results will identify the most critical and appropriate advantage for achieving sustainability in the continuing industrial expansion–society participation and a larger sustainable RESC (Eid et al., 2016).

This study aims to contribute to the existing body of knowledge by offering a holistic understanding of the potential benefits of Industry 5.0 in the context of renewable energy supply chains and sustainable development. Our findings not only fill the current research gap but also provide actionable insights for policymakers and industry leaders striving to advance sustainable energy solutions in the era of Industry 5.0.

3. Methods

The general flow of the current study is depicted in Fig. 1. A considerable literature study is initially conducted to identify the significant SDCs in the RESC and the approaches required to solve them via Industry 5.0 advantages. Such criteria are then calculated and given to the case organization's decision panel for finalization (Goloviankoet al., 2023; Yadav et al., 2020). Depending on the views of the experts, a framework is created and assessed throughout the case organization

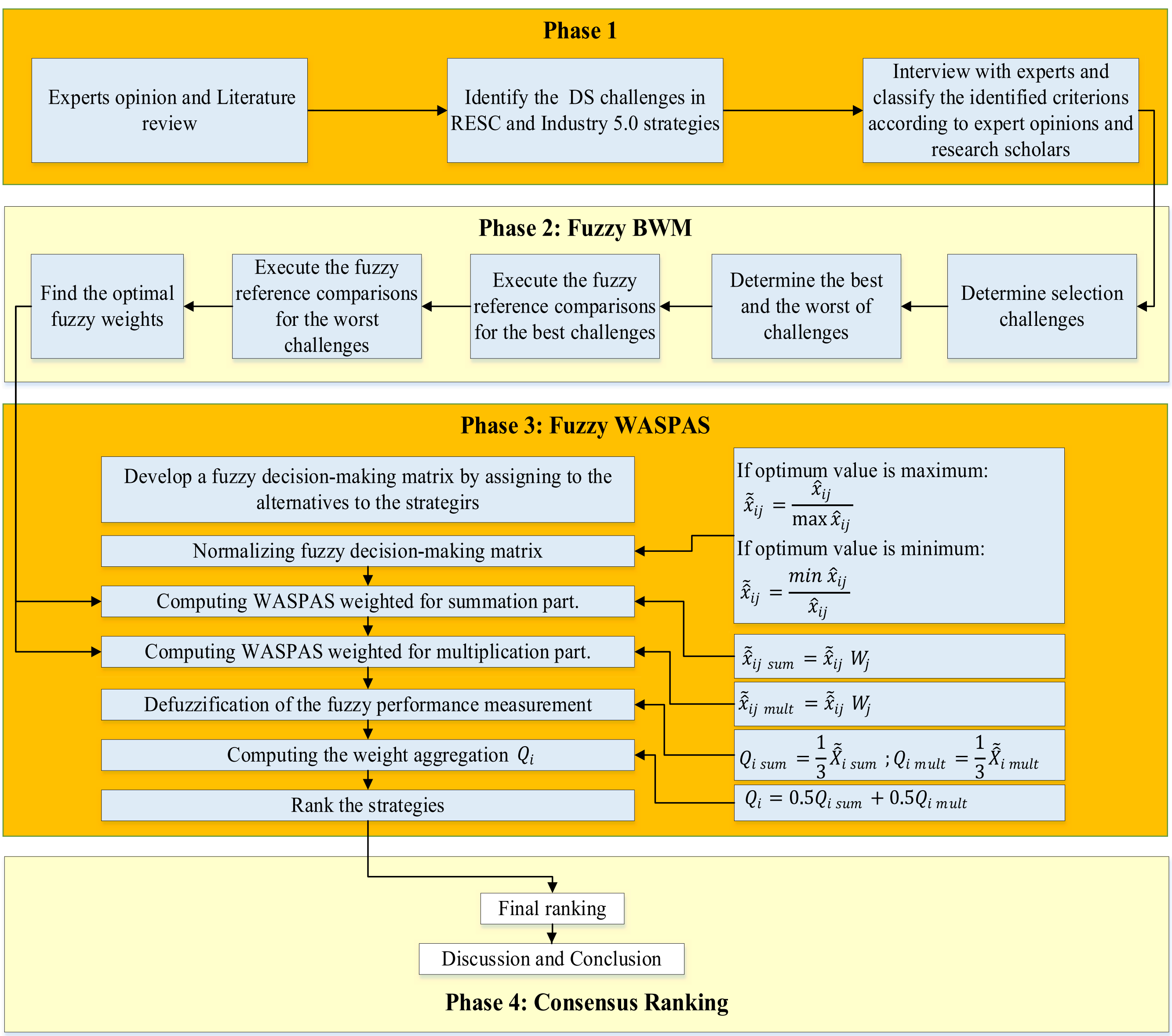

Fig. 1. Research framework.

Table 4
MCDM methods used in sustainability challenge evaluation in the context of the industrial revolution.

Reference	MCDM method	Method type	Context	Type of supply chain	Country
(Yadav et al., 2020)	BWM - ELECTRE	Crisp	I4.0	Automotive	India
(Ozkan-Ozen et al., 2020)	ANP	Fuzzy	I4.0	Food	Turkey
(Majumdar et al., 2021)	ISM	Crisp	I4.0	Textile	India
(Sharma et al., 2022)	AHP - ELECTRE	Crisp	I4.0	Pharmaceutical	Germany
(Mukherjee et al., 2023)	Dematel	Crisp	I4.0	SEM industry	India
(Karmaker et al., 2023)	BWM - ISM	Fuzzy	I4.0	Automotive	Bangladesh
(Gomathi et al., 2023)	AHP	Crisp	I4.0	Healthcare	India
This research	BWM - WASPAS	Fuzzy	I5.0	Renewable energy	Iran

Table 5
Linguistic variables used in the fuzzy best-worst method.

Significance level	The scale of five points	Triangular fuzzy numbers
Significance (A)	9	(3.5, 4, 4.5)
Very Significance (V)	7	(2.5, 3, 3.5)
Relatively Significance (F)	5	(1.5, 2, 2.5)
Weakly Significance (W)	3	(0.5, 1, 1.5)
Equally Significance (E)	1	(1,1,1)

using a hybrid Fuzzy BWM-WASPAS approach. The weight of SDCs is estimated utilizing the FBWM. Table 4 provides a complete review of the MCDM methods used in the SDCs evaluation in the context of the industrial revolution.

The WASPAS technique considers aggregation functions and normalization techniques, and multiple applications exist in the literature. However, WASPAS is the dominant technique within the compromise methods, depending on its simplicity in the formulation construction and having comparable ranking values. It is efficiently utilized within multi-stage advantage selection processes, as performed in this study. Fuzzy WASPAS is taken from (Turskis et al., 2019).

Hybrid fuzzy BWM and fuzzy WASPAS techniques are decision-making methods that combine the principles of fuzzy logic and multiple criteria evaluation. Here are some advantages of using these mixed techniques:

❖ Incorporation of fuzzy logic: By using fuzzy logic, these hybrid techniques can handle vague and uncertain information effectively. They allow decision-makers to express and manipulate linguistic variables and deal with subjective judgments more flexibly.
❖ Consideration of multiple criteria: Both hybrid fuzzy BWM and fuzzy WASPAS methods can accommodate multiple criteria in decision-making processes. This enables a more comprehensive evaluation of alternatives by considering various factors simultaneously.
❖ Decision transparency: Using fuzzy logic in these techniques clarifies decision-making processes. The linguistic terms and fuzzy sets allow decision-makers to interpret and explain the reasoning behind their evaluations, enhancing the openness and acceptance of the decision outcomes.

The methodology novelties of the paper are:

❖ This paper uses Fuzzy BWM for sustainable development challenges weight calculation. Popular MCDM techniques (WASPAS) integrated with fuzzy set theory are used to rank the set of Industry 5.0 advantages.
❖ Assessment of the set of Industry 5.0 advantages is primarily based on both conventional and environmental criteria.
❖ In addition, a consistency test was performed to test the expert's input's consistency, whereas the approach's' robustness' was checked by performing sensitivity analysis.
❖ In the normalization process, the obtained ranking results remain independent of the adopted normalization function.

3.1. Introducing the fuzzy best-worst method

Subsection 3.1 introduces the FBWM approach presented in (Arman and Kundakcı, 2023). Assume that there are n criteria and that their pairwise comparisons (Sahebi et al., 2021) may be accomplished using verbal terms including "equally important" to "absolutely important." Depending on Table 5, linguistic terms are transformed into fuzzy numbers.

A pairwise comparison $\widetilde{aij}$ is a fuzzy number if i or j are the best and worst elements, respectively. The following is a presentation.

$$\tilde{A} = \begin{matrix} c_1 \\ c_1 \\ c_2 \\ \vdots \\ c_n \end{matrix} \begin{matrix} c_1 & c_2 & \cdots & c_n \\ \left[\begin{matrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{21} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \end{matrix}\right] \\ \tilde{a}_{n1} & \tilde{a}_{n1} & \cdots & \tilde{a}_{nn} \end{matrix} \quad (1)$$

where $\widetilde{aij}$, a triangular fuzzy integer, denotes the fuzzy relevance of the ith criterion over the jth criterion. Assume there are n decision criteria for type $c1, c2, \ldots, cn$, and the best and worst criteria should be determined. The fuzzy comparison for the best to all other criteria (BO) is carried out. The vector BO represents as $A\widetilde{B} = (a\widetilde{B}1, a\widetilde{B}2\ldots, a\widetilde{B}n)$. The fuzzy reference comparison is then carried out for criteria over the worst criteria (OW). The OW vector expresses such fuzzy comparisons $A\widetilde{W} = (a\tilde{1}W, a\tilde{2}W\ldots, a\tilde{n}W)$. The best fuzzy weights must then be determined in the following stage. The best fuzzy criterion's weights must fulfill the equations. $\frac{\widetilde{W}_B}{W_j} = \tilde{a}_{Bj}$ and $\frac{\widetilde{W}_j}{W_w} = \tilde{a}_{jw}$ The maximum absolute gaps $\left|\frac{\widetilde{W}_B}{W_j} = \tilde{a}_{Bj}\right|$ and $\left|\frac{\widetilde{W}_j}{W_w} = \tilde{a}_{jw}\right|$ For all j should be reduced to satisfy these restrictions. Finally, the optimal fuzzy weights $(\widetilde{w}_1^*.\widetilde{w}_2^*.\ldots.\widetilde{w}_n^*)$ obtained as follows:

$$\underset{j}{\overset{vb}{min\,max}} \left\{ \left|\frac{\widetilde{w}_B}{\widetilde{w}_j} - \widetilde{a}_{Bj}\right|, \left|\frac{\widetilde{w}_j}{\widetilde{w}_w} - \widetilde{a}_{jw}\right| \right\} \quad (2)$$

$$s.t. \begin{cases} \sum_{j=1}^{n} R(\widetilde{w}_j) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j = 1, 2, \ldots, n \end{cases}$$

where $\widetilde{w_B} = (l_B^w.m_B^w.u_B^w)$. $\widetilde{w_B} = (l_j^w.m_j^w.u_j^w)$. $\widetilde{w_B} = (l_w^w.m_w^w.u_w^w)$. $\tilde{a}_{Bj} = (l_{Bj}.m_{Bj}.u_{Bj})$. $\tilde{a}_{jw} = (l_{jw}.m_{jw}.u_{jw})$. Eq. (2) could be transformed into the following nonlinearly constrained problem (Eq. (3)):

$$min\tilde{\xi} \quad (3)$$

Table 6
Consistency index for fuzzy best worst method.

Linguistic terms	Equally significance (E)	Weakly significance (W)	Fairly significance (F)	Very significance (V)	AI significance (A)
$\widetilde{a}_{BW}$	(1, 1, 1)	(0.5, 1,1.5)	(1.5, 2, 2.5)	(2.5, 3, 3.5)	(3.5, 4, 4.5)
CI	3.00	3.80	5.29	6.69	

$$s.t.\begin{cases} \left|\dfrac{\widetilde{w}_B}{\widetilde{w}_j}-\widetilde{a}_{Bj}\right| \le \widetilde{\xi} \\ \left|\dfrac{\widetilde{w}_j}{\widetilde{w}_w}-\widetilde{a}_{jw}\right| \le \widetilde{\xi} \\ \sum_{j=1}^{n} R(\widetilde{w}_j)=1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j=1,2,\dots,n \end{cases}$$

where ξ= (l^ξ, m^ξ, u^ξ). Considering $l^\xi \le m^\xi \le u$ we presume $\widetilde{\xi}^* = (k^*, k^*, k^*)$, $k^* \le l^\xi$, then Eq. (3) can be transformed into Eq. (4).

$$\min \widetilde{\xi}^*$$

$$s.t.\begin{cases} \left|\dfrac{(l_B^w.m_B^w.u_B^w)}{l_j^w.m_j^w.u_j^w}-(l_{Bj}.m_{Bj}.u_{Bj})\right| \le (k^*.k^*.k^*) \\ \left|\dfrac{(l_j^w.m_j^w.u_j^w)}{l_w^w.m_w^w.u_w^w}-(l_{jw}.m_{jw}.u_{jw})\right| \le (k^*.k^*.k^*) \\ \sum_{j=1}^{n} R(\widetilde{w}_j)=1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ j=1.2.....n \end{cases} \tag{4}$$

In addition, the consistency ratio of FBWM shall be computed as *K*CI* where the consistency index concerning various linguistic variables is presented in Table 6 for more comments concerning FBWM mentioned (Arman and Kundakcı, 2023).

3.2. Introducing fuzzy weighted aggregated sum product assessment

(Zavadskas et al., 2014) Introduced a modified version of WASPAS and designated it WASPAS-IFIV. To address the issue of choosing the building location, (Masoomi et al., 2022) provided the combined FST-WASPAS representation. Notably, the two combined representations given below make up WASPAS's foundations (Turskis et al., 2019):

1. WSM (Weighted-Sum Model): This technique incorporates a significant concept based on displaying the total substitute scores (*Ai*) as a weighted sum of quality criteria.
2. WPM (Weighted-Product Model): This concept arose to outperform the substitute (*Ai*) solutions, which had inferior attributes. Each substitute (*Ai*) score is presented as a scale grade result of each quality to equal power to the weight ((wi)̃) of the relevance of the quality.

The fuzzy WASPAS stages are as follows in this regard:

Stage one: Create the fuzzy decision matrix ($\widetilde{y}$);

Stage two: Conduct a formulation of the "Normalized Fuzzy Decision Matrix" (R̃normalized),

This is defined as follows:

$$\widetilde{RNormalized} = [rij]mn$$

Cα and Bα represent price and gain measurement sets, correspondingly.

Eqs. (2) and (3) are used to accomplish the necessary normalizing for the fuzzy decision matrix (y) to construct the ($\widetilde{R}_{Normalized}$) matrix (3).

Stage three: (*i*) For WSM, determine the Weighted Decision Matrix $\widetilde{x}_q$

$$\widetilde{x}_q = \begin{bmatrix} \widehat{x}_{11} & \cdots & \widehat{x}_{1n} \\ \vdots & \ddots & \vdots \\ \widehat{x}_{1m} & \cdots & \widehat{x}_{mn} \end{bmatrix}; \widehat{x}_{ij} = (\widetilde{r}_{ij}) \times (\widetilde{\widetilde{w}}_i); j = (1.2.....n); \text{and } i = (1.2.....m) \tag{5}$$

(ii) For WPM, determine the "Weighted normalized fuzzy decision matrix $\widehat{x}_p$

$$\widehat{x}_p = \begin{bmatrix} \widehat{\widetilde{x}}_{11} & \cdots & \widehat{\widetilde{x}}_{1n} \\ \vdots & \ddots & \vdots \\ \widehat{\widetilde{x}}_{1m} & \cdots & \widehat{\widetilde{x}}_{mn} \end{bmatrix}; \widetilde{\widetilde{x}}_{ij} = \widetilde{r}_{ij}^{\widetilde{w}_i} \tag{6}$$

Step four: Determine the optimality function's values:

(i) Based on the WSM, for every advantage;

$$\widetilde{\widetilde{q}}_i = \sum_{j=1}^{n} \widehat{x}\ ij; i = 1.2.....m; \tag{7}$$

(ii) For every alternative, based on the WPM;

$$\widetilde{\widetilde{p}}_i = \prod_{j=1}^{n} \widehat{\widetilde{x}}\ ij; i = 1.2.....m; \tag{8}$$

Every advantage's FPM yields fuzzy integers. $\widetilde{\widetilde{q}}$ and $\widetilde{\widetilde{p}}_i$. The "center of gravity" advantage is the most basic and valuable for defuzzification.

$$q_i = \frac{1}{3}(q_{ia} + q_{ib} + q_{ic}) \tag{9}$$

$$p_i = \frac{1}{3}(p_{ia} + p_{ib} + p_{ic}) \tag{10}$$

Step five: The following formula may be used to determine the value of an integrated utility function (IUF) for an alternative (Ai):

$$k_1 = \beth \sum_{j=1}^{n} q_1 + (1 - \beth) \sum_{j=1}^{n} p_1; \beth = 0.....1; 0 \le k_1 \le 1 \tag{11}$$

Considering that "the total of the WSM scores must match the total of the WPM scores, "the ℶ value in Eq. (19) is calculated as follows:

Table 7
Expert's introduction.

EXs	Features of Experts	Work Experience (year)
Ex. 1	Professor in the field of sustainability	18
Ex. 2	RE Funding	17
Ex. 3	RE logistic management	22
Ex. 4	Professor of RE	17
Ex. 5	Professor of digital SC	18
Ex. 6	Professor of technology management	19
Ex. 7	Digital SC manager	20

Table 8
Identification of 'Best' and 'Worst' SDC and sub-SDC by experts.

List of challenges	Identified as'Best' by experts	Identified as'Worst' by experts
Economic- SDC1	2	
SDC11	5	1,5
SDC12		2,4,6,7
SDC13	6	3
SDC14	1,2,3,4,7	
Environmental-SDC2		1
SDC21	1,3,4,5,6,7	
SDC22	2	4
SDC23		1,2,3,5,6,7
Organizational-SDC3	3	6
SDC31		5
SDC32	1	7
SDC33		1,2,3,4,6
SDC34	2,3,5,6,7	
SDC35	4	
Process- SC4		2,3,4,5,7
SDC41		2,3,4,5,7
SDC42		6
SDC43	1,3	
SDC44		
SDC45	2,4,5,6,7	
SDC46		1
Social- SC5	1,4,5,6,7	
SDC51		3
SDC52	1	1,2,4,5,6,7
SDC53		
SDC54	2	
SDC55	3,4,5,6,7	

$$\beth = \frac{\sum_{i=1}^{n} p_i}{\sum_{i=1}^{m} q_i + \sum_{i=1}^{m} p_i}; \tag{12}$$

Step six: Rank the preference order and choose an alternative (*Ai*) with the highest obtained $KI^{"}$ *value*.

3.3. Case study and data collection

Implementing SDCs in RESC is more challenging than in other industries (Jelti et al., 2021). More sustainability is required for RE because of the rising significance of increasing RE usage and reducing land degradation and heating. Due to the high sensitivity of green energy and the expansion of RE, it isn't elementary for practitioners to embrace sustainability properly in the RESC structure (Mastrocinque et al., 2020). As a result, a RE firm in Iran has been selected for the current research. This company places a high value on its workforce. The organization intends to develop its business worldwide, and as a result, it aims to include sustainability and technology into its current supply chain. The case organization's management desires to ensure the effective deployment of a sustainable supply chain. Two project managers in energy technologies, two university professors from industry 4.0, 5.0, and RE, one top manager from the digital supply chain, and two representatives from the renewable energy funding department make up the decision-making panel of seven experts for this goal. The specialists have had >17 years of exposure to supply chain activity. Table 7 contains the information provided by the specialists. In this research, the snowball method was used to select the experts. This number of samples is quite suitable for achieving the research goal and is even more than some similar studies using the FBWM (Kalpoe, 2020; Li et al., 2020).

The case organization specialists are employed at three distinct stages by conducting brainstorming sessions to obtain a strong knowledge of the SDCs and Industry 5.0 advantages. The first phase entails finalizing the SDCs. After that, the impediments discovered via the literature review are divided into five main categories of challenges: (economic, managerial, organizational, environmental, social, and process). There have been identified 23 challenges in all. In the following step, the finalization of the advantages of Industry 5.0 is recognized. In this stage, 19 advantages were found.

Consequently, a structure is created by connecting the central and subgroup challenges to Industry 5.0 advantages. Furthermore, a survey is designed to gather data. The input judgments from the questionnaire were used to estimate the weights of the challenges using the FBWM throughout the second phase. Ultimately, in the third step, the expert panel compares the SDCs with Industry 5.0 advantages to determine the final rankings of advantages. This comparison provides the inputs for the FWASPAS.

4. Results

4.1. Fuzzy best-worst method

According to FBWM, the "worst" criteria, as determined by the expert, are the least essential SDC and sub-SDC. In contrast, the "best" criterion is the most significant SDC and sub-SDC. As indicated in Table 8, each of the seven experts evaluates the list of SDC and sub-SDC (Ref: Table 2) for "best" and "worst" options. As stated in Table 8, the main SDC and sub-SDC were classified as "best" and "worst," respectively.

The BO and OW matrix for SDC (SDC1 to SDC5) are shown in Table 7 based on the comparison of expert ratings. Each expert did pairwise comparisons of each subcategory SDC1 to SDC4 (Table A1), SDC21 to SDC23 (Table A2), SDC31 to SDC35 (Table A3), SDC41 to SDC46 (Table A4), and SDC51 to SDC55 (Table A5). Tables A2 to A5 in the appendix provide the pairwise comparison matrix for the sub-SDC BO and OW scores.

According to Table 9, the fuzzy comparison by BO and OW can be

Table 9
Pairwise comparison matrix.

Best to Others	Economic SDC1	Environmental SDC2	Organizational SDC3	Process SDC4	Social SDC5
Best SDC: Social SDC5	5	3	3	9	1
Other-to-worst				*Worst SDC:*	*Process* SDC4
Economic SDC1				3	
Environmental SDC2				5	
Organizational SDC3				3	
Process SDC4				1	
Social SDC5				9	

obtained as follows:

$$\widetilde{A}_B = \left[\left(\frac{3}{2}, 2, \frac{5}{2}\right), \left(\frac{2}{3}, 1, \frac{3}{2}\right), \left(\frac{2}{3}, 1, \frac{3}{2}\right), \left(\frac{7}{2}, 4, \frac{9}{2}\right), (1, 1.1)\right] \tag{13}$$

$$\widetilde{A}_w = \left[\left(\frac{2}{3}, 1, \frac{3}{2}\right), \left(\frac{3}{2}, 2, \frac{5}{2}\right), \left(\frac{2}{3}, 1, \frac{3}{2}\right), (1, 1.1), \left(\frac{7}{2}, 4, \frac{9}{2}\right)\right] \tag{14}$$

Now, according to Eq. (4), the optimal criteria weights can be derived from solving the following nonlinear optimization problem:

$$\begin{aligned}
&\left|\frac{(l_{SDC5}, m_{SDC54}, u_{SDC5})}{(l_{SDC1}, m_{SDC1}, u_{SDC1})} - \left(\frac{3}{2}, 2, \frac{5}{2}\right)\right| \le (k^*, k^*, k^*)\\
&\left|\frac{(l_{SDC5}, m_{SDC54}, u_{SDC5})}{(l_{SDC2}, m_{SDC2}, u_{SDC2})} - \left(\frac{2}{3}, 1, \frac{3}{2}\right)\right| \le (k^*, k^*, k^*)\\
&\left|\frac{(l_{SDC5}, m_{SDC54}, u_{SDC5})}{(l_{SDC3}, m_{SDC3}, u_{SDC3})} - \left(\frac{2}{3}, 1, \frac{3}{2}\right)\right| \le (k^*, k^*, k^*)\\
&\left|\frac{(l_{SDC5}, m_{SDC54}, u_{SDC5})}{(l_{SDC4}, m_{SDC4}, u_{SDC4})} - \left(\frac{7}{2}, 4, \frac{9}{2}\right)\right| \le (k^*, k^*, k^*)\\
&\left|\frac{(l_{SDC4}, m_{SDC4}, u_{SDC4})}{(l_{SDC1}, m_{SDC1}, u_{SDC1})} - \left(\frac{2}{3}, 1, \frac{3}{2}\right)\right| \le (k^*, k^*, k^*)\\
&\left|\frac{(l_{SDC4}, m_{SDC4}, u_{SDC4})}{(l_{SDC3}, m_{SDC3}, u_{SDC3})} - \left(\frac{3}{2}, 2, \frac{5}{2}\right)\right| \le (k^*, k^*, k^*)\\
&\left|\frac{(l_{SDC4}, m_{SDC4}, u_{SDC4})}{(l_{SDC3}, m_{SDC3}, u_{SDC3})} - \left(\frac{2}{3}, 1, \frac{3}{2}\right)\right| \le (k^*, k^*, k^*)
\end{aligned} \tag{15}$$

$$\begin{aligned}
&\frac{1}{6}(l_i + 4m_i + u_i) = 1 \forall i = 1, .., 5\\
&l_i \le m_i \le u_i \qquad \forall i = 1, .., 5\\
&l_i > 0 \ \forall \qquad i = 1, .., 5\\
&k \ge 0
\end{aligned}$$

Applying FBWM Eq. (4), the ideal fuzzy weights ($l^w_w . m^w_w . u^w_w$) were obtained by solving Eq. (15). Consequently, depending on Table 8's depiction of the consistency values of SDCs in RESC, since these values appear to be significantly near zero, the input data could be said to demonstrate a high degree of consistency.

As demonstrated in Table 10, this leads to calculating the major SDC's average weight and the sub-SDC's local weight.

Sub-SDCs with global weight (GW) and cumulative global weight propose that global weights contribute to the top 9 sub-SDCs 76 % of the total weightage. The first nine identified based on their corresponding global weight GW sub-SDCs are non-consideration of human factors (SDC55), Inadequate regulation and implementation of environmental standards (SDC21), Commitment of inadequate management for adopting sustainability (SDC34), Non-uniform alignment of sustainability, organization, and goal and customer expectation (SDC54), lack of availability of resources (financial, technical, human, etc.) (SDC14), Ineffective employee training and culture (SDC52), Adaption with the new industrial revolution (SDC51), Insufficient attention to research and development sustainability (SDC22) and Work polarization (SDC53) (Figs. 2-4) (Table 15).

4.2. Fuzzy weighted aggregated sum product assessment

Table 11 demonstrates the linked matrix. The final normalized decision matrix is shown in Table 12. The weighted standardized decision matrices (WSM and WPM) are then presented. The obtained weighted standardized decision matrix for FWASPAS from Eq. (5) is similar to that of WSM. ($\widehat{X}q$), as demonstrated in Table 13. Every element value of a "weighted normalized fuzzy decision matrix" (X p) is produced for WPM determination. It is as follows:

$$(\widehat{X}p_{11}) = \left[(1.00)^{0.0152}; (1.00)^{0.0152}; (1.00)^{0.0152}\right)\right];$$

The calculating processes for the remaining items will be similar. The weighted normalized matrix for WPM (X ̂p) is depicted in Table 14.

The rate of optimality function is assessed utilizing Eqs. (7) and (8) in both WPM and WSM. For WSM, each function's optimality value may be computed as follows:

$$\widetilde{\widetilde{Q}}_1 = (0.3411, 0.3695, 0.3938);$$

Similar to this, other WSM optimality function values are computed; the optimality function value for WPM is determined as follows:

$$\widetilde{\widetilde{p}}_1 \ (0.9068; 0.9417; 0.9702)$$

Then, defuzing the obtained result by using Eqs. (9) and (10):

$$Q_{1[defuzzification]} = \frac{1}{3}(0.3411 + 0.3695 + 0.3938) = (1.1044);$$

$$P_{1[defuzzification]} = \frac{1}{3}(0.9068 + 0.9417 + 0.9702) = (2.8188);$$

By using Eq. (12), the value of the integrated utility function (IUF) in FWASPAS for an advantage (A_i) Is calculated as:

$$\lambda = 0.4912; K_1 = (0.4912^* 1.1044) + (1–0.4912)^* (2.8188) = 1.9767$$

K_i also be valued for other options similarly. Table 13 provides determined ki values. The maximum K_i Value determines the highest advantage rank. The highest score belongs to IA2, followed by IA19. Consequently, the FWASPAS and FBWM hybrid technique results of the first to tenth rank are ordered IA2 > IA19 > IA3 > IA6 > IA4 > IA12 > IA14 > IA16 > IA18 > IA17.

5. Discussion

It is difficult to determine which advantage of defeating SDCs is essential for the effective and remarkable execution of RESC's sustainability. According to the findings of the FBWM analysis, "non-consideration of human factors (SDC55)", which has the most significant weight (0.238), is the SDCs to the successful application in RESC. According to the analysis's findings, Social SDCs (0.483) holds the most weight among the main groups, followed by Organizational SDCs (0.180), Economic SDCs (0.108), Environmental SDCs (0.180), and Process SDCs (0.047). In addition, (Yadav et al., 2020) study demonstrates that inappropriate execution of social activities significantly hinders the adoption of sustainability in SC. To a similar extent, (Belhadi et al., 2022; Friedman and Ormiston, 2022) argued that the failures of sustainable development might be attributed to organizationally and economically driven actions.

Industry 5.0's advantages, such as human-machine collaboration, set it apart from traditional manufacturing, Industry 4.0, and other potential approaches. It offers a more holistic and flexible framework for addressing complex sustainability challenges by prioritizing human values and adaptability, ultimately making it a more effective and relevant solution in pursuing sustainable development. Industry 5.0 leverages automation but emphasizes collaboration between humans and machines.

5.1. Economic challenges

Among the overall sub-SDCs, non-consideration of human factors (SDC55) (0.259), Inadequate regulation and implementation of environmental standards (SDC21) (0.136), the commitment of inadequate management for adopting sustainability (SDC34) (0.103), non-uniform

Table 10
Local weight, global weight, and global ranking of challenges.

SDCs	Weight of SDC	Sub-SDC	Sub-SDC Abbreviation	Local weight of sub-SDC	Aggregated consistency values of sub-SDC	Global weight of sub-SDC	Global ranking of sub-SDC
Economic- SDC1	0.109	Strong sense of poor economic returns	SDC11	0.141	0.0566	0.0152	15
		High disposal costs	SDC12	0.066		0.0071	19
		The high amount of infrastructure	SDC13	0.141		0.0152	14
		Lack of availability of resources (financial, technical, human, etc.)	SDC14	0.650		0.0703	5
Environmental- SDC2	0.180	Inadequate regulation and implementation of environmental standards	SDC21	0.758	0.0650	0.1366	2
		Insufficient attention to research and development sustainability	SDC22	0.164		0.0295	8
		Inappropriate system of reverse logistics	SDC23	0.076		0.0137	16
Organizational- SDC3	0.180	Collaborative robotics with human co-workers	SDC31	0.099	0.0579	0.0178	13
		The threat posed by cyber security	SDC32	0.138		0.0248	10
		Ineffective integration of sustainability with available processes	SDC33	0.050		0.0090	17
		The commitment of inadequate management to adopting sustainability	SDC34	0.574		0.1034	3
		Unavailability of sustainability standards and regulations	SDC35	0.138		0.0248	11
Process- SDC4	0.048	Overproduction phenomenon	SDC41	0.039	0.0517	0.0018	23
		Absence of autonomy in the current systems	SDC42	0.114		0.0054	21
		Challenge of acquiring high-quality and integration	SDC43	0.190		0.0090	18
		Challenging drawing regulatory mechanisms	SDC44	0.081		0.0038	22
		Design complexity for RE consumption reduction	SDC45	0.460		0.0218	12
		Complexity within supply chain configuration	SDC46	0.114		0.0054	20
Social- SDC5	0.484	Adaption with the new industrial revolution	SDC51	0.104	0.0489	0.0503	7
		Ineffective employee training and culture	SDC52	0.121		0.0585	6
		Work polarization	SDC53	0.052		0.0251	9
		Non-uniform alignment of sustainability	SDC54	0.202		0.0977	4
		Non-consideration of human factors	SDC55	0.537		0.2598	1

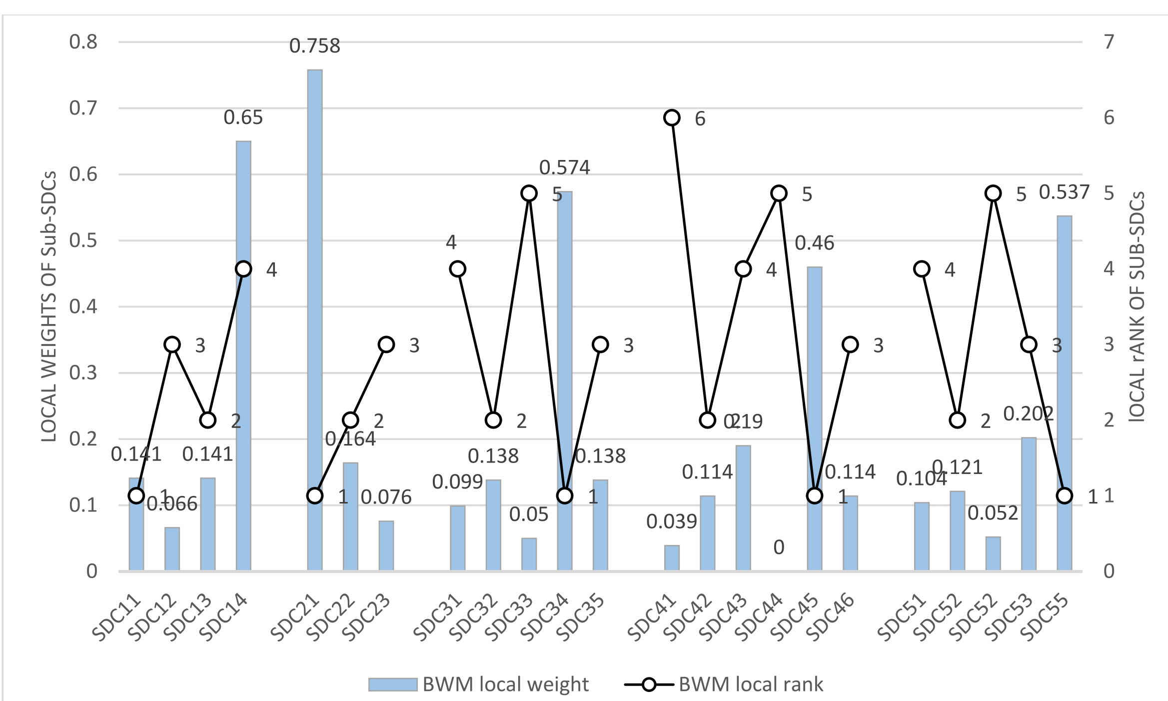

Fig. 2. Local weight and local ranking of challenges.

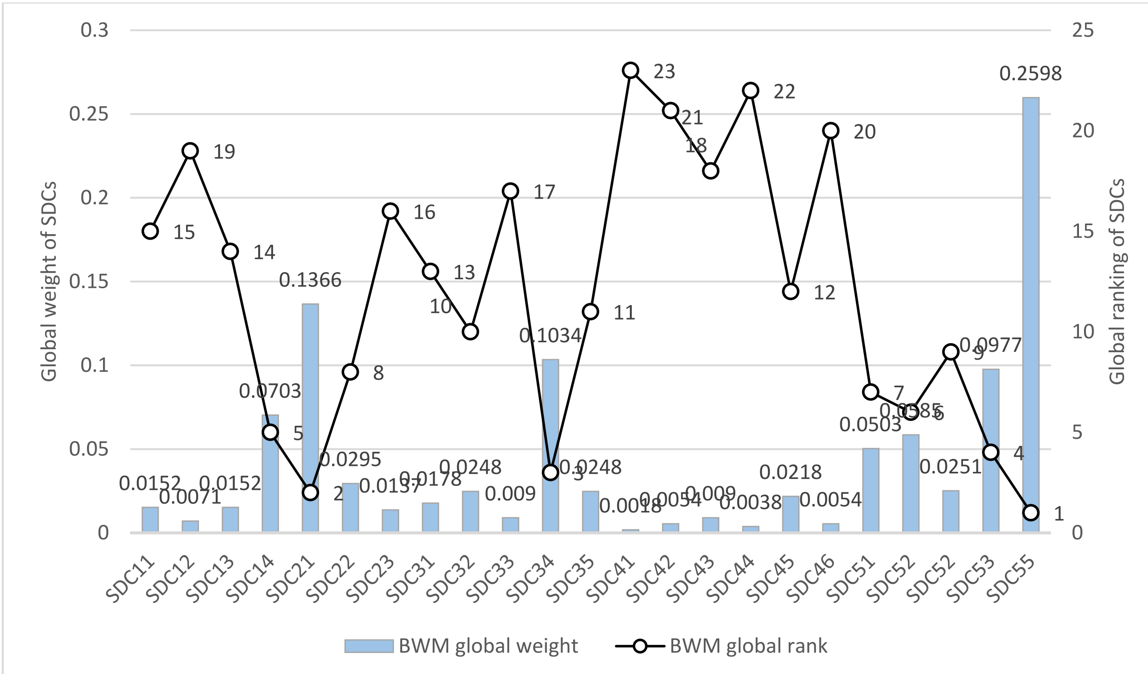

Fig. 3. Global weight and global ranking of challenges.

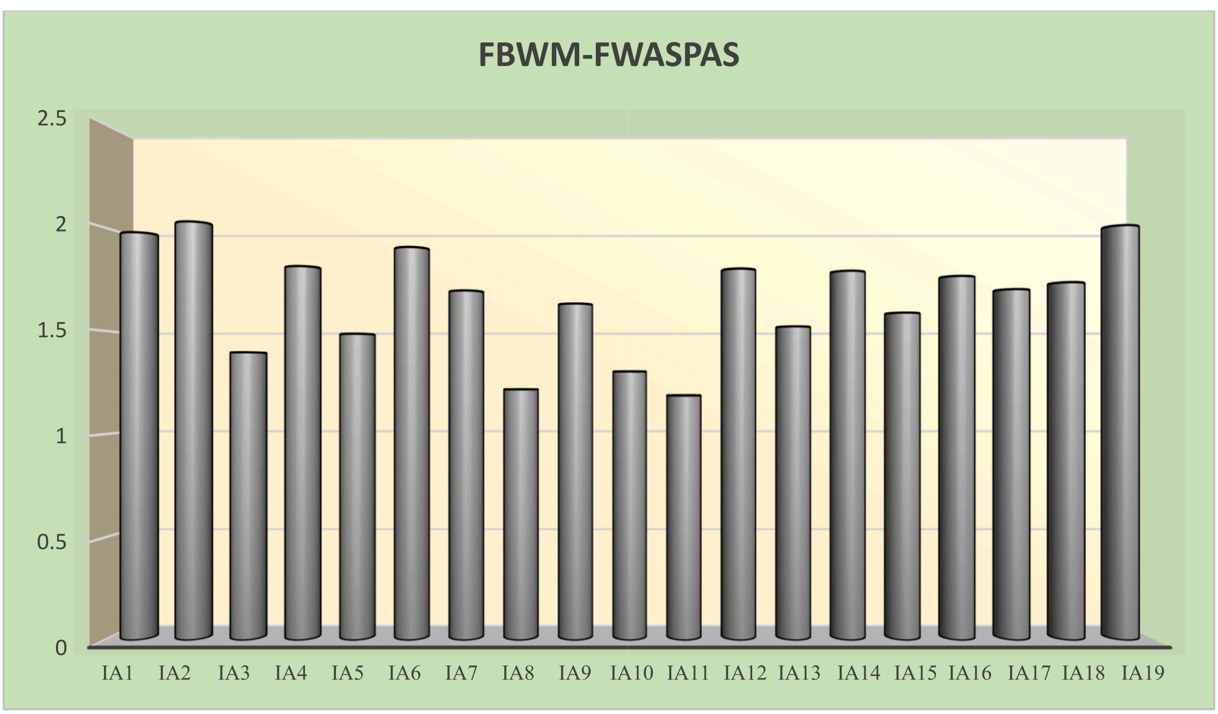

Fig. 4. Final ranking obtained by hybrid fuzzy BWM - WASPAS.

alignment of sustainability, organization, and goal and customer expectation (SDC54) (0.097) and lack of availability of resources (financial, technical, human, etc.) (SDC14) (0.070), are identified as the most significant SDCs preventing SD adoption in the supply chain. Numerous research (Song et al., 2022; Yadav et al., 2020) have revealed that one of the main reasons SD failures occur is a lack of staff training in sustainability. (Ghasemian Sahebi et al., 2023) also observed in most organizations, employees resist change, limiting the penetration of sustainable development in existing SC.

In terms of organizational SDCs, the commitment of inadequate management for adopting sustainability (SDC34) (0.103), the unavailability of sustainability standards and regulations (SDC35) (0.0248), and the threat posed by cyber security (SDC32) (0.0248) are issues of high intensity. Lack of resources (financial, technological, human, etc.) (SDC14) (0.0703), High amount of infrastructure (SDC13) (0.0152), and a strong sense of poor economic returns (SDC11) (0.0152) seem to be the most critical SDCs in the energy sector. According to (Delabre et al., 2020), many organizations strongly believe that adopting sustainability would be expensive and ultimately worsen organizational performance.

According to the results, the advantages of Industry 5.0 directly

Table 11
Weighted normalized decision-making matrix.

SDCs	*Advantages*													
	IA_1			IA_2			….	….	IA_{18}			IA_{19}		
*SDC*11	6.333	8.333	9.666	4.333	6.333	8	….	….	5	7	8.666	5.6667	7.666	9
*SDC*12	6.333	8	9.333	5.666	7.666	9.333	….	….	3.666	5.666	7.666	5	7	8.666
*SDC*13	3	5	7	5	6.666	8	….	….	4.333	6.333	8	5.666	7.666	9
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
*SDC*53	5	7	8.666	3	5	6.666	….	….	4.333	6.333	8.333	6.333	8	9.333
*SDC*54	3.666	5.666	7.666	6.333	8.333	9.666	….	….	5.666	7.666	9.333	3	5	7
*SDC*55	6.333	8.333	9.666	6.333	8	9.333	….	….	8.333	9.666	10	7	8.666	9.666

Table 12
Normalized decision-making matrix.

SDCs	*Advantages*													
	IA_1			IA_2			….	….	IA_{18}			IA_{19}		
*SDC*11	1	1	1	0.684	0.759	0.827	….	….	0.789	0.840	0.896	0.894	0.919	0.931
*SDC*12	1	1	1	0.894	0.958	1	….	….	0.578	0.708	0.821	0.789	0.875	0.928
*SDC*13	0.529	0.652	0.777	0.882	0.869	0.888	….	….	0.764	0.826	0.888	1	1	1
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
*SDC*53	0.789	0.875	0.928	0.473	0.625	0.714	….	….	0.684	0.791	0.892	1	1	1
*SDC*54	0.578	0.679	0.793	1	1	1	….	….	0.894	0.919	0.965	0.473	0.600	0.724
*SDC*55	0.904	0.961	1	0.904	0.923	0.965	….	….	0.428	0.576	0.724	1	1	1

Table 13
Weighted- sum normalized decision-making matrix.

SDCs	*Advantage*													
	IA_1			IA_2			….	….	IA_{18}			IA_{19}		
*SDC*11	0.028	0.028	0.028	0.019	0.021	0.023	….	….	0.022	0.023	0.025	0.025	0.026	0.026
*SDC*12	0.009	0.009	0.009	0.008	0.009	0.009	….	….	0.005	0.006	0.007	0.007	0.008	0.008
*SDC*13	0.015	0.018	0.022	0.025	0.024	0.025	….	….	0.021	0.023	0.025	0.028	0.028	0.028
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
*SDC*53	0.019	0.022	0.023	0.011	0.015	0.018	….	….	0.017	0.020	0.022	0.025	0.025	0.025
*SDC*54	0.052	0.062	0.072	0.091	0.091	0.091	….	….	0.081	0.0839	0.088	0.043	0.054	0.066
*SDC*55	0.215	0.228	0.238	0.215	0.219	0.229	….	….	0.102	0.137	0.172	0.238	0.238	0.238

address the non-consideration of human factors (SDC55), which have been a significant challenge in pursuing sustainable development. Industry 5.0 promotes seamless collaboration between humans and machines. In sustainable development, this is crucial because it ensures that the decision-making process incorporates human values, ethical considerations, and social responsibility. While Industry 4.0 mainly focuses on automation, Industry 5.0 places humans back at the center of production and sustainability decisions, addressing the concern that purely automated systems might not adequately consider ethical and social implications. Industry 5.0 integrates sustainability as a core principle. It emphasizes the responsible use of resources, reduction of waste, and environmental stewardship. This addresses the challenge of unsustainable resource consumption and pollution often associated with industrialization.

(Ghobakhloo et al., 2022) Highlighted the importance of supply chain modularity, research, and innovation in resolving social and human challenges and adopting social and environmental innovation to improve sustainability features. In contrast, (Sharma et al., 2021) examined the situation of developing countries. Creating safer and more complex hyperconnected networks is one of the most critical factors in accelerating SD adoption in RESC. This rating seems more significant since, from practitioners' viewpoint, it will be easy for them to concentrate on highly rated techniques and monitor the number of eliminated challenges.

Table 14
Weighted- product normalized decision-making matrix.

SDCs	*Advantage*													
	IA_1			IA_2			….	….	IA_{18}			IA_{19}		
*SDC*11	1	1	1	0.989	0.992	0.994	….	….	0.993	0.995	0.996	0.996	0.997	0.997
*SDC*12	1	1	1	0.998	0.999	1	….	….	0.994	0.996	0.998	0.997	0.998	0.999
*SDC*13	0.982	0.987	0.992	0.996	0.996	0.996	….	….	0.992	0.994	0.996	1	1	1
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….	….	….	….	….	….	….
*SDC*53	0.994	0.996	0.998	0.981	0.988	0.991	….	….	0.990	0.994	0.997	1	1	1
*SDC*54	0.951	0.965	0.979	1	1	1	….	….	0.989	0.992	0.996	0.934	0.954	0.970
*SDC*55	0.976	0.990	1	0.976	0.981	0.991	….	….	0.817	0.877	0.926	1	1	1

5.2. Environmental challenges

Among the environmental SDCs, Inadequate regulation and implementation of environmental standards (SDC21) (0.1366), Insufficient attention to research and development sustainability (SDC22) (0.0295), and Inappropriate system of reverse logistics (SDC23) (0.0137) have emerged as the most significant obstacles. According to (Masoomi et al., 2022), environmental issues are crucial in attaining supply chain sustainability. (Silvestre and Ţîrcă, 2019) Underlined how understanding sustainable raw material standards might contribute to the successful adoption of sustainable development in SC.

According to the results, Industry 5.0 can automate the generation of regulatory reports. Environmental data required for compliance can be collected and processed automatically, reducing the administrative burden on companies. This ensures accurate reporting and minimizes the risk of errors and omissions that could lead to non-compliance. Industry 5.0 automates the generation of regulatory reports. Environmental data required for compliance can be collected and processed automatically, reducing the administrative burden on companies. Industry 5.0 facilitates end-to-end traceability and transparency in the supply chain. Every step, from raw material sourcing to final product delivery, can be monitored and recorded. This transparency ensures that companies can track the environmental impact of their entire value chain and verify compliance with regulations.

Design complexity for RE consumption reduction (SDC45) (0.0218), the challenge of acquiring high quality and integration (SDC43) (0.0090), and the absence of autonomy in the current systems (SDC42) (0.0054) are the process SDCs that have the most impact on the effectiveness of supply chain SD. In terms of social SDCs, non-consideration of human factors (SDC55) (0.2598), non-uniform alignment of sustainability, organization, and goal and customer expectation (SDC54) (0.0977), and Ineffective employee training and culture (SDC52) (0.0585) are issues of high intensity.

The WASPAS is regarded as the rating of Industry 5.0 advantages for overcoming supply chain SDCs. The FWASPAS findings indicate that "Supply chain modularity (IA2)" is ranked first for overcoming SDCs. The Supply chain modularity assists in overcoming numerous obstacles, including lack of availability of resources (financial, technical, human, etc.) (SDC14), Inadequate regulation and implementation of environmental standards (SDC21), lack of sustainability standards and laws (SDC35), overproduction phenomenon (SDC41), Design complexity for RE consumption reduction (SDC45), the challenge of acquiring high quality and integration (SDC43), and inadequate employee training and culture (SDC52).

Supply chain modularity is crucial in addressing sustainable development challenges in the renewable energy supply chain by offering several key benefits. Modularity enables the RESC to adapt and respond to sustainability challenges more effectively. With modular subunits, the supply chain can quickly incorporate new technologies, processes, or materials that improve environmental performance. By establishing modular production units closer to the end markets or renewable energy sources, transportation-related sustainability challenges, such as energy consumption and emissions, can be minimized (Davies and Joglekar, 2013). Also, supply chain modularity enhances resource allocation efficiency by optimizing renewable energy components and materials. It enables the monitoring and controlling of resource flows at each module, ensuring optimal utilization, waste reduction, and recycling. By leveraging supply chain modularity, the renewable energy industry can enhance its sustainability performance, including reducing carbon emissions, promoting resource efficiency, minimizing waste generation, and supporting circular economy principles. It provides a framework for addressing sustainability challenges at different stages of the supply chain, ultimately contributing to the overall sustainable development of the renewable energy sector.

5.3. Social challenges

Research and innovation in social and human problems (IA19) seems to be the second-highest advantage to surpassing supply chain SDCs. Research and innovation in social and human issues are impressive in overcoming various challenges, including Insufficient attention to research and development sustainability (SDC22), Inappropriate system of reverse logistics (SDC23), Collaborative robotics with human coworkers (SDC31), unavailability of sustainability standards and regulations (SDC35), Challenging to draw regulatory mechanisms (SDC44), Adaption with the new industrial revolution (SDC51), Ineffective employee training and culture (SDC52), Work polarization (SDC53), Non-uniform alignment of sustainability, organization, and goal and customer expectation (SDC54) and Non-consideration of human factors (SDC55).

Research and innovation efforts can focus on understanding and engaging with various stakeholders affected by the renewable energy supply chain, including local communities, Indigenous groups, policymakers, and NGOs. This engagement facilitates participatory decision-making processes, incorporates diverse perspectives, and addresses social acceptance challenges. Involving stakeholders in the planning, implementation, and monitoring stages can develop innovative solutions that align with local needs and values, ensuring sustainable and socially acceptable renewable energy projects (Dawson and Daniel, 2010). Research can examine the socioeconomic impacts of the RESC, particularly in the transition from fossil fuels to renewable energy sources. It can explore topics such as job creation, local economic development, inclusive growth, and the mitigation of potential negative social consequences. Overall, research and innovation in social and human problems significantly address sustainable development challenges in the RESC. By focusing on stakeholder engagement, social acceptance, socioeconomic impacts, labor practices, human rights, gender equality, social inclusion, and behavioral change, these efforts contribute to developing sustainable and socially responsible renewable energy practices and ensure a just and equitable transition to a renewable energy future.

Industry 5.0 enables customization and flexibility in production processes. This is particularly valuable for addressing social and human problems since it allows for tailoring solutions to meet local communities' specific needs and preferences. For example, renewable energy technologies can be adapted to suit different regions' cultural and environmental contexts, promoting social acceptance and sustainable development. Industry 5.0 allows for rapid prototyping and testing of solutions. This is invaluable in research and innovation for social and human problems since it enables researchers to quickly iterate on ideas and refine solutions based on real-world feedback. It reduces the time-to-market for innovative approaches to sustainable development. A lack of concern for human factors, inadequate staff training and culture, an uneven alignment of sustainability, organization, and objective, and consumer expectations constrain the adoption of sustainability. There is disagreement among investigators (Liu, 2022; Winter and Knemeyer, 2013) regarding the relationship between the management's lack of commitment to adopting sustainable development practices and the non-consideration of human factors, inadequate employee training, organizational culture, and sustainability policies.

"Building safer and complicated hyper-connected networks (IA1)" is the third highest-rated advantage for overcoming supply chain SDCs. Building safer and more complicated hyper-connected networks overcomes a variety of challenges, including high infrastructure (SDC13), the threat posed by cyber security (SDC32), Ineffective integration of sustainability with available processes (SDC33), absence of autonomy in current systems (SDC42), design complexity for RE consumption reduction (SDC45), and sophistication within supply chain configuration (SDC46).

RESC can enable real-time energy generation, consumption, and distribution monitoring by leveraging hyper-connectivity, sensors, and

Table 15
Ranking the industry 5.0 advantages.

Industry 5.0 Advantages	Aggregate summation value	Aggregate multiplication value	Qi	Ranking
Building safer and complicated hyper-connected networks (IA1)	1.1041	2.8181	1.9762	*3*
Supply chain modularity (IA2)	1.151	2.876	2.028	*1*
Use of lean innovation approach (IA3)	0.5996	1.8154	1.3957	*16*
Rewards and incentives for greener activities (IA4)	0.9987	2.6955	1.8120	*5*
Audit (IA5)	0.6225	1.9140	1.4856	*15*
Sustainable thinking (IA6)	1.0021	2.7230	1.9044	*4*
Circular intelligent products (IA7)	0.7952	2.4812	1.6942	*11*
Integrity (IA8)	0.4963	1.6782	1.2167	*18*
Employee technical assistance (IA9)	0.7441	2.4245	1.6310	*12*
Supplier Commitment and involvement for Sustainability adoption (IA10)	0.5204	1.7651	1.3035	*17*
Smart production processes (IA11)	0.4214	1.5460	1.1865	*19*
Workers' appropriate skills to interact with technologies before implementation (IA12)	0.9750	2.6251	1.8001	*6*
Distributed and responsive supply chain (IA13)	0.6840	1.9941	1.5210	*14*
Focus on customer and employee experience (IA14)	0.9214	2.5995	1.7901	*7*
Sustainable resource management (IA15)	0.7004	2.1025	1.5875	*13*
Adoption of Cloud Technology an among the existing supply chain activity (IA16)	0.9004	2.5710	1.7647	*8*
Green Purchasing (IA17)	0.8312	2.5004	1.7010	*10*
Supply chain adaptability (IA18)	0.8875	2.5521	1.7346	*9*
Research and innovation in social and human problems (IA19)	1.141	2.848	2.010	*2*

Table A5
Social (SDC5) comparison by BO and OW rating.

Best to Others (BO)	SDC51	SDC52	SDC53	SDC54	SDC55	
Best SDC: SDC55	7	5	9	3	1	
Other-to-worst (OW)					*Worst SDC:*	*SDC53*
SDC51						3
SDC52						3
SDC53						1
SDC54						5
SDC55						9

data-sharing platforms. This allows stakeholders to identify inefficiencies, optimize energy usage, reduce waste, and make informed decisions to maximize renewable energy utilization. Real-time monitoring also helps identify maintenance needs, improving system reliability and performance. Hyper-connected networks enable sophisticated energy management systems that can facilitate demand response mechanisms. These systems monitor energy consumption patterns and provide real-time feedback to consumers, encouraging them to adjust their energy usage during peak demand periods or when renewable energy generation is high. Hyper-connected networks optimize energy demand and supply and contribute to a more sustainable and balanced energy grid (Mercan et al., 2021). In summary, hyper-connected networks contribute to the sustainable development of the renewable energy supply chain through real-time monitoring, energy management, integration of distributed resources, supply chain traceability, collaboration, knowledge sharing, and predictive maintenance. By harnessing the power of data and connectivity, these networks enable more efficient, reliable, and transparent renewable energy systems, promoting sustainability and supporting the global transition to clean energy sources.

5.4. Managerial implications

Significant theoretical and practical contributions are made to the subject of sustainable RESC and Industry 5.0 by the present study. Literature review and conception of Industry 5.0 reveal that extensive networking effects characterize Industry 5.0. The continually changing market demands have required business professionals to accurately recognize the primary difficulties in sustainability adoption. The current study offers a comprehensive list of SDCs in RESC described by different investigators in the literature. Manufacturing and service professionals are always looking for inventive industry professionals to improve the performance of their supply chains. In recent years, Industry 5.0 has acquired prominence in this context. Few studies in the literature describe the facilitators that may assist people in developing sustainability inside the organization. Academics working in related sectors will be able to create new frameworks with the aid of the list of Industry 5.0-based advantages, ultimately leading to a rise in the adoption rate of sustainability.

Nevertheless, from a framework viewpoint, several works of literature have provided barrier/challenge-specific frameworks. Yet, a framework combining SDCs in RESC with measures for Industry 5.0 initiatives is not noticed. As a result, the framework proposed in this research will significantly aid practitioners in increasing sustainability rates in the RE industry.

Findings indicate that each advantage might address some of RESC's sustainable development challenges. For instance, “Supply chain modularity” and “Research and innovation in social and human issues” may improve renewable energy supply chain visibility, traceability, and transparency; all three are critical to the organization's ultimate sustainable development goal. However, there is a strong complementarity between the highlighted challenges and advantages. The collaborative development of all indicated challenges and advantages and the associated synergies would give super-additional benefits for sustainable development goals.

Implementing sustainability into the renewable energy supply chain is the industry's future. Consequently, it is projected that the government will enact rules encouraging the use of Industry 5.0. Policymakers must develop subsidies for organizations whose process structures include sustainable approaches. These initiatives will heighten an organization's involvement in green, human, and social culture and motivate them to develop a brand image that represents the essential elements of Industry 5.0. However, policymakers are recommended to conduct sustainability awareness programs to educate organizations and their consumers, who may contribute significantly to enhancing the performance of recycling procedures. To establish successful policies that benefit organizations and end users, government officials may use this research's final rankings of solution measures to contribute to the growth of the nation's economy.

The study's findings will provide energy sector managers with a thorough analysis of problems and potential solutions depending on their ranking, as indicated by the hybrid Fuzzy BWM-WASPAS approach. Most frameworks described in the literature are validated using the case study method.

Our proposed framework offers a holistic approach by combining sustainable development challenges in the renewable energy sector with specific measures and principles of Industry 5.0. This integration allows practitioners to consider the broader sustainability context while leveraging the potential of Industry 5.0 technologies and practices, enabling a more comprehensive and practical approach to sustainability in the renewable energy industry. The framework contributes unique insights and knowledge synthesis by bridging the gap between sustainable development challenges in the renewable energy sector and Industry 5.0 advantages. By combining these two domains, the framework identifies areas where existing approaches and theories fall short and proposes innovative solutions offering new perspectives. This knowledge synthesis enriches the understanding of how Industry 5.0 advantages specifically address sustainability challenges in the renewable energy industry and promotes knowledge exchange among practitioners, researchers, and policymakers. Overall, the proposed framework significantly aids practitioners in increasing sustainability rates in the renewable energy industry by providing a systematic, practical, and context-specific approach to addressing sustainable development challenges through Industry 5.0 advantages.

Some strategies can address the challenges of human factors and social sustainability in the renewable energy sector: Implementing training and capacity-building programs to enhance the skills and knowledge of local communities and workers in the renewable energy sector. This empowers them to actively participate in planning, constructing, operating, and maintaining renewable energy projects, fostering job creation, economic development, and sustainable livelihoods. Another strategy is to design renewable energy projects that provide direct socioeconomic benefits to host communities. This can include community-led investment models, revenue-sharing mechanisms, and shared ownership arrangements. Such approaches incentivize local support, create economic opportunities, and enable communities to actively participate in and benefit from renewable energy projects. Promote public awareness campaigns to educate communities about the importance of renewable energy, its positive impacts on climate change mitigation, and the tangible benefits it brings to local economies and societies. Encourage dialogue and address concerns to build trust and maximize social acceptance. By implementing these strategies, the renewable energy sector can effectively address human factors and promote social sustainability. These approaches contribute to the overall success and acceptance of renewable energy projects, fostering a fair and equitable transition to a sustainable energy future.

Based on the results, to encourage the adoption of Industry 5.0 principles in the renewable energy supply chain, governments should implement specific policy measures that create incentives, provide support, and establish a conducive regulatory framework. Here are some policy measures that should be enacted:

- ❖ Research and Development Funding: Governments should fund research and development initiatives integrating Industry 5.0 technologies into renewable energy. This funding supports innovation in human-machine collaboration, data analytics, and customization for sustainable energy solutions.
- ❖ Tax Incentives: Tax incentives, such as investment tax credits or accelerated depreciation, encourage businesses in the renewable energy sector to invest in Industry 5.0 technologies.
- ❖ Training and Education Programs: Establishing training and education programs in collaboration with universities and vocational institutions ensures the workforce is equipped with the skills required for Industry 5.0 adoption.
- ❖ Regulatory Frameworks: Governments should create regulatory frameworks that support the safe and ethical use of Industry 5.0 technologies in the renewable energy sector. This includes standards for data privacy, cybersecurity, and environmental sustainability.
- ❖ Energy Market Reforms: Governments should reform energy markets to accommodate decentralized and localized renewable energy production enabled by Industry 5.0. This may include revising feed-in tariffs, net metering policies, and grid integration regulations.

5.5. Limitations and future research

Ultimately, the research identified characteristics that might help Industry 5.0 reach its goals for sustainable growth. Scientists are encouraged to complete a survey to supplement the present study's list. Any structural equation modeling (SEM) must be used to characterize the structural relationship between the studied components. Other literature studies on the challenges of adopting sustainability also corroborate the current research results. According to several studies, acquiring sustainability across service businesses is much simpler than in manufacturing industries. This also illustrates the critical requirement for research that might address issues and solutions in the same framework, identify the severity of challenges, and prioritize solutions. As a result, this research may be used as a reference to comprehend the MCDM approaches used, the criteria chosen, or the finalized advantages.

Consequently, it will fully understand the aims of Industry 5.0. However, despite its shortcomings, it may be a starting point for further study. Results might be ambiguous if there was any bias in determining the relative relevance of the criterion and enablers. Therefore, the panel of experts must objectively evaluate the questionnaire.

Moreover, despite our best efforts, we still lack considerable information about the future course of this incident. As a result, further study in the areas mentioned below should be encouraged to expand on our results. Therefore, future research should be encouraged to improve our findings in the below-mentioned areas. We could only identify the contextual links between the functions by using the opinions of European experts owing to methodological restrictions. Like Industry 4.0, we think Industry 5.0 will become a worldwide phenomenon even though it is a European project. Future research might investigate the relationships between Industry 5.0's sustainable development functions and the opinions of a broader range of socioeconomically varied professionals (Ghobakhloo et al., 2022).

Some specific suggestions for future research address the limitations and provide a more comprehensive understanding of the SDCs based on Industry 5.0 advantages on a global scale:

- ❖ Conducting surveys targeting a broader range of socioeconomically diverse professionals from various regions worldwide. This includes experts from different industries, academia, policy-making bodies, non-governmental organizations, and community groups—the surveys are designed to gather opinions and insights on the Industry 5.0 advantages for overcoming the SDCs.
- ❖ Performing comparative analysis across multiple countries to identify commonalities and differences in the perspectives and practices related to SDCs and Industry 5.0 advantages.
- ❖ Conducting longitudinal studies that track the evolution and impacts of Industry 5.0 advantages SDCs over time in different global regions. Longitudinal studies can capture the dynamic nature of the interactions between Industry 5.0 advantages and SDCs, allowing for a deeper understanding of the long-term effects, lessons learned, and adaptation strategies.

By implementing these suggestions, future research can broaden the scope, enhance inclusivity, and provide a more comprehensive understanding of the SDCs in the Industry 5.0 era in a global context.

6. Conclusion

Industry 5.0 focuses on the delivery of life-improving products and services to society. Several aspects of Industry 4.0, such as mass personalization, co-working robots and AI systems, sustainable practices, and bioeconomy, have not been investigated or implemented. Now is peak time, with massive natural disturbances created by irresponsible human actions; such behaviors must alter, and solid, sustainable alternatives must be included in our enterprises and daily lives. Nowadays, the knowledge and technology necessary to execute superior methods are accessible; consequently, efforts must be made to integrate them into our society and maintain our ecosystem. Experts agree that Industry 5.0 emerged to counteract the ongoing digital industrial transition's adverse social and environmental effects. Industry 5.0 has been promoted as an eco-friendly method of progress. As mentioned, Industry 5.0 aims to optimize resource utilization by leveraging technologies. Using smart sensors, connected devices, and advanced data analytics, Industry 5.0 enables real-time monitoring and control of energy consumption, minimizing waste and improving energy efficiency. This reduction in resource consumption contributes to environmental sustainability. Studies have shown that applying IoT and AI technologies in industrial processes can lead to significant energy savings and resource efficiency improvements. While Industry 5.0 is still an emerging concept, its core principles and technologies align with sustainability goals. By promoting resource efficiency, circular economy practices, sustainable supply chains, and renewable energy integration, Industry 5.0 offers the potential for eco-friendly industrial processes that minimize environmental impact and contribute to a more sustainable future.

One prominent example of Industry 5.0 adoption in the renewable energy sector is the implementation of smart grids. Smart grids leverage real-time data and advanced communication technologies to efficiently integrate renewable energy sources into the grid. These grids can balance supply and demand dynamically, optimize energy distribution, and reduce losses. For instance, the Energiewende Co. initiative combines renewable energy sources with advanced grid technologies to achieve Germany's more sustainable and decentralized energy system. Also, decentralized solar energy production is becoming an essential strategy for sustainable development in regions with abundant sunlight. Industry 5.0 facilitates the customization of solar panels to local conditions, such as weather patterns and energy demand. Additionally, AI-driven analytics optimize the placement of solar panels and energy storage units. In Bangladesh, the Grameen Shakti initiative deploys solar home systems tailored to individual households' needs, promoting sustainable energy access in rural areas.

However, it is unclear how Industry 5.0 will handle the above-mentioned issues while preserving long-term growth. By completing an extensive literature assessment on the significant SD challenges in RESC and making Industry 5.0-based suggestions, this study aims to fill this knowledge gap. According to the literature, Industry 5.0 may promote the principles of sustainable development by addressing a unique set of 23 challenges in RESC and 19 advantages. The case study findings indicate that social challenges are the leading reason for sustainability failures. Nonetheless, non-consideration of human factors, poor staff training and culture, and non-uniform alignment of sustainability, organization, purpose, and customer expectations impede sustainable adoption among the subgroup problems.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Morteza Ghobakhloo reports financial support was provided by European Commission (European Union's Horizon 2020 research and innovation programme under grant agreement No 810318).

Acknowledgments

This research has been a part of a project that received support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 810318.

Appendix A

Table A1
Economic (SDC1) comparison by BO and OW rating.

Best to Others (BO)	SDC11	SDC12	SDC13	SDC14	
Best SDC: SDC14	5	9	5	1	
Other-to-worst (OW)				*Worst SDC:*	*SDC12*
SDC11					3
SDC12					1
SDC13					3
SDC14					9

Table A2
Environmental (SDC2) comparison by BO and OW rating.

Best to Others (BO)	SDC21	SDC22	SDC23		
Best SDC: SDC21	1	5	9		
Other-to-worst (OW)				*Worst SDC:*	*SDC23*
SDC21					9
SDC22					3
SDC23					1

Table A3
Organizational (SDC3) comparison by BO and OW rating.

Best to Others (BO)	SDC31	SDC32	SDC33	SDC34	SDC35	
Best SDC: SDC34	7	5	9	1	5	
Other-to-worst (OW)					*Worst SDC:*	*SDC33*
SDC31						3
SDC32						5
SDC33						1
SDC34						9
SDC35						3

Table A4
Process (SDC4) comparison by BO and OW rating.

Best to Others (BO)	SDC41	SDC42	SDC43	SDC44	SDC45	SDC46
Best SDC: SDC45	9	5	3	7	1	5
Other-to-worst (OW)					*Worst SDC:*	*SDC41*
SDC41						1
SDC42						3
SDC43						3
SDC44						5
SDC45						9
SDC46						5

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