Annals of Operations Research
https://doi.org/10.1007/s10479-024-06093-3

ORIGINAL RESEARCH

Decarbonised closed-loop supply chains resilience: examining the impact of COVID-19 toward risk mitigation by a fuzzy multi-layer decision-making framework

Hannan Amoozad Mahdiraji[1] · Fatemeh Yaftiyan[2] · Jose Arturo Garza-Reyes[3,4] · Seyed Hossein Razavi Hajiagha[5] · Yigit Kazancoglu[6]

Received: 27 April 2022 / Accepted: 31 May 2024

Abstract

Today's primary challenges in supply chains (SCs) include considerable greenhouse gas emissions, waste, and disruptions. Addressing these requires the examination of three interconnected SC paradigms, i.e. decarbonisation, resilience, and Closed-Loop SCs (CLSCs). This paper seeks to investigate and assess the criteria for decarbonised resilient CLSCs, as influenced by the global pandemic, specifically within the context of Iran's small and medium pharmaceutical enterprises, employing a mixed-method approach. Initially, a Systematic Literature Review was employed to identify a categorised list of decarbonised resilient CLSC criteria by determining the impact of COVID-19 on SCs. Afterwards, the list was indigenised via the fuzzy-Delphi method. Two popular Fuzzy Multi-Criteria Decision-Making methods, i.e. fuzzy Decision-Making Trial and Evaluation Laboratory and fuzzy Interpretive Structural Modelling-Matrix-based Multiplication Applied to a Classification (MICMAC), were then employed to investigate the finalised criteria. This paper has innovatively enhanced these methods by incorporating a multi-scenario analysis approach. The findings indicate that technological advancements, issues related to market and communication, and raw material markets significantly affect other criteria. Transportation and logistics are also crucial in reducing lead times, waste, and CO_2 emissions. Two countermeasures are recommended for senior managers, i.e. (i) the identification and application of suitable basic and advanced technologies across each SC process and (ii) engaging in a coevolutionary process beginning with SMEs' cooperation and collaboration towards their co-creation. The importance of regulatory bodies was also emphasised in devising effective policies to improve the markets for raw materials and finished products.

Keywords Global pandemics · Closed loop supply chain resilience · Fuzzy-Delphi · Fuzzy-DEMATEL · Fuzzy ISM-MICMAC

1 Introduction

The recent global pandemic initiated a significant outbreak of acute respiratory infections and severely disrupted economic systems across various supply chain networks (Singh et al.,

Extended author information available on the last page of the article

Published online: 03 August 2024

2021). SC networks refer to companies that distribute goods, services, financial resources, and informational flows between primary suppliers and consumers. The multidimensional impacts of pandemics on SCs included border closures, lockdowns in the supply market, demand and supply fluctuations, vehicle movement restrictions, interruption in export and import activities (i.e., international trade), labour shortage, etc. (Ghadir et al., 2022). For example, the panic purchasing and stockpiling behaviour of consumers led to additional challenges in the food and healthcare supply chains (Coopmans et al., 2021). Comprehensively, Chowdhury (2021) provided four broad themes for recent research that occurred in this domain, including (i) identifying the impacts of the outbreak (Karunathilake, 2020), (ii) developing appropriate strategies and countermeasures to cope with such effects as well as maintaining SCs resilience (Cai & Luo, 2020), (iii) discussing the role of new technologies, e.g. blockchain, Internet of Things (IoT), data analytics, robotics, etc., in improving SC resilience and sustainability (Xu et al., 2020), and (iv) evaluating SCs' economic, environmental, and social sustainability in the light of this health crisis (Sharma et al., 2020).

On the one hand, propagating disruptions across SC networks has dramatically highlighted the SCs resilience theme, particularly in the recent epidemic era (Mishra et al., 2022). There are different definitions of resilience as an abstract concept. Considering the social-ecological systems, SC resilience reveals the ability of the system to predict, withstand, and adapt to challenges or appropriately respond to disruption propagation (Scala & Lindsay, 2021). Recently, most researchers have increasingly focused on SC disruption management and resilience risk mitigation in light of global pandemics. For instance, Burgos and Ivanov (2021) used a discrete-event simulation model to assess the food SC operations and performance dynamics during the COVID-19 crisis. Similarly, Belhadi et al., (2021) used qualitative and quantitative techniques to investigate the impacts of this outbreak on automobile and airline SC resilience and explored the response strategies to maintain it.

Although the global pandemic resulted in an extensive lockdown of physical businesses, online commerce companies flourished due to a rise in global demand for delivering goods directly to customers. It accompanied the increasing importance of studying Reverse SCs (RSCs) and Forward SCs (FSCs). The integration of FSCs and RSCs results in CLSCs. CLSCs reflect the management of both forward logistics in the chain, e.g. procurement of materials, production, and distribution, whereas reverse logistics collect and process returns of products and/or parts (used or unused) to ensure sustainable recovery (i.e., economic, ecological and societal) (Arabi & Gholamian, 2023). Since 1995, CLSC management has received considerable attention from industry and academia, especially due to environmental concerns (Scopus, 2021). The context of CLSC resilience has been emphasised more during the global outbreak of COVID-19. For instance, Duan et al., (2021) employed system dynamics to simulate a CLSC material flow and capital flow to explore the sudden interruption impact of material flow on a CLSC system when an uncertain emergency occurred. The results revealed that COVID-19 impacted the material flow of CLSC more than the flow of capital. It also revealed the high vulnerability of recyclers and manufacturers in the wake of the pandemic.

Contemporarily, accomplishing carbon neutrality (decarbonisation) is another ambition of CLSCs to tackle global warming. Thus, investigating (or green) CLSCs has recently become a popular research trend. For instance, Ghomi-Avili et al., (2018) developed a mathematical model of green CLSC to optimise CO_2 emissions. More recently, Xu et al., (2023) designed an optimisation model to minimise the carbon footprint emitted by manufacturing, delivery and return CLSC processes. Fulfilling decarbonised resilient CLSC under disruptions is a target for organisations and researchers alike. For instance, Yavari and Zaker (2019) proposed a multi-layer mathematical model of green CLSC resilience to minimise the cost

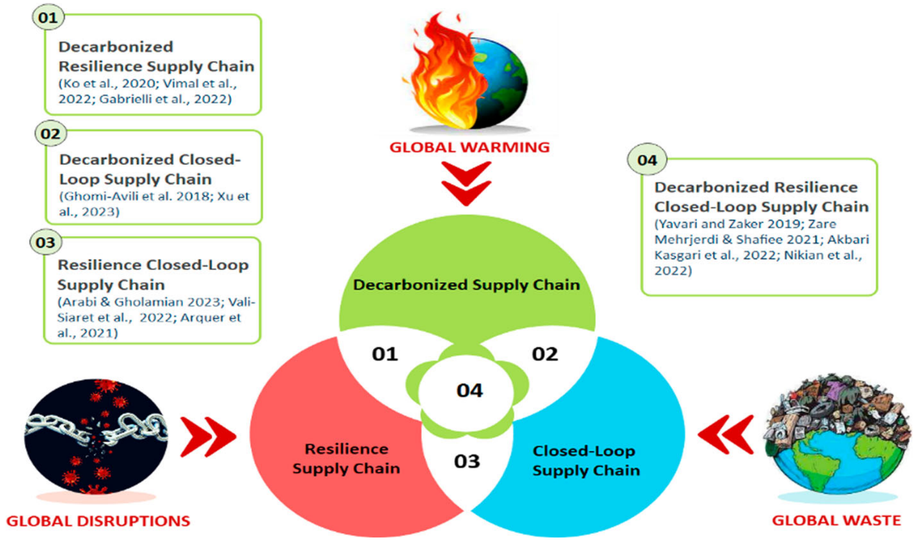


Fig. 1 Theoretical framework of decarbonised resilient CLSCs networks

and carbon emissions considering unexpected events. Later, Mehrjerdi and Shafiee (2021) combined a mathematical model and fuzzy TOPSIS to optimise three dimensions of a sustainable CLSC resilience network under electrical disruption in perishable product companies. Similarly, Akbari-Kasgari et al., (2022) developed a model of sustainable CLSC resilience under disruption of earthquakes in mines to control profit, water utilisation, carbon footprint and unemployment rate. More relevant to the current study, Nikian et al., (2022) developed a mathematical model of sustainable CLSC resilience under a global pandemic disruption to optimise profit criteria, water and energy utilisation, and CO_2 emissions. Consequently, studying the theoretical framework of decarbonised resilient CLSC networks under different disruptions (Fig. 1) is a significant modern demand in the extant literature. Nevertheless, recent scholars have mainly focused on optimising the criteria for decarbonised resilient CLSCs. However, research to identify decarbonised resilient CLSC criteria referring to the impacts of worldwide disruptions is still limited. Furthermore, investigating the interactions and priority of these criteria impacted by disruptions like global pandemics is a fundamental research gap that should be addressed to support future studies. Therefore, bridging these fundamental gaps could provide industries with appropriate solutions to tackle global warming, waste management, and risk mitigation and develop an avenue for future research in this field.

Thus, this research contributes to investigating decarbonised resilient CLSCs' criteria under the disruption of global pandemics on pharmaceutical SMEs of emerging economies, particularly Iran. As a backbone of healthcare systems, the pharmaceutical sector has been greatly hit by COVID-19 (Chowdhury et al., 2020). As a result, several recent scholars have attempted to identify the effects of the COVID-19 outbreak on pharmaceutical SCs to overcome accompanying challenges. For instance, Ayati et al., (2020) discussed this predicament's short/long-term impacts on the pharmaceutical sector. Furthermore, Mondal and Roy (2021) developed a multi-objective mathematical programming model to investigate the sustainability of healthcare and CLSC during COVID-19. Parallelly, Poursoltan et al., (2021) proposed a mathematical programming model, which was tested on Iranian medical ventilator production, to design a green CLSC. Hence, the pharmaceutical industry of emerging economies is a relevant case to be investigated under such disruptions.

Methodologically, former studies have mainly employed different mathematical models to design a green and resilient CLSC with optimum criteria. Nonetheless, cause-and-effect interactions of such criteria and their priority have not yet been discussed. Moreover, previous research that investigated the impacts of disruptions like global pandemics on SC resilience criteria has often applied qualitative research methodologies, including empirical literature reviews and researchers' opinions. However, quantitative methodologies have been mostly limited to mathematical programming models and simulation. Nevertheless, Sharma et al., (2021) and Chowdhury et al., (2021) recommended using Multi-Criteria Decision-Making (MCDM) approaches to enhance the robustness of recent research outcomes when investigating the impacts of disruptions on SCs. Accordingly, the integration of literature review and fuzzy-Delphi, as well as F-DEMATEL and fuzzy ISM-MICMAC (F-ISMMICMAC), has been acknowledged as a powerful MCDM multi-layer technique to (i) firstly identify and screen research items and then (ii) evaluate and map conceptual level-based network relationship frameworks of the finalised items. That is embedded with multi-scenario analyses under uncertainty and experts' views. Studies that have proposed such frameworks in diverse fields have proved the robustness of this combined approach. Therefore, this paper employed an integrated MCDM framework. This research pursues the following objectives to bridge the identified research gaps.

RO_1 To provide a categorised list of decarbonised resilient CLSCs' criteria impacted by the disruption of global pandemics in the pharmaceutical industry of emerging economies, taking Iran as a reference.

RO_2 To investigate fuzzy level-based causal network relationships and power maps of the finalised criteria under three optimistic, probable, and pessimistic scenarios.

RO_3 To recommend appropriate countermeasures towards decarbonised resilient CLSCs to neutralise epidemic disruptions in the pharmaceutical industry under the three abovementioned scenarios.

The rest of this article is organised as follows. The extant body of literature is systematically reviewed in the next section to extract an initial categorised list of decarbonised resilient SCs criteria impacted by the COVID-19 outbreak. The research framework, including data collection and analysis, approaches, i.e. fuzzy-Delphi, F-DEMATEL, and F-ISMMICMAC, is presented in Sect. 3. The results of the data analysis are included in Sect. 4 while Sect. 5 discusses the theoretical, practical, and managerial implications. Finally, this paper ends with concluding remarks and future research recommendations in Sect. 6.

2 Literature review

The spread of the COVID-19 virus impacted global economic systems, including different SCs. Recent scholars defined the COVID-19 impact as a ripple effect, which propagated disruption on SC structural design and planning parameters (Paul et al., 2023). This section reviews the extant literature on SCs' decarbonised resilient disruption due to the COVID-19 pandemic to (i) reveal the current state of knowledge and the research gaps in this field and (ii) establish a categorised list of the SCs' decarbonised resilient criteria impacted by the COVID-19 crisis. To this end, a keyword search including *"impacts of the COVID-19 outbreak on supply chains"*, *"impacts of the COVID-19 outbreak on closed-loop supply* *chains", "impacts of the COVID-19 outbreak on resilience supply chains", "impacts of the COVID-19 outbreak on decarbonised supply chains", "impacts of the COVID-19 outbreak on decarbonised resilient closed-loop supply chains", "supply chains resilience criteria impacted by the COVID-19 outbreak",* and *"supply chains decarbonised criteria impacted by the COVID-19 outbreak"* was performed in five databases that included ScienceDirect, Emerald, Wiley, Taylor and Francis, and Springer. The search time horizon covered the COVID-19 outbreak from 2020 to March 2023. Consequently, 70 articles in this field were identified by reviewing their titles and abstracts. After fully studying these papers, 19 were deemed irrelevant. Thus, 51 relevant papers were considered for the present study. These are summarised in Table 1.

Table 1 indicates that enhancing SC resilience, sustainability pillars (economic, social, and ecological), and closed-loop building blocks are indisputable issues to discuss during global pandemics. Several scholars have contributed to this field by exploring the COVID-19 impacts on SCs and providing the countermeasures to cope with them. This demand has been exacerbated by growing concerns related to global warming and waste management. Therefore, developing decarbonised CLSC towards carbon neutrality and waste reduction is a new target of many nations to offset climate change (Xu et al., 2023). However, this paradigm has yet to be connected to the impact of COVID-19. Hence, studying a novel integrated SC paradigm, including decarbonised resilient CLSC during epidemics, is a significant research gap (Nikian et al., 2022) that this paper addresses by considering three global concerns, i.e. climate change, waste, and disruptions management.

Moreover, the extant literature needs to identify and investigate decarbonised resilient CLSC criteria from four perspectives, i.e. causal network relationships, cause-and-effect group, driving and dependence power, and priority. To the best of our knowledge, in the case of COVID-19, these criteria can be explored by extracting the COVID-19 impact on diverse facets of SCs (economic, social, ecological, technological, and industrial). Thus, the main contribution of this study is to address the aforementioned research gaps by establishing and determining such impacts.

As indicated by Table 1, recent scholars have mainly employed qualitative methods, e.g. literature review, case study, interview, expert opinions, etc., to identify the COVID-19 impacts on SCs. In this domain, an SLR is acknowledged as a rigorous qualitative approach to tracing the evidence impartially, examining its quality, and synthesising it (Gupta et al., 2022). Through an objective, transparent, and rigorous method, an SLR minimises prejudice and warrants future replicability (Queiroz et al., 2022). Hence, this paper initially aimed to identify the varied impacts of COVID-19 on supply chains by systematically reviewing the existing literature. Subsequently, coding techniques were employed to produce a categorised list of criteria for decarbonised resilient CLSCs based on the effects identified. This list was not specific to the chosen case study. Therefore, recent scholars have recommended employing the fuzzy-Delphi method and systematic literature review (SLR) to meticulously examine, filter, and compile a bespoke list of research items, drawing on expert opinions and uncertainties.

Furthermore, several recent papers analysing the impact of COVID-19 were based on a qualitative data analysis method like interpretive analysis. However, other recent papers (e.g., Sharma et al., 2021) recommended using Multi-Criteria Decision Making (MCDM) tools to provide more robustness to the outcomes of previous research. Nonetheless, quantitative methods such as statistical analysis, discrete-event simulation, structural equation modelling, and the best–worst method, have rarely been employed (see Table 1, Column 6). On the other hand, various studies have focused on analysing SC resilience criteria by applying mathematical modelling to optimise such criteria (Paul et al., 2022). Therefore, employing

Table 1 COVID-19 impacts on SCs: Relevant research overview

Scholar (s)	Year	Main Contribution	SC Paradigm				COVID-19 Impacts Extraction Approach	Data Analysis Approach		Data Type	Case Study/ Application
			Traditional	Resilience	Sustainable	Closed-loop		Qualitative	Quantitative		
Karunathilake	2020	Interpretively analysing the positive and negative impacts of the COVID-19 outbreak on SCs	*				LR	IRA	-	-	-
Cai and Luo	2020	Exploring the impacts of the COVID-19 outbreak on SCs and suggesting pathways to overcome	*				LR, C	C	-	-	EI, AI, FI, SI
Chowdhury et al.	2020	Exploring the impacts of the COVID-19 outbreak on SCs and suggesting pathways to overcome		*	*		LR, C	Q, C	-	-	FI in Bangladesh
Ivanov	2020	Prevising impacts of the COVID-19 outbreak on worldwide SCs	*				LR	-	DES	Crisp	SCs in China
Coopmans et al.	2021	Promote SCs resilience by analysing the impacts of the COVID-19 pandemic		*			I, Q	ES	SM	Crisp	AFI
Narasimha et al.	2021	Analyse the impacts of the COVID-19 pandemic on transportation and SCs	*				LR, I	Q, ES	SM	Crisp	Stand MSC in India
Burgos and Ivanov	2021	Evaluate SCs operations and performance, focusing on the impacts of the COVID-19 pandemic		*			LR	-	DES	Crisp	FI
Butt	2021	Exploring the impacts of the COVID-19 outbreak on SCs and suggesting pathways to overcome	*				LR, I	C, CODE	-	-	CI, PI, AI, FI
Sajjad	2021	Examining impacts of COVID-19 on sustainable SCs and providing reliable proceedings toward resilient, sustainable SC		*	*		LR	SLR	-	-	-
Singh et al.	2021	Simulate the distribution network by observing the impacts of COVID-19 on SCs		*			LR	-	DES	Crisp	FI
Velayutham et al.	2021	Discussing the role of accounting information in SC disruptions management by assessing the impacts of the COVID-19 outbreak	*				LR	C	-	-	HI

Table 1 (continued)

Scholar (s)	Year	Main Contribution	SC Paradigm				COVID-19 Impacts Extraction Approach	Data Analysis Approach		Data Type	Case Study/ Application
			Traditional	Resilience	Sustainable	Closed-loop		Qualitative	Quantitative		
Dorcheh et al.	2021	Providing a strategic plan to struggle with the SCs' COVID-19 disruptions by exploring this pandemic's impacts	*				LR	SWOT	QSPM	Crisp	FI
Udofia et al.	2021	Study different impacts of the COVID-19 outbreak on SCs	*				LR	Q	SEM, CFA	Crisp	SMEs
Chowdhury et al.	2021	Performing a comprehensive SLR in the context of the SCs disruptions during the COVID-19 pandemic	*				LR	SLR	-	-	-
Rukasha et al.	2021	Interactively analyse the impacts of the COVID-19 outbreak on SCs	*				LR	SLR	-	-	AFI in Zimbabwe
Herold et al.	2021	Hold SC resilience by managing counteractions of the logistic firms		*			LR, I	IRA	-	-	-
Love et al.	2021	Study impacts of the COVID-19 outbreak on SCs and their reactions to overcome	*				LR	IRA	-	-	FI
Sharma et al.	2021	Study impacts of the COVID-19 outbreak on SCs and their reactions to overcome			*		LR	IRA	-	-	FI in India
Belhadi et al.	2021	Exploring the impacts of the COVID-19 outbreak on SCs and suggesting pathways to overcome		*			LR	I/O	SM	Crisp	AI, ArSC
Shen and Sun	2021	Exploring the impacts of the COVID-19 outbreak on SCs and suggesting pathways to overcome		*			C	C	-	-	SC in China
Pereira et al.	2021	Exploring the Impacts of the COVID-19 Outbreak on SCs Social Sustainability			*		I/O	C	-	-	Brazilian CP
Luckstead et al.	2021	Exploring the impacts of the COVID-19 outbreak on SCs workers	*				Q	-	SM	Crisp	FI
Magableh	2021	Evaluate the impacts of the COVID-19 outbreak on SCs	*				LR	IRA	-	-	-
Queiroz et al.	2022	Systematically reviewing the extant literature about the impacts of the COVID-19 outbreaks on SCs	*				SLR	SLR	-	-	CSCs
Ghadir et al.	2022	Examining impacts of the COVID-19 outbreak on SCs risk criteria	*				LR	FMEA	BWM	Crisp	AI

Table 1 (continued)

Scholar (s)	Year	Main Contribution	SC Paradigm				COVID-19 Impacts Extraction Approach	Data Analysis Approach		Data Type	Case Study/ Application
			Traditional	Resilience	Sustainable	Closed-loop		Qualitative	Quantitative		
Paul et al.	2022	Proposing a model for evaluating the impacts of the COVID-19 outbreak on SCs and providing some coping strategies	*				LR		MM	Stochastic	HSFMSC
Badhotiya et al.	2022	Proposing SC resilience strategies to cope with the COVID-19 impacts		*			LR	ISM	BN	Conditional Probability	Indian MI
Zahraee et al.	2022	Examining different impacts of the COVID-19 outbreak on sustainable, resilient SC and providing the strategies to deal with it		*	*		SLR	SLR	-	-	ABSC
Khan and Ponce	2022	Examining impacts of the COVID-19 outbreak on perishable products SCs	*				Q	-	SEM	Crisp	FI in Ecuador
Gupta et al.	2022	Systematically reviewing the extant literature on the impacts of the COVID-19 outbreaks on SCs	*				SLR	-	SLR	-	-
Agarwal et al.	2022	Assisting in SMEs manufacturing activities with the circular economy by overcoming the impacts of the COVID-19 outbreak on SCs		*	*	*	LR	-	EWM, GRA	Crisp	Manufacturing SMEs
Kumar and Singh	2022	Exploring impacts of the COVID-19 outbreak on perishable products SCs to enhance its resilience		*			LR, I/O	-	BWM, QFD	Crisp	AFI
Mishra et al.	2022	Evaluating the importance of SC resilience in dealing with the COVID-19 impacts		*			C	-	C	-	AFI
Paul et al.	2023	Examining the challenges hindering SC sustainability impacted by the COVID-19 outbreak			*		LR, ES	-	BWM	Crisp	FI

I/O: Interview, stakeholders view, experts opinion, LR: A literature review, Q: Questionnaire, CODE: open coding, axial coding and selective coding, C: Case Study, Multiple case study, DM: Delphi Method, SM: Statistical Method. ES: Online expert survey, DES: discrete-event simulation model, SWOT: strengths, weaknesses, opportunities and threats, QSPM: SWOT-Quantitative Strategic Planning Matrix, SEM: Structural equation model, CFA: Confirmatory factor analysis, SLR: Systematic Literature Review, IRA: Interpretive Research Approach, FMEA: Failure Mode and Effects Analysis, BWM: Best-Worst Method, MM: Mathematical Model, QFD: Quality Function Deployment, EWM: Entropy Weight Method, GRA: Grey Relational Analysis, BN: Bayesian Network, ISM: Interpretive Structural Modelling, FI: Food Industry, AI: Automobile Industry, AFI: Agri-food Industry, ArSC: Airline Supply Chain, ABSC: Agricultural Biomass Supply Chain, CP: Coffee Producers, HSFMSC: Hand Sanitizer and Face Masks Supply Chains, CSCs: Commercial Supply Chains, CI: Construction Industry, PI: Pharmaceutical Industry, HI: Healthcare Industry, EI: Electronics Industry, SI: Semiconductor Industry, STand MSC: Seaport Transportation and Maritime SC, SMEs: Small and Medium Enterprises.

an appropriate multi-layer decision-making method to examine these criteria is a fundamental research gap. Furthermore, excluding Paul et al., (2022) and Badhotiya et al., (2022), other scholars have applied crisp data in a certain environment. Albeit, uncertainty is an inseparable part of the socioeconomic environment. In this domain, fuzzy logic is an authentic theory that struggles with this vagueness (Razavi Hajiagha et al., 2021). Moreover, although the importance of studying emerging economies such as China, India, Brazil, Bangladesh, etc., can be proved by the last column of Table 1, most of the recent studies have focused on the food and auto industries. In contrast, some others suggest that the pharmaceutical industry would be significantly affected by the supply disruption caused by COVID-19. Thus, investigating the decarbonised resilient CLSC criteria of Iran's pharmaceutical SMEs needs to be considered in the era of the COVID-19 outbreak.

The SLR identified 51 relevant articles, see Table 1, that were then coded. A qualitative data analysis approach with three stages was then manually performed based on the extant theories (SC sustainability pillars). The 2015 segments of the 51 articles were initially recognised as values in the open coding stage. The same segments were combined, and 92 codes (sub-criteria) were applied. The common sub-criteria were merged in the axial coding part, and 17 concepts (criteria) were designated. Eventually, in the theme creation stage, five themes (main categories) were determined by dividing 17 criteria into five main categories. An overview of this coding process is illustrated in Table 2.

3 Methodology

This paper consists of research that conducted DEMATEL and ISM-MICMAC analyses separately and then compared their results to attain comprehensive implications (Kumar & Dixit, 2018; Nasrollahi et al., 2021; Trivedi et al., 2021). Accordingly, ISM-MICMAC is a holistic approach while DEMATEL is a part-based approach to discovering factors' direct and indirect interactions. ISM-MICMAC considers only binary options (0, 1) to recognise relationships among the factors and provide a power map. Conversely, DEMATEL includes other interval values. Moreover, ISM-MICMAC can level factors according to their relationships. Finally, the reliability of such studies is guaranteed due to conceptual similarities between the results of either approach.

Despite at least six available approaches that include Hesitant Fuzzy Set (HFS), Intuitionistic Fuzzy Set (IFS), Pythagorean Fuzzy Set (PyFS), Fermatean Fuzzy Set (FFS), Picture Fuzzy Set (PFS), and Spherical Fuzzy Set (SFS), this paper employed fuzzy set theory to consider uncertainty. We avoided overdoing a consideration of vagueness by comprehensively analysing each available uncertainty approach in Table 3. When experts cannot evaluate the importance of some alternatives by binary (0 (no), 1 (yes)) logic, they must use one of the uncertainties mentioned in the above approaches, depending on the problem and alternative characteristics and experts' views (Zadeh, 1965). For instance, if the neutral membership degree of alternatives is not sensed among experts owing to alternative essentiality, employing PFS and PFS is not suggested (Ashraf et al., 2019; Cuong, 2013). Orthopair fuzzy sets (IFS, PyFS, and FFS) could be substituted in these circumstances. However, when the sum of the membership degree and non-membership degree equals one, the fuzzy set theory and HFS are suitable. Instead of Orthopair fuzzy sets, they must be used to avoid time-consuming and complex questionnaires and computation (Senapati & Yager, 2020). Nonetheless, when experts do not have a set of possible values for membership degree (or they can assess the importance of an alternative through only one membership value), HFS should not be

Table 2 A categorised list of decarbonised resilient SCs criteria from SLR

Main-category	Criteria	Definition	Sub-criteria
Economic	Turnover (T)	Reflects companies' sales volume and price per product. It is useful in computing a firm's revenue and profit. Eventually, returns of investment can be released to stakeholders	General sales; Products price; Revenues (or Incomes); Profits (or Profit/Gross margins); Return on investment
	Finance (F)	Finance bankruptcy risk can also be predicted by referring to the firms' liquidity, capacity, and capability to repay loans, rent, invoices, trade receivables, etc	Liquidity; Repayment capacity; Capability to pay invoices and/or rent; Trade receivables; Bankruptcy risk
	Total costs (TCs)	It reflects the firm's total costs, including labour, raw materials, transportation, logistics, RandD expenditure, and operational costs (manufacturing goods and service-providing costs)	Labors cost; Raw materials costs; Transportation costs; RandD expenditure; Production/ Operating costs; Goods/ Services cost structure
	Sales based on channel (SBC)	Recognises sales volume through each existing channel, such as wholesalers, retailers, third parties, and online platforms	Wholesale; Retail sale; Local sales through the third party; Online sales
	Lead times (LTs)	Distinguishing SCs cycle time starts with supplying raw materials and ends with products/ service delivery. Thus, operational delays (manufacturing goods/services and delivery delays) can be estimated	Delays in procuring goods/services; Cycle time; Operational delays; Delivery times
	Raw materials market (RMM)	It highlights concerns related to raw material marketplaces, such as the accessibility level of high-quality raw materials and suppliers, which depends on local/global material production and flows	Raw materials accessibility; Production of raw materials and spare parts; Global material flows; Raw material supplies

Table 2 (continued)

Main-category	Criteria	Definition	Sub-criteria
	Transport and logistics (TandL)	This concept reflects two controversial SC issues: (i) transportation and (ii) inventory. Transportation facilities, mode availability and efficiency, average vehicle utilisation, and backlogs relate to the first concept. Moreover, supply and distribution warehouse capacity, utilisation and shortage, inventory availability, and waste level all cover the second term	Transportation facilities; Transportation mode availability; Transport efficiency; The average number of vehicles used; Transport and logistics backlogs; Suppliers' and distribution centres capacity; Capacity utilisation; Warehouse and storage; Inventory shortages and surpluses at distribution centres; Inventory level; Available inventory; Inventory waste level
	Labor market (LM)	This refers to recruiting high-skilled workers impacted by labour market issues such as permanent, seasonal, and family labour availability	Permanent labour availability; Seasonal labourers availability; Family labour availability; Recruiting and resourcing labour
	Production and operations performance (POP)	Refers to different elements that reveal SC's operational performance level, e.g., business volume and productivity (efficiency and effectiveness), that leads to profitability. In detail, production cycle, capacity and quality (i.e., the volume of finished and defective products, total product backlog, number of non-fulfilled orders, product re-work hours), and service level are all subsets of those indicators	Production cycle; Business volume; Finished products; Production capacity; Defect product; Total product backlog; Number of non-fulfilled orders; Product re-work hours; Product Quality; Functionality; Service Level; Operations efficiency; Productivity; Profitability

Table 2 (continued)

Main-category	Criteria	Definition	Sub-criteria
Ecological	Environmental pollution (EP)	Refers to different types of environmental pollution, e.g., air, water and sound. Nonetheless, the worldwide concern about global warming highlights air pollution between them. Which mainly results from greenhouse gas and CO2 emissions	Air pollution; Water pollution; Sound pollution; Greenhouse gas emissions
	Wastage (W)	This reflects SC's waste management, which includes reducing expired products and promoting waste disposal	Expired products; waste disposal
Societal	Labour livelihoods and well-being (LWB)	Reflects job creation concerns and workers' psychological and physical needs, including physical and mental health and safety, work-life balance (conflicts within the household), employee morale, fatigue (Gloominess, Depression, Suicidal thoughts, Anxiety, or panic attacks), attending to the workplace (particularly female workers), income satisfaction, foreign labour travel, and education	Physical and mental health and safety; Work-life balance (Conflicts within the household); Employee morale; Fatigue (Gloominess, Depression, Suicidal thoughts, Anxiety, or panic attacks); Attend to the workplace (particularly female workers); Income satisfaction; Foreign labour travel; Education filed; Job creation
Technological	Technological advancements (TAs)	Indicates the different levels of advanced technology utilisation. These technologies in CLSCs are beyond significant due to materials traceability urgency and minimising cyber-security risks	Traceability requirements; Cyber-security risks

Table 2 (continued)

Main-category	Criteria	Definition	Sub-criteria
Industrial	Market-related issues (MRI)	Refers to different elements related to the marketplace covering market instability, accessibility, and share, competition level, customers purchasing power, demand patterns and market composition (e.g., panic buying and Hoarding), supply and demand fluctuation, the possibility of international trade (import and export volumes), and interest rates	Market instability; Market accessibility; Market share; Competition; Supply and demand fluctuation; Purchasing power; Demand patterns and market composition (e.g., Panic buying and Hoarding); International trade (import and export volumes); Interest rates
	Communication-related issues (CRI)	Reflects SC's broad communication network, which can be extended by enhancing the visibility and transparency of real-time information sharing. This leads to more trust within SC partners, increased global trade relationships, establishing interlinkage with competitors and other stakeholders, and preparing communication infrastructure	Global trade relations; Interlinkages; Communication infrastructure; Visibility and transparency
	Contributions to GDP (CGDP)	This indicator refers to the degree of importance of an SC's product/service. It can be estimated by recognising how this SC contributes to national economic growth	Contribution to national economic growth
	Local/global pricing systems (PSs)	It reveals the type of pricing system (cost-based, perceived value, and market-based pricing) prevalent in any industry	Cost-based pricing; Perceived value pricing; Market-based pricing

Table 3 Comprehensive analysis of available uncertainty approaches

Available Uncertainty Approaches	Developer	Year	Indices: $\tilde{P}_A(x)$	$P_A(x)$	$H_A(x)$	$I_A(x)$	$N_A(x)$	Definition	Condition		Logical Application
Fuzzy Set	Zadeh	1965	✓					*A* is an FS on a universe set *X* in the form of $A = \{x, \tilde{P}_A(x) \mid x \in X\}$.	$0 \leq P_A(x) \leq 1$	When experts cannot binary (0, 1) assess an alternative.	Instead, they can evaluate it only: i.e., $\tilde{P}_A(x)$ at any point has one possible (fuzzy) value in [0, 1].
HFS	Torra	2010			✓			An HFS on a universe set X is a function that, when exerted to each x in X, returns a subset of values in [0,1]. *A* is an HFS on a universe set *X* in the form of $A = \{< x, H_{A(x)} > \mid x \in X\}$.	$0 \leq H_A(x) \leq 1$		However, they hesitate between several possible membership values. i.e., $P_A(x)$ at any point has a set of some (crisp) values in [0, 1].
IFS	Atanassov	1986							$0 \leq P_A(x) + N_A(x) \leq 1$		
PyFS	Yager	2013		✓			✓	*A* is an IFS (or PyFS or FFS) on a universe set *X* in the form of $A = \{x, P_A(x), N_A(x) \mid x \in X\}$. ***Note that *A* will be a <u>FS</u> when $N_A(x) = 1 - P_A(x)$.**	$0 \leq P^2{}_A(x) + N^2{}_A(x) \leq 1$		Instead, they need to examine both membership and non-membership values. i.e., $P_A(x)$ and $N_A(x)$ at any point have one possible (crisp) value in [0, 1].
FFS	Senapati and Yager	2020							$0 \leq P^3{}_A(x) + N^3{}_A(x) \leq 1$		
PFS	Cuong	2013		✓		✓	✓	*A* is a PFS (or SFS) on a universe set *X* in the form of $A = \{x, P_A(x), I_A(x), N_A(x) \mid x \in X\}$. ***Note that *A* will be an <u>IFS (or PyFS or FFS)</u> when $I_A(x) = 0$.**	$0 \leq P_A(x) + I_A(x) + N_A(x) \leq 1$		Instead, they evaluate it via three values: membership, neutral, and non-membership. i.e., $P_A(x)$, $I_A(x)$, and $N_A(x)$ at any point have one possible (crisp) value in [0, 1].
SPS	Ashraf et al.	2019							$0 \leq P^2{}_A(x) + I^2{}_A(x) + N^2{}_A(x) \leq 1$		

($\tilde{P}_A(x)$: fuzzy membership degree, $H_A(x)$: Set of possible membership degrees, $P_A(x)$: membership degree, $I_A(x)$: neutral-membership degree, and $N_A(x)$: non-membership degree in [0, 1]) employed instead of a fuzzy set (Torra, 2010). All conditions above were true in this research, in which applying a fuzzy set was considered to cope adequately with uncertainty and vagueness.

The research framework followed by this study, illustrated in Fig. 2, consisted of three stages. First, the literature review extracted the SCs resilience criteria impacted by COVID-19 from the economic, ecological, societal, technological, and industrial perspectives. A quantitative expert-based method, Fuzzy-Delphi, was used to screen and finalise the pharmaceutical CLSC resilience criteria impacted by the COVID-19 crisis. Using a multi-layer expert-based MCDM technique, F-DEMATEL, and F-ISMMICMAC, the influential network relationship and the level-based conceptual framework of the finalised criteria were analysed in stage 3, respectively.

Data collection approach Data was collected from the recent relevant literature and opinions from academics and executive managers of pharmaceutical SC SMEs in the emerging economy of Iran. In the first stage, the secondary data were applied to identify an initial list of SCs' decarbonised resilient criteria impacted by the COVID-19 outbreak. Afterwards, the primary data pertinent to the experts' views were collected to perform 2nd and 3rd stages. To

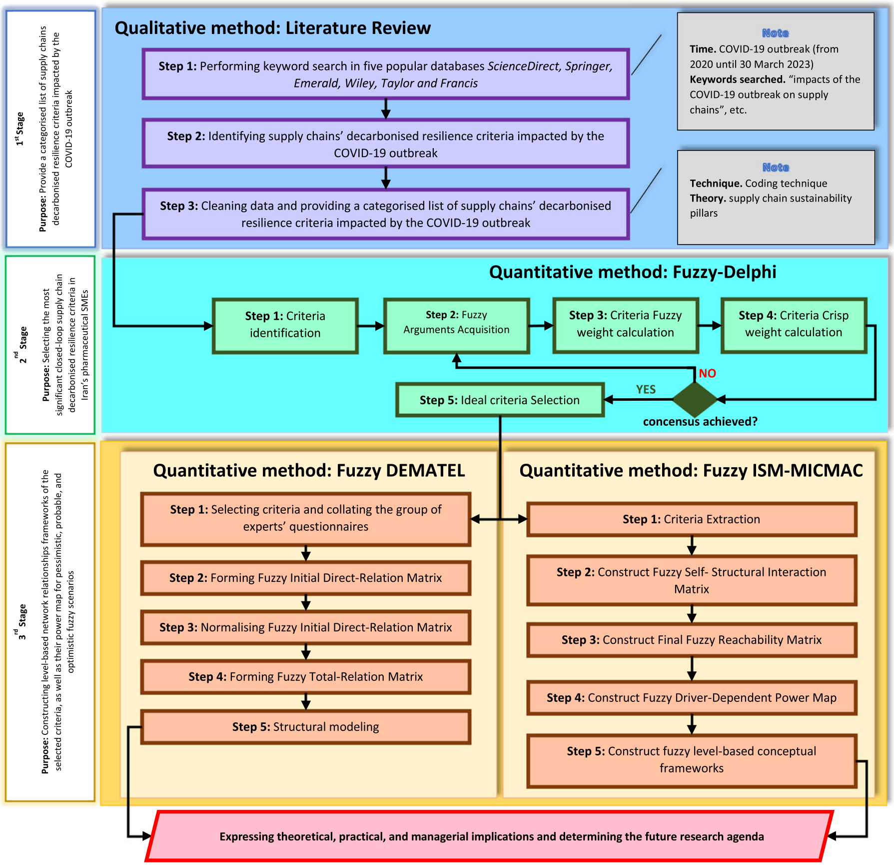


Fig. 2 Research methodology framework

Table 4 Experts profile

Age	Education	Expertise	Experience	Area
40^S	MSc	Supply chain	5	I
50^S	MSc	Industrial Engineering	25	I
40^S	PhD	Industrial Engineering	15	A
40^S	PhD	Operations Management	10	I
40^S	PhD	Supply Chain	15	A
40^S	PhD	Supply Chain	15	A
40^S	PhD	Operations Management	15	A
50^S	MSc	Industrial Engineering	30	A
40^S	MSc	Supply Chain	20	I
40^S	PhD	Operations Research	10	A

I industry, *A* academia

this end, Snowball sampling, a non-probability sampling technique, was applied. According to this pattern, ten experts participated in this research since it is a fast and cost-effective method of finding reliable and liable samples. The expert qualifications and their profile are presented in Table 4.

The experts (i) were at least 30 years old, (ii) had at least three years of managerial experience, (iii) had been the central decision-makers of pharmaceutical SC SMEs for at least four years, (iv) were familiar with closed-loop decarbonised resilient SC management concepts (i.e. attending relevant courses or workshops), and (v) had a university qualification degree of at least master degree in engineering or management. Furthermore, one academic professional (Associate Professor) attended these sessions with each expert (research team members) to facilitate the data-gathering process. These academic experts were SC management, operations management, operations research, and industrial engineering professionals.

In this line, structured questionnaires and in-depth online interviews were used in two stages. To prepare the experts, each questionnaire was emailed one week before participating in each online session. In the 2nd stage, after 15 min of briefing from the scholars, each expert spent close to an hour filling out the online Fuzzy-Delphi structured questionnaire, see Appendix A. Next, another online structured questionnaire including two parts of F-DEMATEL and ISM-MICMAC was prepared to collect data for the 3rd stage. To this end, after a 30 min briefing by the group of scholars, a 6 h online expert session took place on two different days, each including 3 h.

Preliminaries The fuzzy set theory was introduced by Zadeh in 1965 to represent the degree of elements belonging to particular sets. The membership function is an essential component of each fuzzy set. Generally, a specific membership function represents fuzziness in a particular fuzzy set toward a unique model performance (Arslan & Kaya, 2001). Hence, there are various membership functions with distinct curves. The three most popular curves are triangular, trapezoidal, and Gaussian (Rutkowska, 2016). There needs to be a meticulous procedure for selecting the membership functions. Nonetheless, some criteria were suggested by recent scholars to do so, including being in the yield of 0 and 1, problem size and type, data distribution, complexity (computational time, memory used), and experts' experience (Sadollah, 2018).

With this in mind, the Gaussian membership function is useful for specifying fuzzy sets due to the curve's smoothness and nonzero points. However, it was mainly used when there were some priorities on the membership function shapes, for instance, stemming from histograms on specimens. Besides, triangular and trapezoidal membership functions were recommended for employment in simple problems without the abovementioned considerations (like this research) (Hameed, 2011). Several scholars have compared system responses resulting from triangular and trapezoidal membership functions. They suggest that the triangular membership function prevails (Zhao et al., 2002). A comprehensive comparison of either membership function, illustrated in Table 5, helped the researchers select the triangular membership function.

This research problem supported the use of a triangular membership function. A symmetric membership function could be shaped in which the peak point was recognisable. However, the support points were not diagnosed. Moreover, the usefulness of this curve was confirmed by experts and previous research (Mahdiraji et al., 2023). Above all, it is simple to use, fast for calculation and requires a low memory size (Princy & Dhenakaran, 2016). Interestingly, the triangular membership function illustrates fuzzy numbers instead of fuzzy intervals (Sadollah, 2018).

Fuzzy numbers are a specific type of fuzzy set. In contrast to classical logic, each number has an approximate value in fuzzy logic. A Triangular Fuzzy Number (TFN) can be displayed as a triplet $\widetilde{A} = (l, m, u)$ where l, m, and u denote the lower (or minimum values), medium (or the most probable values), and upper (or maximum values) bounds of TFN $\widetilde{A}$, respectively, which are crisp and real numbers ($l \leq m \leq u$). The membership function of a TFN can be expressed as below. Not that, when $l = m = u$, the TFN is transferred to a crisp number.

$$\mu_{\widetilde{a}}(x) = \begin{cases} 0 & x < l \\ \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0 & x > u \end{cases} \tag{1}$$

Assume $\widetilde{A}_1 = (l_1, m_1, u_1)$ and $\widetilde{A}_2 = (l_2, m_2, u_2)$ are any two TFNs and $\lambda \geq 0$, then the operations of TFNs can be defined as below.

$$\tilde{A}_1 \oplus \tilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

$$\tilde{A}_1 \ominus \tilde{A}_2 = (l_1 - u_2, m_1 - m_2, u_1 - l_2) \tag{3}$$

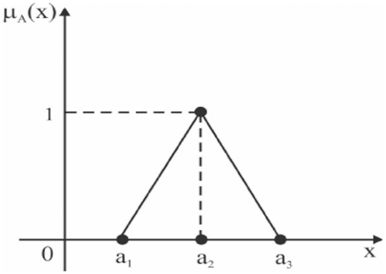
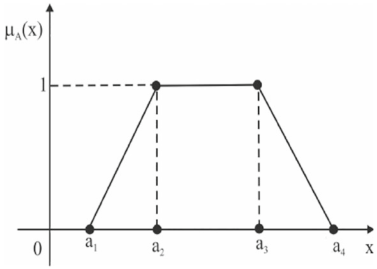
$$\tilde{A}_1 \otimes \tilde{A}_2 = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \tag{4}$$

$$\widetilde{A}_1 \oslash \widetilde{A}_2 = (l_1/u_2, m_1/m_2, u_1/l_2) \tag{5}$$

$$\lambda \odot \widetilde{A} = \begin{cases} (\lambda l, \lambda m, \lambda u) \\ (\lambda u, \lambda m, \lambda l) \end{cases} \tag{6}$$

Fuzzy-Delphi Fuzzy-Delphi is a group knowledge acquisition method used to acquire the most reliable consensus of a group of expert opinions through intensive questionnaires and controlled feedback to legitimise the research methodology. This quantitative method has widely been used to screen key items. Accordingly, based on experts' opinions, the Fuzzy-Delphi method was chosen to screen or finalise the important pharmaceutical CLSC resilience criteria impacted by the COVID-19 outbreak. The steps are explained as follows (Amoozad Mahdiraji et al., 2020).

Table 5 Comparison of triangular and trapezoidal membership functions

Comparison indices	Membership functions	
	Triangular	Trapezoidal
Function	$\mu_{\tilde{A}}(x) = \begin{cases} 0 x < \alpha_1 \\ \frac{x-\alpha_1}{\alpha_2-\alpha_1} \alpha_1 \le x \le \alpha_2 \\ \frac{\alpha_3-x}{\alpha_3-\alpha_2} \alpha_2 \le x \le \alpha_3 \\ 0 x > \alpha_3 \end{cases}$	$\mu_{\tilde{A}}(x) = \begin{cases} 0 x < \alpha_1 \\ \frac{x-\alpha_1}{\alpha_2-\alpha_1} \alpha_1 \le x \le \alpha_2 \\ 1 \alpha_2 \le x \le \alpha_3 \\ \frac{\alpha_4-x}{\alpha_4-\alpha_3} \alpha_3 \le x \le \alpha_4 \\ 0 x > \alpha_4 \end{cases}$
Shape		
Advantage	Simple to implement, Fast for computation, Space simplicity (low memory size and operation time), It is superior to any other membership function in several recent cases	Simple to implement, Causing system response as good as triangular membership function
Disadvantage	Fixed shape	Space complexity (high memory size and operation time), Fixed shape
Where to use	Symmetric membership function, The peak point is known	Asymmetric membership function, The support points are known

Step 1 Criteria identification Different methods can be applied to identify criteria, including literature review, case study, survey, etc. Hence, the output of the literature review section, a categorised list of SCs resilience criteria impacted by the COVID-19 outbreak, was employed as an input set of the fuzzy-Delphi algorithm.

Step 2 Fuzzy Arguments Acquisition Firstly, ten experts were invited to evaluate the importance degree of 17 extracted criteria in Iranian pharmaceutical SMEs by a five-point linguistic term {Very high, High, Moderate, Low, Very low}. Afterwards, the acquired linguistic terms were transformed into the corresponding TFNs {(0.9,1.0,1.0), (0.7,0.9,1.0), (0.3,0.5,0.7), (0,0.1,0.3), (0, 0,0.1)} (Kumar et al., 2019).

Step 3 Criteria Fuzzy weight In this step, the acquired fuzzy information was aggregated by a simple average. Assume the TFN $\widetilde{Z}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ to be the j^{th} criteria assessed by the i^{th} expert, then the fuzzy weight of the criteria $\widetilde{W}_j = \left(l_j, m_j, u_j\right)$ is calculated as follows.

$$\widetilde{W}_j = \frac{\sum_{i=1}^{n} \widetilde{Z}_{ij}}{n} = \left(\frac{\sum_{i=1}^{n} l_{ij}}{n}, \frac{\sum_{i=1}^{n} m_{ij}}{n}, \frac{\sum_{i=1}^{n} u_{ij}}{n}\right) \tag{7}$$

where $i = 1, 2, 3, \ldots, n = 10$ and $j = 1, 2, 3, \ldots, m = 17$.

Step 4 Criteria Crisp weight With the aid of the most popular defuzzification technique, Center of Gravity (CoG), the criteria crisp weight S_j is measured as follows.

$$x_j^1 = \frac{\left(l_j + m_j + u_j\right)}{3}; x_j^2 = \frac{\left(l_j + 2m_j + u_j\right)}{4}; x_j^3 = \frac{\left(l_j + 4m_j + u_j\right)}{6} \tag{8}$$

$$S_j = max\left\{x_j^1, x_j^2, x_j^3\right\} \tag{9}$$

In this step, the consensus of experts was also tested by measuring the standard deviation of the crisp weights (S_j). The consensus is attained if the standard deviation is less than 0.2; otherwise, the process is repeated from step 2.

Step 5 Ideal criteria Selection Finally, the most significant criteria were selected by comparing the criteria crisp weight with a threshold value α via the below rule. Note that α was set at 0.6 according to the experts' unanimous decision.

$$\begin{cases} if\, S_j \geq \alpha, then\ j^{th}\ selected, \\ if\, S_j < \alpha, then\ j^{th}\ removed \end{cases}$$

F-DEMATEL method DEMATEL is a well-suited method to analyse the cause-and-effect relationship among criteria. As such, DEMATEL assisted us in tackling a decision-making dilemma when an effect has multiple causes or vice versa. Besides, it provides visual and numerical advantages for visualising the intensity of the relations and their importance with the aid of graph theories and matrix computation (Kumar & Dixit, 2018). The details are explained as follows (Mahdiraji et al., 2021).

Step 1 Determine criteria and acquire the group experts' assessment First, the criteria were identified via a mixed method of SLR and Fuzzy-Delphi. Later, ten experts were again invited to determine the different degrees of "influence" between criteria by a nine-point linguistic term *{Very very high, High, Very high, Nearly high, Neither high nor low, Nearly low, Low, Very low, Very very low}*. To this end, Pairwise Comparisons (PWC) were performed based on the experts' opinions.

Step 2 Forming Fuzzy Initial Direct-Relation Matrix In this step, the linguistic terms of PWC were converted into the corresponding TFNs {(9,9,9), (7,8,9), (6,7,8), (5,6,7), (4,5,6), (3,4,5), (2,3,4), (1,2,3), (1,1,1)} (Lee et al., 2008). Each TFN $\widetilde{E}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ measures the direct relations between two criteria, such as E_i and E_j. A simple average (Eq.10) was then applied to aggregate all experts' viewpoints.

$$\widetilde{d}_{ij} = \frac{\sum_{k=1}^{K} \widetilde{E}_{ij}^{k}}{K} = \left(\frac{\sum_{k=1}^{K} l_{ij}^{k}}{K}, \frac{\sum_{k=1}^{K} m_{ij}^{k}}{K}, \frac{\sum_{k=1}^{K} u_{ij}^{k}}{K} \right) \tag{10}$$

where $\widetilde{E}_{ij}^{k} = \left(l_{ij}^{k}, m_{ij}^{k}, u_{ij}^{k}\right)$ is the fuzzy evaluation of the k^{th} expert. The fuzzy initial direct-relation matrix D for n criteria $E_1, E_2, \ldots, E_n$ is an $n \times n$ matrix as follows.

$$\widetilde{D} = \begin{bmatrix} 0 & \cdots & \widetilde{d}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{d}_{n1} & \cdots & 0 \end{bmatrix} \tag{11}$$

Step 3 Normalising Fuzzy Initial Direct-Relation Matrix The normalised fuzzy initial direct-relation matrix was measured as follows, where $\widetilde{n}_{ij} = \frac{\widetilde{d}_{ij}}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} u_{ij}}$.

$$\tilde{N} = \begin{bmatrix} \tilde{n}_{11} & \cdots & \tilde{n}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{n}_{n1} & \cdots & n_{nn} \end{bmatrix} \tag{12}$$

Step 4 Forming Fuzzy Total-Relation Matrix Deficiently, several scholars who have employed F-DEMATEL mainly applied defuzzification in this step to produce quantifiable results in crisp logic. Recently, Yaftiyan et al., (2023) generated a solution to avoid defuzzification and depict results also in fuzzy logic. They constructed a total-relation matrix for each bound of TFNs (instead of a defuzzified value) located in $\widetilde{N}$. Hence, three total-relation matrices were formed. Each one belonged to one of the TFNs bounds. Accordingly, the fuzzy total-relation matrix $\widetilde{T}$ of this research was calculated as follows.

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \cdots & \tilde{t}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \cdots & \tilde{t}_{nn} \end{bmatrix} = \lim_{\omega \to \infty} \left(\tilde{N}^{1} \oplus \tilde{N}^{2} \oplus \ldots \oplus \tilde{N}^{\omega} \right) \tag{13}$$

where $\widetilde{t}_{ij} = \left(l_{ij}^{t}, m_{ij}^{t}, u_{ij}^{t}\right)$ and is measured as follows.

$$Matrix\left[l_{ij}^{t}\right] = N_l \times (I - N_l)^{-1} \tag{14}$$

$$Matrix\left[m_{ij}^{t}\right] = N_m \times (I - N_m)^{-1} \tag{15}$$

$$Matrix\left[u_{ij}^{t}\right] = N_u \times (I - N_u)^{-1} \tag{16}$$

where I is a unit matrix and N_l, N_m and N_u are $n \times n$ matrices with entries from the lower, middle, and upper bounds of TFN of N matrix, respectively.

Step 5 Structural modeling Firstly, three scenarios related to three acquired total-relation matrices were defined. (i) Pessimistic scenario (or lower bound) by high uncertainty and vagueness where negative senses result from less foreseeability. (ii) Probable scenario (or middle bound) by mediating a range of uncertainty and vagueness where anticipation could be performed but restricted by some lack of conviction. (iii) Optimistic scenario (or upper bound) by low-level uncertainty and vagueness. Accordingly, positive viewpoints exist due to more predictability. Next, the causal network relationship frameworks were formed for three scenarios. To this end, three binary relationship matrices for pessimistic, probable, and optimistic scenarios were created by comparing the elements of $\left[l_{ij}^t\right]$, $\left[m_{ij}^t\right]$ and $\left[u_{ij}^t\right]$ with three distinct threshold values v_l, v_m and v_u, which are equal to their upper quartile (Q_3). For instance, in the pessimistic scenario, if the relationship between the criterion i and j ($\widetilde{l}_{ij}^t$) is higher than or equal to v_l, then $\widetilde{l}_{ij}^t$ is replaced with 1; otherwise, it is replaced with 0. Number 1 shows a connection arrow from criterion i to j in those frameworks. Afterwards, $\left(\widetilde{D}_i + \widetilde{R}_j\right)$ and $\left(\widetilde{D}_i - \widetilde{R}_j\right)$ were determined, where $\widetilde{D}_i$ and $\widetilde{R}_j$ denote the sum of rows and columns of the matrix $\widetilde{T}$, respectively. While $\left(\widetilde{D}_i + \widetilde{R}_j\right)$ illustrates the importance of criteria i, $\left(\widetilde{D}_i - \widetilde{R}_j\right)$ illustrates the net effect of criteria i.

F-ISM-MICMAC method The ISM technique transforms unclear, poorly articulated mental models into visible and well-defined conceptual models by programming an algorithm with MICMAC analysis (Kumar & Dixit, 2018). As a further advantage, the ISM-MICMAC algorithm checks the validity of the questionnaire by the experts and avoids the inconsistency problems coping with methods, e.g. DEMATEL (Nasrollahi et al., 2021). Details are described below (Yaftiyan et al., 2023).

Step 1 Criteria Extraction The extracted criteria in step 1 of F-DEMATEL were used in this step.

Step 2 Construct Fuzzy Self-Structural Interaction Matrix (FSSIM) The relationship between every two criteria and its significant degree was assessed based on ten experts' opinions via the ISM questionnaire. To this end, five-point linguistic terms {Extremely Impressive (EI), Highly influenced (HI), Nearly Influenced (NI), Meagerly influenced (MI), and No relation (NR)}, along with the following five rules were employed to construct FSSIM.

1. *V* (or *A*) together with *EI*, *HI*, *NI*, *MI*, if criteria (i) leads to criteria (j) (or vice versa),
2. *X* together with *EI*, *HI*, *NI*, *MI*, if criteria (i) and criteria (j) both lead to each other,
3. *O* together with *NR* if there is no relationship between criteria (i) and criteria (j).

Step 3 Construct a Final Fuzzy Reachability Matrix (FFRM) The following rules transform FSSIM into the Initial Fuzzy Reachability Matrix (IFRM).

1. If (i,j) in the FSSIM has a value of *"V"* (or *"A"*) together with *EI, HI, NI, MI,* then (i,j) in the IFRM gets the values of *EI, HI, NI, MI* (or *"NR"*) and (j,i) scores *"NR"* (or *EI, HI, NI, MI)*;
2. If (i,j) in the FSSIM draw *"X"* together with *EI, HI, NI, MI*, both (i,j) and (j,i) in the IFRM score *EI, HI, NI, MI*;
3. If (i,j) in the FSSIM has *"O"*, both (i,j) and (j,i) in the IFRM obtain *"NR"*.

Afterwards, the acquired linguistic terms were converted to the equivalent TFNs {(0.9,1.0,1.0), (0.7,0.9,1.0), (0.3,0.5,0.7), (0,0.1,0.3), (0,0,0.1)} (Kumar et al., 2019). Subsequently, an aggregated IFRM ($\widetilde{R}$) was computed using the arithmetic mean.

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{r}_{n1} & \cdots & r_{nn} \end{bmatrix} = \begin{bmatrix} \left(\tilde{r}_{11}^l, \tilde{r}_{11}^m, \tilde{r}_{11}^u\right) & \cdots & \left(\tilde{r}_{1n}^l, \tilde{r}_{1n}^m, \tilde{r}_{1n}^u\right) \\ \vdots & \ddots & \vdots \\ \left(\tilde{r}_{n1}^l, \tilde{r}_{n1}^m, \tilde{r}_{n1}^u\right) & \cdots & \left(\tilde{r}_{nn}^l, \tilde{r}_{nn}^m, \tilde{r}_{nn}^u\right) \end{bmatrix} \tag{17}$$

In addition, similar to the fourth step of F-DEMATEL, the authors avoided defuzzification and formed IFRM for each bound of TFNs in $\widetilde{R}$. Three defined scenarios of the fifth step of F-DEMATEL were conceptually applied here. Accordingly, the IFRM was formed for pessimistic $\widetilde{R}_l$, probable $\widetilde{R}_m$, and optimistic $\widetilde{R}_u$ conditions as follows:

$$\widetilde{R}_l = \begin{bmatrix} \widetilde{r}^l_{11} & \cdots & \widetilde{r}^l_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{r}^l_{n1} & \cdots & \widetilde{r}^l_{nn} \end{bmatrix}, \widetilde{R}_m = \begin{bmatrix} \widetilde{r}^m_{11} & \cdots & \widetilde{r}^m_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{r}^m_{n1} & \cdots & \widetilde{r}^m_{nn} \end{bmatrix}, \widetilde{R}_u = \begin{bmatrix} \widetilde{r}^u_{11} & \cdots & \widetilde{r}^u_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{r}^u_{n1} & \cdots & \widetilde{r}^u_{nn} \end{bmatrix} \tag{18}$$

Then, three binary relationship matrices for pessimistic, probable, and optimistic scenarios were constructed by comparing the elements of $\widetilde{R}_l, \widetilde{R}_m, \widetilde{R}_u$ with three distinct threshold values t_l, t_m and t_u, which are equal to their upper quartile (Q_3). For instance, in the pessimistic scenario, if the relationship between the criteria i and j ($\widetilde{r}^l_{ij}$) is higher than or equal to t_l, then $\widetilde{r}^l_{ij}$ obtains 1; otherwise, 0. Besides, the transitivity rule, "if criteria A is related to criteria B and criteria B is related to criteria C, then criteria A is logically related to criteria C" was checked by MATLAB to validate experts' opinions. For possible inconsistencies, a revision was applied to the IFRM by replacing (1^*) instead of zero, and three reliable matrices, namely FFRM, were constructed for further investigations.

Step 4 Construct a Fuzzy Driver-Dependent Power Map (FDDPM) This step is related to fuzzy MICMAC analysis. The fuzzy driver power of criteria i, $DRP(i)$ and fuzzy dependence power of criteria j, $DEP(j)$ were measured for each scenario as follows:

$$DRP(i) = \sum_{j=1}^{n} a_{ij}, DEP(j) = \sum_{i=1}^{n} a_{ij} i = j = 1, 2, \ldots, n \tag{19}$$

where a_{ij} denotes the value of the FFRM. Based on values of $DRP(i)$ and $DEP(j)$, then three Fuzzy Power Maps (FPMs) were designed. Accordingly, a classification of criteria into four groups, namely: dependent (low DRP and high DEP), driver (high DRP and low DEP), linkage (high DRP and high DEP), and autonomous (low DRP and low DEP), was extracted.

Step 5 Construct fuzzy level-based conceptual frameworks To level the criteria, it is required to identify three sets of reachability (or output), antecedent (or input), and common criteria i. The list of criteria affected by the criteria i forms the output set. The list of criteria that affect the criteria i forms the input set. The common set for criteria i shows the list of reachable and antecedent criteria. If common and antecedent sets are equal for criteria i, it is considered high-level criteria and deleted from the FFRM. This process was repeated for each scenario until all criteria were levelled (Mohit & Sadeghi, 2021).

4 Results

The SLR embedded with a coding technique identified a categorised list of 17 decarbonised resilient CLSC criteria impacted by COVID-19. Later, that general list, presented in Table 2, was specialised for Iran's pharmaceutical SMEs. Next, a fuzzy-Delphi analysis was performed, and the results are included in Table 6. According to the experts' unanimous decision, the threshold value alpha (α) was set at 0.6. Since the standard deviation of crisp weights (0.151) was below 0.2, the consensus of opinions was accomplished in the first round, and the algorithm stopped.

Consequently, the specialised category of decarbonised resilient CLSC criteria impacted by COVID-19 included four categories and 13 criteria in Iran's pharmaceutical SMEs, as shown in Fig. 3.

Table 6 Fuzzy-Delphi results

Criteria	Fuzzy weight	Crisp weight	A/R	Criteria	Fuzzy weight	Crisp weight	A/R
T	**(0.74, 0.9, 0.97)**	**0.89**	**A**	**POP**	**(0.46, 0.63, 0.77)**	**0.63**	**A**
F	**(0.72, 0.89, 0.97)**	**0.88**	**A**	**EP**	**(0.74, 0.9, 0.97)**	**0.89**	**A**
TCs	**(0.76, 0.91, 0.97)**	**0.90**	**A**	**W**	**(0.52, 0.63, 0.72)**	**0.63**	**A**
SBC	**(0.64, 0.81, 0.91)**	**0.80**	**A**	LWB	(0.33, 0.5, 0.67)	0.50	R
LTs	**(0.7, 0.88, 0.97)**	**0.87**	**A**	**TAs**	**(0.44, 0.6, 0.74)**	**0.60**	**A**
RMM	**(0.55, 0.72, 0.84)**	**0.71**	**A**	**MRI**	**(0.46, 0.62, 0.75)**	**0.62**	**A**
TandL	**(0.7, 0.86, 0.94)**	**0.85**	**A**	**CRI**	**(0.48, 0.6, 0.7)**	**0.60**	**A**
LM	(0.41, 0.56, 0.7)	0.56	R	CGDP	(0.37, 0.52, 0.66)	0.52	R
				PSs	(0.32, 0.46, 0.61)	0.46	R

A accept, *R* reject

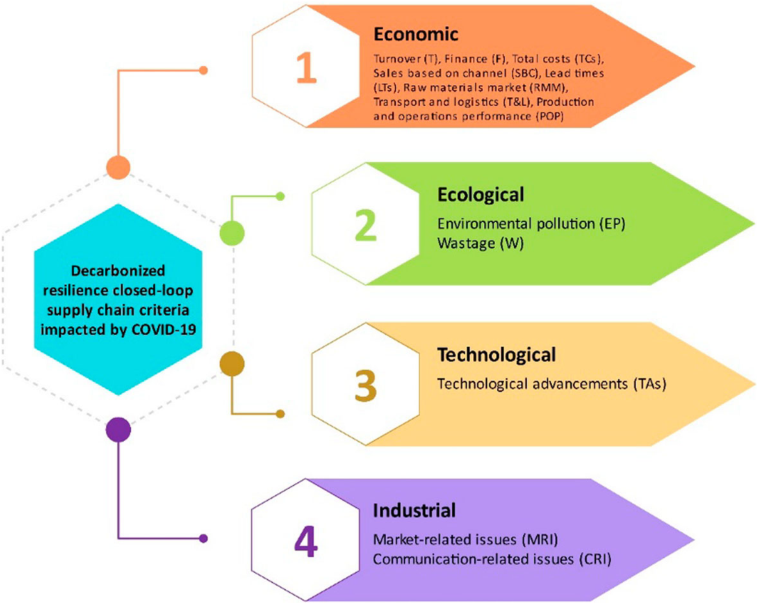


Fig. 3 A specialised category of decarbonised resilient CLSC criteria impacted by COVID-19

Table 7 F-DEMATEL results

	T	F	TCs	SBC	LTs	RMM	TandL	POP	EP	W	TAs	MRI	CRI
Pessimistic Scenario													
D_i	0.91	0.99	1.24	1.26	1.49	1.69	1.4	1.3	0.63	1.33	2.1	2.25	1.7
R_j	1.74	1.6	1.88	1.35	1.39	0.56	1.74	2.02	1.59	1.82	0.8	0.67	1.1
D_i+R_j	2.65	2.6	3.12	2.61	2.88	2.25	3.14	3.32	2.22	3.15	3	2.92	2.7
D_i-R_j	**-0.8**	**-0.6**	**-0.6**	**-0.1**	0.1	1.13	**-0.34**	**-0.7**	**-1**	**-0.5**	1.3	1.58	0.6
Type	E	E	E	E	C	C	E	E	E	E	C	C	C
Probable Scenario													
D_i	1.34	1.44	1.7	1.7	2	2.27	1.81	1.82	1.12	1.77	2.8	2.86	2.3
R_j	2.33	2.22	2.39	1.9	1.95	0.91	2.35	2.61	2.14	2.36	1.2	0.98	1.5
D_i+R_j	3.67	3.65	4.09	3.6	3.95	3.19	4.16	4.43	3.26	4.13	4	3.84	3.8
D_i-R_j	**-1**	**-0.8**	**-0.7**	**-0.2**	0.04	1.36	**-0.54**	**-0.8**	**-1**	**-0.6**	1.5	1.89	0.8
Type	E	E	E	E	C	C	E	E	E	E	C	C	C
Optimistic Scenario													
D_i	2.01	2.12	2.41	2.39	2.78	3.17	2.44	2.61	1.87	2.46	3.7	3.8	3.3
R_j	3.24	3.16	3.17	2.74	2.82	1.44	3.28	3.52	2.97	3.2	1.9	1.45	2.2
D_i+R_j	5.25	5.28	5.58	5.13	5.6	4.61	5.72	6.13	4.84	5.66	5.6	5.25	5.4
D_i-R_j	**-1.2**	**-1**	**-0.8**	**-0.4**	**-0**	1.73	**-0.83**	**-0.9**	**-1.1**	**-0.8**	1.9	2.34	1.1
Type	E	E	E	E	E	C	E	E	E	E	C	C	C

Henceforth, these criteria were employed as an input set of F-DEMATEL and F-ISMMICMAC to analyse (i) cause-and-effect, (ii) driving and dependence power, (iii) causal network relationships and (iv) level-based frameworks. To this end, as explained in Sect. 3, F-DEMATEL was initially conducted stage by stage. The threshold values v_l, v_m and v_u were determined in order of 0.153, 0.195 and 0.258. As a result, F-DEMATEL outputs for three scenarios are illustrated in Table 7 (E: Effect, C: Cause).

Considering the cause-effect matrix, 13 criteria were divided into cause-and-effect groups from three viewpoints, see Fig. 4. As illustrated in Fig. 4, causes (MRI, RMM, TAs, CRI, LTs) and effects (EP, SBC, F, T, TCs, TandL, W, POP) in a pessimistic scenario were analogous to the most probable. However, with a slight difference, LTs were transferred to the effect group in the optimistic view. Nonetheless, each criterion's intensity and degree of influence were undeniably different in each mood. Overall, T, TCs, SBC, RMM, W, MRI, and TAs experienced descending importance from pessimistic to optimistic. On the opposite side, F, LTs, TandL, EP, and CRI demonstrated an ascending orientation in this path. Exclusively, POP was the most important criterion with the highest sum of D_i and R_j in all three conditions.

Considering three binary-relation matrices of F-DEMATEL, three causal network relationship frameworks were also mapped for each scenario, see Fig. 5.

As indicated in Fig. 5, the criteria of economic and industrial categories had internal relations in all conditions. For instance, MRI often impacts CRI. Interestingly, the industrial class affects the economic category in all moods. Moreover, the influence of TAs on ecological and economic categories is undeniable. Subsequently, F-ISMMICMAC was progressively performed following five steps explained in the methodology section. As a result, FFRM for each of the three scenarios, as well as three sets of reachability, antecedent and common, along with level, dependence and driver power for each criterion, are demonstrated in Table 8.

Taking into consideration each criterion's driving and dependence power, the results of the first two scenarios (pessimistic and most probable) are the same. Hence, two power

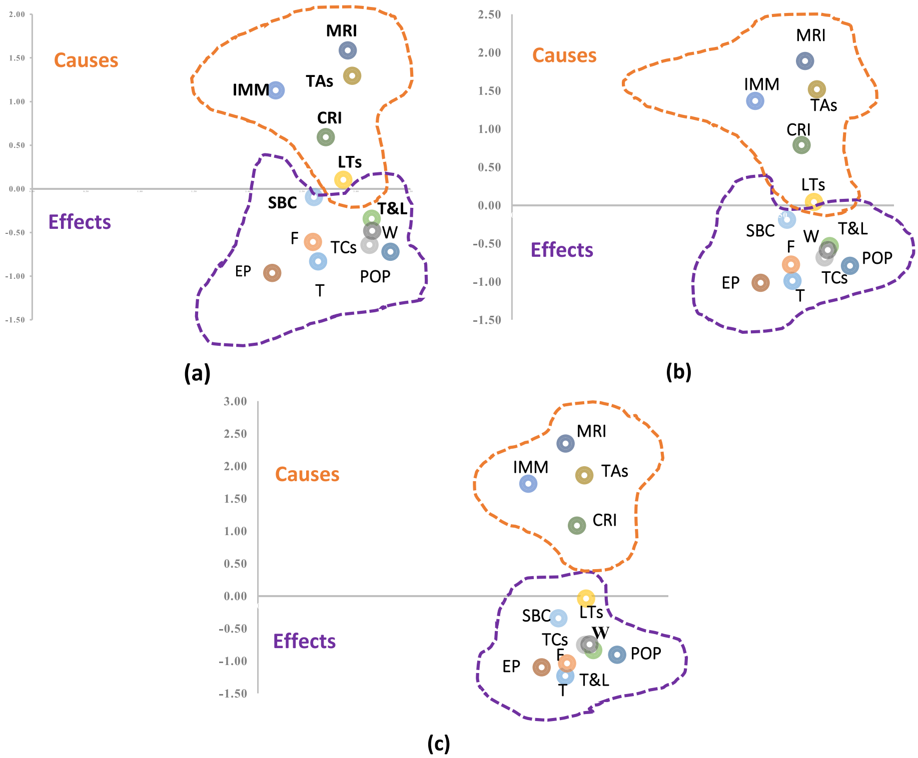


Fig. 4 Cause and effect diagram in the **a** pessimistic, **b** most probable and **c** optimistic moods

maps were mapped, see Fig. 6. As indicated by Fig. 6, from pessimistic and probable points of view, 13 criteria were divided into three classes independent (TAs, CRI, MRI, RMM), linkages (LTs, TandL, W), and dependent (T, F, TCs, SBC, POP, EP). On the other hand, independent (RMM, TAs, MRI) and linkages (T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI) were two groups of optimistic power maps that covered these criteria. Fortunately, the autonomous group was empty in three scenarios. This indirectly authenticates the robustness of fuzzy-Delphi results.

Moreover, Fig. 7 depicts two level-based relationship frameworks for the three scenarios. As demonstrated, 13 criteria were prioritised in six pessimistic and probable scenarios levels. From an optimistic point of view, 13 criteria were prioritised by two levels. The first level included all ecological, economic, and industrial criteria, excluding RMM and MRI. Hence, the second level covered the technological category and criteria of RMM and MRI, which affected all the other ten criteria in the first level.

Thus, the results of F-DEMATEL and F-ISM-MICMAC were compared below from two points of view, i.e. (i) the criteria's cause-and-effect group and (ii) the criteria's interactions. As demonstrated in Fig. 8, in the pessimistic and probable scenario, TAs, RMM, MRI, and CRI were assigned to the cause group, and F, T, TCs, EP, SBC, and POP covered the effect group by the fuzzy method. Moreover, LTs are a cause criterion, and W and TandL are effects in the F-DEMATEL. However, these three criteria had cause-and-effect natures based on F-ISMMICMAC outputs. Regarding the optimistic view, the unity of two applied fuzzy methods

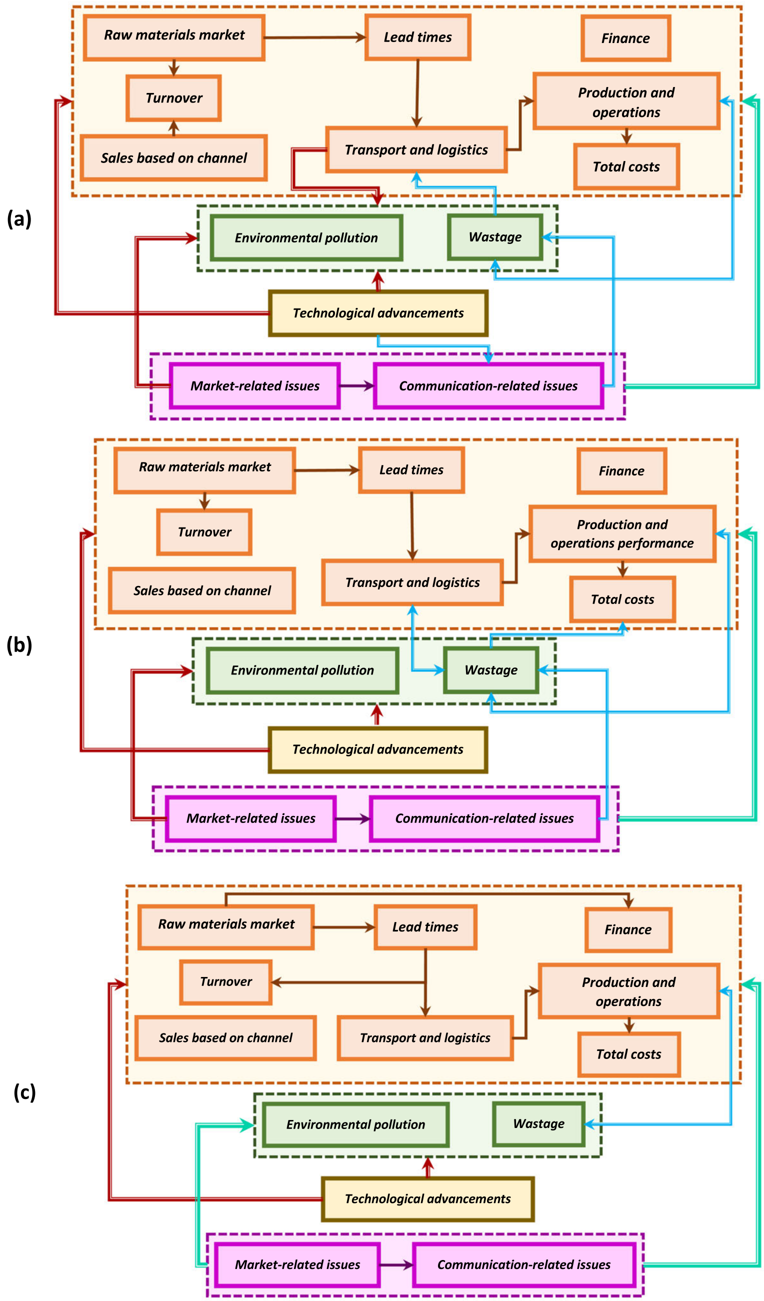


Fig. 5 Causal network relationship framework for the **a** pessimistic, **b** most probable, and **c** optimistic moods

Table 8 Fuzzy ISM-MICMAC results

i/j	T	F	TCs	SBC	LTs	RMM	TandL	POP	EP	W	TAs	MRI	CRI	Reachability set	Antecedent set	Common set	Level	DEP(j)	DRP(i)
Pessimistic Scenario																			
T	1	1	0	0	0	0	0	0	0	0	0	0	0	T	T, TCs, SBC, LTs, RMM, TandL, W, TAs, MRI, CRI	T	2	10	2
F	0	1	0	0	0	0	0	0	0	0	0	0	0	F	T, F, TCs, SBC, LTs, RMM, TandL, W, TAs, MRI, CRI	F	1	11	1
TCs	1	1	1	0	0	0	0	0	0	0	0	0	0	TCs	TCs, LTs, RMM, TandL, POP, W, TAs, MRI, CRI	TCs	3	9	3
SBC	1	1*	0	1	0	0	0	0	0	0	0	0	0	SBC	SBC, LTs, RMM, TandL, W, TAs, MRI, CRI	SBC	3	8	3
LTs	1*	1*	1	1	1	0	1	1	1	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	9
RMM	1*	1*	1	1	1	1	1*	1	1*	1	0	0	0	RMM	RMM	RMM	5	1	10
TandL	1*	1*	1	1*	1	0	1	1	1	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	9
POP	0	0	1*	0	1*	0	1*	1	0	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	5
EP	0	0	0	0	0	0	0	0	1	0	0	0	0	EP	LTs, RMM, TandL, EP, W, TAs, MRI, CRI	EP	1	8	1
W	1	1*	1	1*	1	0	1	1	1*	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	9
TAs	1*	1*	1*	1*	1*	0	1*	1	1	1	1	0	1	TAs	TAs	TAs	6	1	11
MRI	1	1*	1*	1*	1	0	1	1*	1*	1	0	1	0	MRI	MRI	MRI	5	1	10
CRI	1	1*	1*	1*	1	0	1*	1*	1*	1	0	0	1	CRI	TAs, CRI	CRI	5	2	10
Probable Scenario																			
T	1	1	0	0	0	0	0	0	0	0	0	0	0	T	T, TCs, SBC, LTs, RMM, TandL, W, TAs, MRI, CRI	T	2	10	2
F	0	1	0	0	0	0	0	0	0	0	0	0	0	F	T, F, TCs, SBC, LTs, RMM, TandL, W, TAs, MRI, CRI	F	1	11	1
TCs	1	1	1	0	0	0	0	0	0	0	0	0	0	TCs	TCs, LTs, RMM, TandL, POP, W, TAs, MRI, CRI	TCs	3	9	3
SBC	1	1*	0	1	0	0	0	0	0	0	0	0	0	SBC	SBC, LTs, RMM, TandL, W, TAs, MRI, CRI	SBC	3	8	3
LTs	1*	1*	1	1	1	0	1	1	1	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	9
RMM	1*	1*	1	1	1	1	1*	1	1*	1	0	0	0	RMM	RMM	RMM	5	1	10
TandL	1*	1*	1	1*	1	0	1	1	1	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	9
POP	0	0	1*	0	1*	0	1*	1	0	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	5
EP	0	0	0	0	0	0	0	0	1	0	0	0	0	EP	LTs, RMM, TandL, EP, W, TAs, MRI, CRI	EP	1	8	1
W	1*	1*	1	1*	1	0	1	1	1*	1	0	0	0	LTs, TandL, POP, W	LTs, RMM, TandL, POP, W, TAs, MRI, CRI	LTs, TandL, POP, W	4	8	9
TAs	1*	1*	1*	1*	1*	0	1*	1	1	1	1	0	1	TAs	TAs	TAs	6	1	11
MRI	1	1*	1*	1*	1	0	1	1*	1*	1	0	1	0	MRI	MRI	MRI	5	1	10
CRI	1	1*	1*	1*	1	0	1*	1*	1*	1	0	0	1	CRI	TAs, CRI	CRI	5	2	10
Optimistic Scenario																			
T	1	1	1*	1*	1*	0	1	1*	1*	1*	0	0	1	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
F	1*	1	1*	1*	1*	0	1*	1	1	1*	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
TCs	1	1	1	1*	1	0	1	1*	1*	1*	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
SBC	1	1	1*	1	1*	0	1*	1	1	1	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
LTs	1	1	1	1	1	0	1	1	1	1	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
RMM	1*	1*	1	1	1	1	1*	1	1*	1	0	0	1*	RMM	RMM	RMM	2	1	11
TandL	1	1*	1	1	1	0	1	1	1	1	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
POP	1*	1*	1	1*	1*	0	1	1	1	1	0	0	1	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
EP	1*	1*	1*	1*	1*	0	1*	1	1	1*	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
W	1	1	1	1	1	0	1	1	1*	1	0	0	1*	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10
TAs	1	1	1	1	1	0	1	1	1	1	1	0	1	TAs	TAs	TAs	2	1	11
MRI	1	1*	1	1	1	0	1	1	1*	1	0	1	1	MRI	MRI	MRI	2	1	11
CRI	1	1	1*	1*	1	0	1	1	1*	1	0	0	1	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	T, F, TCs, SBC, LTs, RMM, TandL, POP, EP, W TAs, MRI, CRI	T, F, TCs, SBC, LTs, TandL, POP, EP, W, CRI	1	13	10

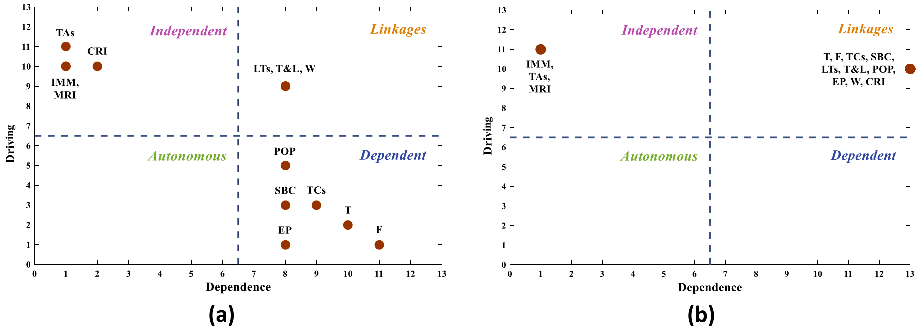


Fig. 6 Power maps for the **a** pessimistic and most probable and **b** optimistic moods

was associated with the cause nature of TAs, RMM, and MRI. F-ISMMICMAC recognised all other criteria with cause-and-effect natures. Nevertheless, CRI is still a cause criterion, and F, T, TCs, SBC, TandL, POP, EP, and W were affected according to F-DEMATEL. Besides, LTs moved to the effect group by this method.

Moreover, the criteria interactions in the pessimistic scenario resulting from F-DEMATEL were the same as the F-ISMMICMAC. Similarly, the most probable interaction framework of F-DEMATEL was analogous to F-ISMMICMAC with a slight difference. Nonetheless, from an optimistic perspective, there were some differences between the two methods. For example, the influence of MRI on CRI was recognised by F-DEMATEL. However, it is ignored by other techniques. This issue oppositely occurs due to the impacts of TAs on CRI. In contrast to F-DEMATEL, F-ISMMICMAC transparently revealed the mutual interaction between ecological and economic categories and the impacts of W on EP.

As expected, F-DEMATEL and F-ISMMICMAC results validated and complemented each other. Apart from slight differences in the results of these two approaches, the cause and effect in F-DEMATEL was conceptually similar to the driving-dependence relationship of F-ISMMICMAC. For instance, in pessimistic and most probable scenarios, LTs were a cause factor by F-DEMATEL (with higher $D_i + R_j$ (3.95) than D_i-R_j (0.04)). Not only was it not a dependent factor by F-ISMMICMAC in these models, but it was also a linkage with higher driving power (9) than dependence power (8). However, in the optimistic scenario, LTs were an effect factor by F-DEMATEL (with higher $D_i + R_j$ (5.06) than D_i-R_j (-0.04)). Although there was still a linkage by F-ISMMICMAC in this scenario, its driving power (10) became lower than the dependence power (13). This logic is also true for other factors. Therefore, the robustness and reliability of F-DEMATEL results were generally confirmed with the F-ISMMICMAC results and vice versa (Kumar & Dixit, 2018). Hence, the integrated results of these methods provided this study with transparent theoretical, practical, and managerial implications. These are discussed in the next section.

5 Discussion and implications

Investigating the integration of three SC paradigms, decarbonised resilient CLSC, in pharmaceutical SMEs of emerging markets is a novel theoretical need of the extant literature (Scala & Lindsay, 2021). This consideration seems necessary in pharmaceutical SMEs as a backbone of healthcare systems, which were greatly hit in the wake of the COVID-19 crisis

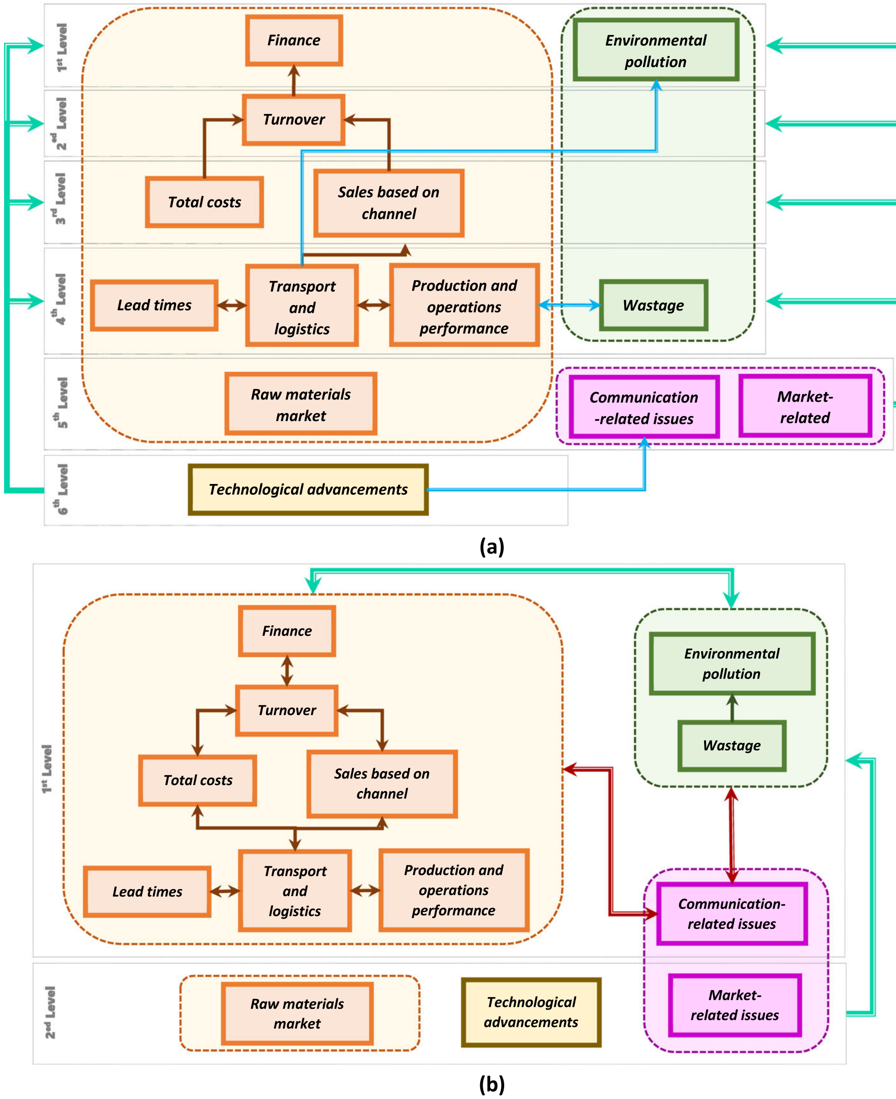


Fig. 7 Level-based relationship frameworks for the **a** pessimistic and most probable and **b** optimistic moods

(Ayati et al., 2020). This is one of the first articles that provides qualitative and quantitative insights into selecting and examining the most significant decarbonised resilient CLSC criteria influenced by COVID-19. A combination of SLR embedded with a coding technique and fuzzy-Delphi method was applied to identify a categorised list of decarbonised resilient CLSC criteria. This list covered the impacts of COVID-19 on SCs and then distinguished a definitive categorised list of criteria for Iran's pharmaceutical SMEs based on experts' opinions. Afterwards, two widely used methods, F-DEMATEL and F-ISMMICMAC, were employed. As another novelty of this paper, the authors avoided defuzzification and analysed the results of these methods in fuzzy logic under three different scenarios, which are useful for

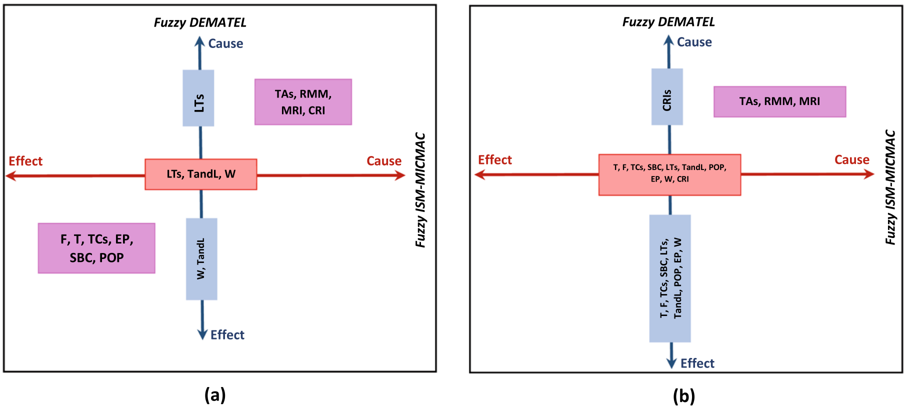


Fig. 8 Comparison of F-DEMATEL and F-ISM-MICMAC cause-and-effect group of **a** pessimistic and probable, and **b** optimistic scenario

deciding different levels of uncertainty and predictability compatible with global disruptions' cycle effects. To our knowledge, proposed integrated frameworks would not only respond to recent papers' recommendations associated with confirming the robustness of their qualitative results but also help future scholars focus on the most significant decarbonised resilient CLSC criteria.

In practice, amidst the pursuit of $\mathbf{RO_1}$ and subsequent discoveries (Tables 1 and 6, and Fig. 3), developing a decarbonised resilient CLSC for pharmaceutical SMEs of emerging economies similar to Iran needs greater attention on the economic (T, F, TCs, SBC, LTs, RMM, TandL, and POP), ecological (EP, and W), industrial (MRI, and CRI), and technological (TAs) categories compared to other ones. Keeping $\mathbf{RO_2}$ and the pursuant findings (e.g. Tables 7 and 8, as well as Figs. 4, 5, 6, 7 and 8) in mind, the importance degree of the abovementioned criteria based on their cause-and-effect (driving or dependence) power, interactions, and level can be analysed during each period of the COVID-19: **phase (a)** advent and outbreak, and **phase (b)** post-COVID-19. Interestingly, the pessimistic and probable scenarios could have coincided with the advent of global disruption and its outbreak time, in which a high level of vagueness and unpredictability is undeniable. Conversely, the optimistic scenario could be imagined as a post-global disruption time when a lower level of uncertainty and high foreseeability is pleasant.

Regarding **phase (a)**, the TAs has the greatest impact with a rating of 11, followed closely by both industrial (MRI and CRI) and economic dimension (RMM), both having a high causality rating of 10. However, the internal system slightly impacts them, ranging from 1 to 2 degrees. These issues align with previous research (Duan et al., 2021), which confirms that the material flow of decarbonised resilient CLSCs is vulnerable and affects capital and information flows. Additionally, several other economic (F, T, TCs, SBC, POP) and ecological criteria (EP) contribute to the effect class with a dependence power ranging from 8 for EP, SBC, and POP to 11 for F. This excludes LTs, TandL, and W, which are considered linkages with striking dependence (8) and driving (9) powers. As for the criteria's level-based interactions in **phase (a)**, the F and EP are the first-level indicators to be remarked on, resulting from a high production, distribution, and retailing rate to meet wide customer demand. Accordingly, T should be attained as the second level, and TCs and SBC are the third-level criteria. Fortunately, wastage is ranked as a fourth criterion due to high sales and low levels of expired products throughout this period. Plus, TandL, LTs, and POP cover the fourth level of interest. This accentuates the marketing weak points of Iran's pharmaceutical SMEs compared to manufacturing and distribution during the pandemic outbreak. Not surprisingly, two external factors (MRI and RMM), plus CRI, have the fifth priority to be counted, followed by TAs in the last level. These reveal that, although TAs, RMM, CRI, and MRI have a paramount impact on the other dimensions, practitioners and policymakers could not extremely manipulate such items in the first phase of global disruptions due to resource (time, cost, workforce, etc.) and communication limitations as well as unprecedented sub-events.

During phase (b), TAs, RMM, and MRI remained independent criteria. However, the influence of RMM and MRI was elevated by one level, reaching 11. Moreover, the importance of these three factors rose to the second tier. This suggests that the period following COVID-19 represented an optimal time for policymakers and SMEs within Iran's pharmaceutical industry to adopt advanced technologies and address deficiencies in marketing materials and products, thereby enhancing decarbonised resilient CLSCs. Notably, another industrial metric (CRI) shifted into the linkage category, exhibiting higher dependency (13) while maintaining the same level of influence (10). This shift highlights the potential for an expansive communication network post-crisis, attributed to the lifting of relationship and trade restrictions. Yet, its role as a causal factor remains substantial. The emphasis on CRI also changed, moving from a higher level of focus in the initial phase to a reduced one in the subsequent phase, indicating an increased need to focus on CRI post-COVID-19 to mend the weakened connections experienced during the outbreak.

Moreover, while LTs, TandL, and W remained classified as linkage criteria, their dependency and driving scores rose from 8 to 13 and from 9 to 10, respectively, positioning them almost as effect criteria in the aftermath of COVID-19. This means that while the demand for certain products, such as vitamin tablets, may remain high post-pandemic due to increased consumer self-awareness, the demand for other products linked to the virus is expected to decline with the lower infection rate. Consequently, an increase in wastage, expired products, and lower-than-planned production and distribution are anticipated in the post-event period. Moreover, their importance has significantly dropped from four during the pandemic to one in the more optimistic scenario, warranting increased focus in such circumstances. This observation similarly applies to the remaining economic (F, T, TCs, SCB, POP) and ecological (EP) dimensions, which shifted from the dependent category to the linkage group, attaining the same cause-and-effect scores as the previously mentioned linkages in the optimistic outlook. Predictably, such significant improvements in their dependency and driving powers enable Finance to retain its top-level status, with others achieving the highest rank. This indicates that the challenges posed by COVID-19, especially regarding liquidity issues like the substantial loans taken, need to be addressed promptly and creatively in the aftermath of the global disruption. Furthermore, Iran's pharmaceutical sector could utilise a detailed framework of interactions among the 13 categorised criteria, as depicted in Fig. 9, where the nature and direction of relationships remain unchanged across different stages of global disruption.

Iran's Pharmaceutical SMEs and the government could harness the direct influence of TAs across all sectors, including economic, ecological, and industrial—particularly CRI during **phase (a)**, when face-to-face interactions were replaced by online communications due to lockdowns. Indeed, new technological solutions could enhance the flow of materials, information, and capital within a closed-loop system. Additionally, the critical role of (W) in driving economic activities, such as POP, is highlighted consistently. However, the advantageous direct impact of diminished W, spurred by increased demand on TandL and TCs, could contribute to economic and transportation efficiencies in **phase (a)**. Nonetheless, managing

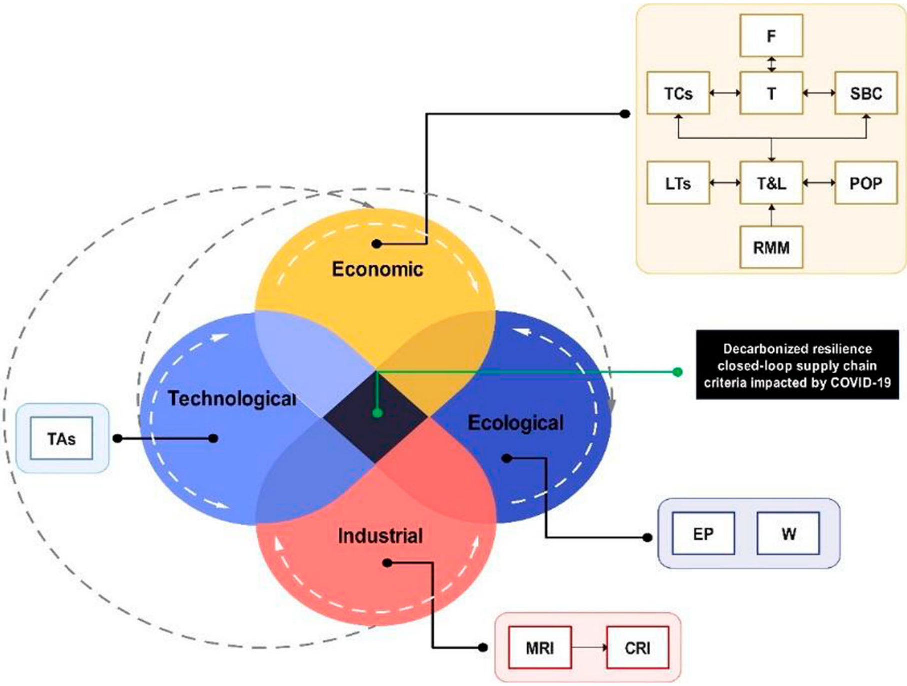


Fig. 9 Comprehensive Framework of decarbonised resilient CLSC criteria impacted by COVID-19

waste becomes a pivotal concern in **phase (b)** with anticipated reduced demand, which could adversely influence EP. Furthermore, the interactions between TandL and EP require careful management in the initial phase. Elevated demand in **phase (a)** and increased waste in **phase (b)** result in greater distribution (transportation) challenges and EP. These challenges could be mitigated by adopting advanced technologies. For instance, facilitating online purchases of products nearing expiration with attractive discounts for consumers could lead to reduced W and EP. Lastly, the complex influence of industrial factors (MRI and CRI) on other areas presents a challenge in the pessimistic scenario. The outbreak of COVID-19 had a significant impact on CRI and MRI (Coopmans et al., 2021), leading to the transformation of COVID-19's propagation effect to all other criteria. Hence, proactive practices are essential to be applied in the **optimistic status** to benefit from MRI and CRI in **phase (a)**. To this end, the pivotal role of TAs such as blockchain, IoT, data analytics, and robotics is acknowledged to provide traceability requirements for visibility and transparency (Burgos & Ivanov, 2021). Moreover, real-time information sharing and trust communication between the SMEs would result in their coevolution by moving from cooperation and collaboration towards co-creation (Duan et al., 2021). These outcomes would lead to CO_2 neutralisation, waste reduction, production and transportation effectiveness and efficiency, short LTs, integration of warehouses, price reduction, and other decarbonised resilient CLSC strategies recommended by scholars (Dorcheh et al., 2021).

To achieve **RO$_3$**, the following managerial countermeasures for Iran's governmental bodies and pharmaceutical SMEs in phases **(a)** and **(b)** using the above-deciphered drawbacks are proposed. In **phase (a)**, regulatory bodies should prioritise industrial criteria (MRI and CRI), which are crucial external factors influencing the remaining categories. To this end, they should (i) launch public awareness campaigns and informative television programmes to enhance consumer awareness and reduce panic purchasing and stockpiling; (ii) provide subsidies to boost consumer buying power; (iii) implement lockdown measures judiciously to maintain local and international communication, as well as access to markets for raw materials and finished goods; and (iv) introduce health and safety measures at customs to facilitate ongoing international trade. Additionally, efforts should be made to address economic (F, RMM, and TandL) and ecological (EP and W) factors by (v) rigorously enforcing a penalty and incentive system to curb hoarding, reduce waste production, and control pollution emissions across the supply chain; (vi) providing a variety of funding options, such as loans, to enhance SME liquidity for essential activities like raw material procurement, manufacturing, distribution, and retailing. Planning, designing, and enforcing a fine and reward system are especially critical in the optimistic scenario. Furthermore, the government is advised to implement two additional strategies in **phase (b)** to address industrial (MRI and CRI) and economic (F) challenges encountered in the initial phase. Firstly, political measures should be considered, such as removing or reducing international sanctions to foster global integration. Secondly, various forms of financial assistance should be offered to increase member capabilities in acquiring advanced technologies related to each supply chain process and mitigate the initial phase's financial shortcomings.

On the other hand, it is recommended that pharmaceutical SMEs adopt the following six measures during **phase (a)**: (i) judiciously manage existing financial resources and utilise funding options provided by governments to enhance financial stability, thereby reducing the risk of insolvency. This also encourages further investment in their ventures. (ii) Employ low-emission drivers to decrease environmental pollution by ensuring the cleaner transportation of raw materials and finished products. (iii) Actively market products that are beneficial to the immune system to boost transactions, such as sales and profit. (iv) Skillfully use online communication platforms for advertising and sales, allowing for strategic decisions regarding SBC in marketing and sales based on online channels. (v) Effectively leverage available TAs to cut costs and enhance productivity. (vi) Wisely utilise the existing broad membership network to foster CRI through collaboration with competitors and consumers, who are key market players during pessimistic times. Notably, the success of SMEs in achieving a decarbonised resilient CLSC amidst global disruption hinges on four actions in **phase (b)** related to industrial (MRI and CRI) and technological TAs aspects, along with one economic SBC factor. These include (i) Developing a comprehensive national and international network of relationships with stakeholders and partners, for instance, through various contracts, to complete the coevolution process, starting with cooperation, then collaboration, and culminating in co-creation. (ii) Equipping factories, businesses, or retail outlets with cutting-edge technologies across different supply chain processes to adopt proactive environmentally friendly practices and enhance productivity and financial capacity. (iii) Designing and extensively using a distinctive, user-friendly online platform for selling products online. (iv) Pursuing internationalisation to expand market reach.

6 Conclusions

To struggle with the triple concerns of climate change, a huge volume of annual waste, and disruptions like the global pandemic, this work mainly emphasises three intertwined SC paradigms, i.e. decarbonised resilient and CLSC. To the best of our knowledge, this is one of the first papers that provided a categorised list of decarbonised resilient CLSC criteria (Table

2) by identifying different impacts of COVID-19 on SCs via an SLR embedded with a coding technique. Moreover, this general list has been contextualised for pharmaceutical SMEs in emerging economies similar to Iran using a quantitative expert-based approach, fuzzy-Delphi. Besides, the finalised categorised list, including four classes and thirteen criteria (Fig. 3), has been evaluated from three perspectives, namely: (i) cause-and-effect group (Figs. 4 and 6), (ii) causal network relationships model (Fig. 5), and (iii) level-based interaction frameworks (Fig. 7). A fuzzy multi-layer decision-making approach, F-DEMATEL and F-ISMMICMAC, has been employed to accomplish this. Innovatively, the final results of this stage have been enriched by a multi-scenario analysis. Furthermore, this article has eventually proposed a comprehensive framework of decarbonised resilient CLSC criteria impacted by COVID-19 (Fig. 9).

Although this research explored and investigated decisional criteria in decarbonised resilient CLSC from different points of view, inevitable limitations still exist. Firstly, fuzzy-delphi might be widely used to specify the general list of research items from the SLR. However, the data it was based on was limited to only ten experts in this research. This issue also occurred in the data-gathering stage of F-DEMATEL and F-ISM-MICMAC. Since this paper was prepared during the COVID-19 outbreak, experts' accessibility was low due to the lockdowns. Hence, employing several distinct future panels with more scholars would lead to more robust results of the applied methodology. Likewise, the practical and managerial implications were limited to a broad case of an emerging economy like that of Iran. Thus, future research should compound a larger and more diverse expert panel worldwide. Secondly, other appropriate data analysis methods, like fuzzy cognitive mapping, could be employed to test the accuracy of these results. Thirdly, other SC paradigms, e.g., sustainable SC, digitalised SC, etc., could be added to the triple themes of this work to gain a more comprehensive framework. Fourthly, the results of this paper were restricted to disruptions only caused by the COVID-19 outbreak; however, other recent disruptions, such as earthquakes and war, could be added to future works. Finally, a policy-making system for Iran's pharmaceutical-decarbonised future scholars could develop resilient CLSC, and the managerial suggestions of this work can be fulfilled step by step.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper. No financial or personal relationships have influenced the work reported in this manuscript.

Appendix A: Fuzzy-Delphi Questionnaire

Dear expert,

Thank you for participating in filling out this questionnaire. A categorised list of **17 criteria associated with decarbonised resilient closed-loop supply chains impacted by**

the COVID-19 outbreak, which were extracted from contemporary literature, are demonstrated in Table 7. Please determine each criterion's "Importance" degree **in Iran's pharma SMEs.** In the last column, you can elect only one linguistic term.

Fuzzy-Delphi questionnaire

Main-category	Decarbonised resilient closed-loop supply chain criteria impacted by the COVID outbreak	Definition	Importance degree of each criterion in Irans pharmaceutical SMEs				
			Very high	High	Moderate	Low	Very low
Economic	Turnover (T)	Reflects a company's sales volume and price per product. It is useful in computing a firm's revenue and profit. Eventually, investment returns can be released to stakeholders.	☐	☐	☐	☐	☐
	Finance (F)	Refers to the firm's liquidity, capacity and capability to repay loans, rent, invoices, trade receivables, etc. By which finance bankruptcy risk can also be predicted.	☐	☐	☐	☐	☐
	Total costs (TCs)	Reflects the firm's total costs, including labour costs, raw material costs, transportation and logistic costs, RandD expenditure and operational costs (manufacturing goods and service providing costs).	☐	☐	☐	☐	☐
	Sales based on channel (SBC)	Recognises sales volume through each existing channel, such as wholesalers, retailers, third parties, and online platforms.	☐	☐	☐	☐	☐
	Lead times (LTs)	Distinguishing SCs cycle time starts with supplying raw materials and ends with products/ service delivery. Thus, operational delays (manufacturing goods/services and delivery delays) can be estimated.	☐	☐	☐	☐	☐
	Raw materials market (RMM)	Highlights concerns related to raw material marketplaces such as accessibility level of high-quality raw materials and suppliers. Which depends on local/global material production and flows.	☐	☐	☐	☐	☐
	Transport and logistics (TandL)	Reflects two controversial SC issues, namely (i) transportation and (ii) inventory. Transportation facilities, mode availability and efficiency, average vehicle utilisation and backlogs relate to the first concept. Moreover, supply and distribution warehouse capacity, utilisation and shortage, inventory availability, and waste level all cover the second term.	☐	☐	☐	☐	☐
	Labor market (LM)	Refers to high-skilled workers recruitment impacted by the labour market issues such as the availability level of permanent, seasonal and family labor.	☐	☐	☐	☐	☐
	Production and operations performance (POP)	Refers to different elements that reveal SC's operational performance level, e.g., business volume and productivity (efficiency and effectiveness) that lead to profitability. In detail, production cycle, capacity and quality (i.e., the volume of finished and defective products, total product backlog, number of non-fulfilled orders, product re-work hours), and service level are all subsets of those indicators.	☐	☐	☐	☐	☐
Ecological	Environmental pollution (EP)	Refers to different types of environmental pollution, e.g., air, water and sound. Nonetheless, the worldwide concern about global	☐	☐	☐	☐	☐

Main-category	Decarbonised resilient closed-loop supply chain criteria impacted by the COVID outbreak	Definition	Importance degree of each criterion in Irans pharmaceutical SMEs				
			Very high	High	Moderate	Low	Very low
		warming highlights air pollution between them. Which mainly results from greenhouse gas and CO_2 emissions.					
	Wastage (W)	Reflects SC's waste management, including expired product reduction and promoting the waste disposal process.	☐	☐	☐	☐	☐
Societal	Labour livelihoods and well-being (LWB)	Reflects job creation concerns and workers psychological and physical needs, including physical and mental health and safety, work-life balance (conflicts within the household), employee morale, fatigue (Gloominess, Depression, Suicidal thoughts, Anxiety, or panic attacks), attending to the workplace (particularly female workers), income satisfaction, foreign labour travel, education filed.	☐	☐	☐	☐	☐
Technological	Technological advancements (TAs)	Indicates the different levels of advanced technology utilisation. These technologies in CLSCs are beyond significant due to materials traceability urgency and minimising cyber-security risks.	☐	☐	☐	☐	☐
Industrial	Market-related issues (MRI)	Refers to different elements related to the marketplace covering market instability, accessibility, and share, competition level, customers purchasing power, demand patterns and market composition (e.g., panic buying and Hoarding), supply and demand fluctuation, the possibility of international trade (import and export volumes), and interest rates.	☐	☐	☐	☐	☐
	Communication-related issues (CRI)	Reflects SC's broad communication network, which can be extended by enhancing the visibility and transparency of real-time information sharing. This leads to more trust within SC partners, increased global trade relationships, establishing interlinkage with competitors and other stakeholders, and preparing communication infrastructure.	☐	☐	☐	☐	☐
	Contributions to GDP (CGDP)	This indicator refers to the degree of importance of an SC's product/service. It can be estimated by recognising how this SC contributes to national economic growth.	☐	☐	☐	☐	☐
	Local/global pricing systems (PSs)	Reveals the type of pricing system (cost-based, perceived value, and market-based pricing) prevalent in any industry.	☐	☐	☐	☐	☐

Appendix B_1: Sample data used in the fuzzy-Delphi method

Criteria / Expert	T	F	TCs	SBC	LTs	RMM	T&L	LM	POP	EP	W	LWB	TAs	MRI	CRI	CGDP	PSs
Expert 1	Very high	High	Very high	Very high	High	High	High	Very high	High	Very high	Very high	Moderate	Moderate	Moderate	High	High	High
Expert 2	Very high	High	Very high	Very high	High	Very high	Very high	High	Very high	Very high	Very high	High	Very high	Very high	Very high	Moderate	Very high
Expert 3	High	High	High	Very high	High	Very high	Very high	Moderate	High	High	Very high	High	Moderate	High	Very high	High	High
Expert 4	High	Very high	High	Moderate	High	Low	High	Very high	High	High	Very high	High	Very high	High	Very high	High	Moderate
Expert 5	High	High	High	Moderate	Moderate	High	Moderate	High	Moderate	High	Low	Moderate	Moderate	High	High	High	Moderate
Expert 6	Moderate	Very high	Very high	High	Very high	Moderate	Very high	Low	Low	Moderate	Low	Moderate	High	Moderate	Low	Low	Low
Expert 7	Very high	High	Moderate	Moderate	High	Moderate	Moderate	Low	Low	Very high	Very high	Low	Low	Moderate	Very low	Moderate	Moderate
Expert 8	High	Moderate	High	High	Very high	High	High	Moderate	High	High	Low	Low	High	High	High	Moderate	Low
Expert 9	High	Very high	Very high	High	High	Moderate	High	Low	Moderate	High	Low	Low	Low	Very low	Low	Very low	Low
Expert 10	Very high	High	Very high	High	High	High	Very high	Moderate	Moderate	Very high	High	Moderate	Moderate	Low	Low	Very low	Very low

Appendix B_2: Sample data used in the F-DEMATEL method

i/j	T	F	TCs	SBC	LTs	RMM	T&L	POP	EP	W	TAs	MRI	CRI
T	-	very very high	very very low	very very low	very low	very very low	nearly high	high	very low	very low	nearly high	nearly low	nearly low
F	very very low	-	very very low	very low	very low	very very low	nearly high	very high	nearly low	nearly low	very very high	low	nearly high
TCs	very very high	very very high	-	nearly low	nearly low	very very low	very high	high	nearly high	nearly high	nearly high	very very low	very very low
SBC	very very high	very high	nearly high	-	nearly high	very very low	nearly high	nearly high	very very high	very very high	very low	very very low	very very low
LTs	high	nearly high	very very high	very high	-	very low	very very high	very very high	nearly high	very high	very very low	very very low	high
RMM	high	nearly high	very very high	high	very very high	-	high	very very high	nearly low	very very high	very low	high	nearly low
T&L	nearly high	low	very very high	very high	very very high	very low	-	very very high	very very high	very very high	very very low	very very low	very very low
POP	nearly high	nearly high	very very high	very low	nearly high	very low	nearly high	-	very very high	very very high	very low	very very low	very high
EP	high	nearly high	very high	low	very low	very low	very low	very low	-	very low	very low	very low	very low
W	very high	nearly low	very very high	very very high	nearly high	nearly low	very very high	very very high	very low	-	very very low	very very low	very low
TAs	nearly high	nearly low	very high	very high	very very high	very high	very very high	very very high	very very high	very very high	-	very high	very very high
MRI	very very high	very high	very very high	very very high	very high	very high	very very high	very very high	very very high	very very high	nearly high	-	very very high
CRI	high	very high	high	very high	very high	very low	nearly high	very very high	nearly high	very very high	nearly low	high	-

Appendix B$_3$: Sample data used in the F-ISMMICMAC method

i/j	T	F	TCs	SBC	LTs	RMM	T&L	POP	EP	W	TAs	MRI	CRI
T	-	X ☐ V ☒ A ☐ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Meagerly Influenced (MI) Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Nearly Influenced (NI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Meagerly Influenced (MI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Meagerly Influenced (MI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Extremely Impressive (EI)
F	-	-	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Meagerly Influenced (MI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Meagerly Influenced (MI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Nearly Influenced (NI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Meagerly Influenced (MI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Nearly Influenced (NI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)
TCs	-	-	-	X ☐ V ☐ A ☐ O ☒ No relation (NR)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Meagerly Influenced (MI) Nearly Influenced (NI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Nearly Influenced (NI)
SBC	-	-	-	-	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Meagerly Influenced (MI)	X ☐ V ☒ A ☐ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Nearly Influenced (NI)
LTs	-	-	-	-	-	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Extremely Impressive (EI) Nearly Influenced (NI)	X ☐ V ☒ A ☐ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Meagerly Influenced (MI) Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Extremely Impressive (EI)
RMM	-	-	-	-	-	-	X ☐ V ☒ A ☐ O ☐ Nearly Influenced (NI)	X ☐ V ☒ A ☐ O ☐ Extremely Impressive (EI)	X ☐ V ☒ A ☐ O ☐ Meagerly Influenced (MI)	X ☐ V ☒ A ☐ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Meagerly Influenced (MI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI)	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI)
T&L	-	-	-	-	-	-	-	X ☒ V ☐ A ☐ O ☐ Extremely Impressive (EI) Highly Influenced (HI)	X ☐ V ☒ A ☐ O ☐ Extremely Impressive (EI)	X ☒ V ☐ A ☐ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)
POP	-	-	-	-	-	-	-	-	X ☐ V ☒ A ☐ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Highly Influenced (HI)	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI)
EP	-	-	-	-	-	-	-	-	-	X ☐ V ☐ A ☐ O ☒ No relation (NR)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Meagerly Influenced (MI)	X ☐ V ☐ A ☒ O ☐ Meagerly Influenced (MI)
W	-	-	-	-	-	-	-	-	-	-	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)	X ☐ V ☐ A ☒ O ☐ Extremely Impressive (EI)
TAs	-	-	-	-	-	-	-	-	-	-	-	X ☒ V ☐ A ☐ O ☐ Nearly Influenced (NI) Meagerly Influenced (MI)	X ☐ V ☒ A ☐ O ☐ Extremely Impressive (EI)
MRI	-	-	-	-	-	-	-	-	-	-	-	-	X ☒ V ☐ A ☐ O ☐ Highly Influenced (HI) Nearly Influenced (NI)

Appendix C Sample calculations related to:

Fuzzy-Delphi

Step 3. For j equals 1 in Eq. (7): [Fuzzy weight (0.74,0.90,0.97) located in Table 6 first row and second column]:

$$\widetilde{W}_{j=1} = \frac{\sum_{i=1}^{10} \widetilde{Z}_{i1}}{10} = \left(\frac{\sum_{i=1}^{10} l_{i1}}{10}, \frac{\sum_{i=1}^{10} m_{i1}}{10}, \frac{\sum_{i=1}^{10} u_{i1}}{10} \right)$$

$$\widetilde{W}_1 = \left(\begin{array}{c} \frac{0.9+0.9+0.7+0.7+0.7+0.3+0.9+0.7+0.7+0.9}{10}, \\ \frac{1+1+0.9+0.9+0.9+0.5+0.9+0.9+1+1}{10}, \\ \frac{1+1+1+1+1+1+1+1+1+0.7}{10} \end{array} \right) = (0.74, 0.90, 0.97)$$

Step 4. For *j* equals 1 in Eq. (8): [Crisp weight (0.89) located in Table 6 first row and third column]:

$$x^1_{j=1} = \frac{(l_{j=1} + m_{j=1} + u_{j=1})}{3}; x^2_{j=1} = \frac{(l_{j=1} + 2m_{j=1} + u_{j=1})}{4};$$
$$x^3_{j=1} = \frac{(l_{j=1} + 4m_{j=1} + u_{j=1})}{6}$$
$$x^1_1 = \frac{(0.74 + 0.90 + 0.97)}{3} = 0.87; x^2_1 = \frac{(0.74 + (2 \times 0.90) + 0.97)}{4} = 0.88;$$
$$x^3_1 = \frac{(0.74 + (4 \times 0.90) + 0.97)}{6} = 0.89$$

$$S_{j=1} = max\left\{x^1_{j=1}, x^2_{j=1}, x^3_{j=1}\right\}$$

$$S_1 = max\{0.87, 0.88, 0.89\} = 0.89$$

Sample calculations related to **F-DEMATEL**

Step 3. For i and j equal to 1 and 2, respectively, in $\widetilde{n}_{ij} = \frac{\widetilde{d}_{ij}}{\max\limits_{1\le i\le n} \sum_{j=1}^{n} u_{ij}}$.

$$\widetilde{n}_{12} = \frac{\widetilde{d}_{12}}{\underset{1\le i\le 13}{max} \sum_{j=1}^{13} u_{1j}} = \frac{1}{\underset{1\le i\le 13}{max} \sum_{j=1}^{13} u_{1j}} \times \left(d^l_{12}, d^m_{12}, d^u_{12}\right)$$
$$= \left(\left(n^l_{12} = \frac{1}{\underset{1\le i\le 13}{max} \sum_{j=1}^{13} u_{1j}} \times d^l_{12}\right), \left(n^m_{12} = \frac{1}{\underset{1\le i\le 13}{max} \sum_{j=1}^{13} u_{1j}} \times d^m_{12}\right), \left(n^u_{12} = \frac{1}{\underset{1\le i\le 13}{max} \sum_{j=1}^{13} u_{1j}} \times d^u_{12}\right)\right)$$
$$\widetilde{n}_{12} = \left(\left(n^l_{12} = 9 \times 0.01 = 0.09\right), \left(n^m_{12} = 9 \times 0.01 = 0.09\right), \left(n^u_{12} = 9 \times 0.01 = 0.09\right)\right)$$
$$= (0.09, 0.09, 0.09)$$

Step 4. Total relation matrix for each scenario using Eqs. (14–16):

$$Matrix\left[l^t_{ij}\right] = N_l \times (I - N_l)^{-1} = \begin{bmatrix} 0 & \cdots & 0.03 \\ \vdots & \ddots & \vdots \\ 0.06 & \cdots & 0 \end{bmatrix} \times \left(\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} - \begin{bmatrix} 0 & \cdots & 0.03 \\ \vdots & \ddots & \vdots \\ 0.06 & \cdots & 0 \end{bmatrix}\right)^{-1}$$
$$= \begin{bmatrix} 0 & \cdots & 0.03 \\ \vdots & \ddots & \vdots \\ 0.06 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} 1 & \cdots & -0.03 \\ \vdots & \ddots & \vdots \\ -0.06 & \cdots & 1 \end{bmatrix}^{-1}$$
$$= \begin{bmatrix} 0 & \cdots & 0.03 \\ \vdots & \ddots & \vdots \\ 0.06 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} 1.05 & \cdots & 0.07 \\ \vdots & \ddots & \vdots \\ 0.15 & \cdots & 1.06 \end{bmatrix}$$
$$Matrix\left[l^t_{ij}\right] = \begin{bmatrix} 0.05 & \cdots & 0.07 \\ \vdots & \ddots & \vdots \\ 0.15 & \cdots & 0.06 \end{bmatrix}$$

$$Matrix\left[m_{ij}^{t}\right] = N_m \times (I - N_m)^{-1} = \begin{bmatrix} 0 & \cdots & 0.04 \\ \vdots & \ddots & \vdots \\ 0.07 & \cdots & 0 \end{bmatrix} \times \left(\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} - \begin{bmatrix} 0 & \cdots & 0.04 \\ \vdots & \ddots & \vdots \\ 0.07 & \cdots & 0 \end{bmatrix} \right)^{-1}$$

$$= \begin{bmatrix} 0 & \cdots & 0.04 \\ \vdots & \ddots & \vdots \\ 0.07 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} 1 & \cdots & -0.04 \\ \vdots & \ddots & \vdots \\ -0.07 & \cdots & 1 \end{bmatrix}^{-1}$$

$$= \begin{bmatrix} 0 & \cdots & 0.04 \\ \vdots & \ddots & \vdots \\ 0.07 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} 1.08 & \cdots & 0.10 \\ \vdots & \ddots & \vdots \\ 0.21 & \cdots & 1.09 \end{bmatrix}$$

$$Matrix\left[m_{ij}^{t}\right] = \begin{bmatrix} 0.08 & \cdots & 0.10 \\ \vdots & \ddots & \vdots \\ 0.21 & \cdots & 0.09 \end{bmatrix}$$

$$Matrix\left[u_{ij}^{t}\right] = N_u \times (I - N_u)^{-1} = \begin{bmatrix} 0 & \cdots & 0.05 \\ \vdots & \ddots & \vdots \\ 0.08 & \cdots & 0 \end{bmatrix} \times \left(\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix} - \begin{bmatrix} 0 & \cdots & 0.05 \\ \vdots & \ddots & \vdots \\ 0.08 & \cdots & 0 \end{bmatrix} \right)^{-1}$$

$$= \begin{bmatrix} 0 & \cdots & 0.04 \\ \vdots & \ddots & \vdots \\ 0.07 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} 1 & \cdots & -0.05 \\ \vdots & \ddots & \vdots \\ -0.08 & \cdots & 1 \end{bmatrix}^{-1}$$

$$= \begin{bmatrix} 0 & \cdots & 0.04 \\ \vdots & \ddots & \vdots \\ 0.07 & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} 1.13 & \cdots & 0.15 \\ \vdots & \ddots & \vdots \\ 0.30 & \cdots & 1.15 \end{bmatrix}$$

$$Matrix\left[u_{ij}^{t}\right] = \begin{bmatrix} 0.13 & \cdots & 0.15 \\ \vdots & \ddots & \vdots \\ 0.30 & \cdots & 0.15 \end{bmatrix}$$

Step 5. For i equal to 1 in Table 7

$D_1^l = 0.05 + \cdots + 0.07 = 0.91$
$D_1^m = 0.08 + \cdots + 0.21 = 1.34$
$D_1^u = 0.13 + \cdots + 0.15 = 2.01$

$\left(D_1^l - R_1^l\right) = 0.91 - 1.74 = -0.8$
$\left(D_1^m - R_1^m\right) = 1.34 - 2.33 = -1$
$\left(D_1^u - R_1^u\right) = 2.01 - 3.24 = -1.2$

$R_1^l = 0.05 + \cdots + 0.15 = 1.74$
$R_1^m = 0.08 + \cdots + 0.10 = 2.33$
$R_1^u = 0.13 + \cdots + 0.30 = 3.24$

$\left(D_1^l + R_1^l\right) = 0.91 + 1.74 = 2.65$
$\left(D_1^m + R_1^m\right) = 1.34 + 2.33 = 3.67$
$\left(D_1^u + R_1^u\right) = 2.01 + 3.24 = 5.25$

References

Agarwal, S., Tyagi, M., & Garg, R. K. (2022). Restorative measures to diminish the covid-19 pandemic effects through circular economy enablers for sustainable and resilient supply chain. *Journal of Asia Business Studies, 16*(3), 538–567.

Akbari-Kasgari, M., Khademi-Zare, H., Fakhrzad, M. B., Hajiaghaei-Keshteli, M., & Honarvar, M. (2022). Designing a resilient and sustainable closed-loop supply chain network in copper industry. *Clean Technologies and Environmental Policy, 24*(5), 1553–1580.

Amoozad Mahdiraji, H., Hafeez, K., Kord, H., & Abbasi Kamardi, A. (2020). Analysing the voice of customers by a hybrid fuzzy decision-making approach in a developing country's automotive market. *Management Decision, 60*(2), 399–425.

Arabi, M., & Gholamian, M. R. (2023). Resilient closed-loop supply chain network design considering quality uncertainty: A case study of stone quarries. *Resources Policy, 80*, 103290.

Arslan, A., & Kaya, M. (2001). Determination of fuzzy logic membership functions using genetic algorithms. *Fuzzy Sets and Systems, 118*(2), 297–306.

Ashraf, S., Abdullah, S., Mahmood, T., Ghani, F., & Mahmood, T. (2019). Spherical fuzzy sets and their applications in multi-attribute decision making problems. *Journal of Intelligent and Fuzzy Systems, 36*(3), 2829–2844.

Atanassov, K. (1986). Intuitionistic fuzzy sets. *Fuzzy Sets and Systems, 20*, 87–96.

Ayati, N., Saiyarsarai, P., & Nikfar, S. (2020). Short and long term impacts of COVID-19 on the pharmaceutical sector. *DARU Journal of Pharmaceutical Sciences, 28*(2), 799–805.

Badhotiya, G. K., Soni, G., Jain, V., Joshi, R., & Mittal, S. (2022). Assessing supply chain resilience to the outbreak of COVID-19 in Indian manufacturing firms. *Operations Management Research, 15*(3–4), 1161–1180.

Barneveld, K., Quinlan, M., Kriesler, P., Junor, A., Baum, F., Chowdhury, A., & Rainnie, A. (2020a). The COVID-19 pandemic: Lessons on building more equal and sustainable societies. *The Economic and Labour Relations Review, 31*(2), 133–157.

Belhadi, A., Kamble, S., Jabbour, C., Gunasekaran, A., Ndubisi, N., & Venkatesh, M. (2021). Manufacturing and service supply chain resilience to the COVID-19 outbreak: Lessons learned from the automobile and airline industries. *Technological Forecasting and Social Change, 163*, 120447.

Burgos, D., & Ivanov, D. (2021). Food retail supply chain resilience and the COVID-19 pandemic: A digital twin-based impact analysis and improvement directions. *Transportation Research Part E: Logistics and Transportation Review, 152*, 102412.

Butt, A. (2021). Understanding the implications of pandemic outbreaks on supply chains: An exploratory study of the effects caused by the COVID-19 across four South Asian countries and steps taken by firms to address the disruptions. *International Journal of Physical Distribution and Logistics Management, 52*(4), 370–392.

Cai, M., & Luo, J. (2020). Influence of COVID-19 on the manufacturing industry and corresponding countermeasures from a supply chain perspective. *Journal of Shanghai Jiaotong University (science), 25*(4), 409–416.

Choi, T.-M. (2020). Innovative "bring-service-near-your-home" operations under coronavirus (COVID-19/SARS-CoV-2) outbreak: Can logistics become the Messiah? *Transportation Research Part E: Logistics and Transportation Review, 140*, 101961.

Chowdhury, M., Sarkar, A., Paul, S., & Moktadir, M. (2020). A case study on strategies to deal with the impacts of the COVID-19 pandemic in the food and beverage industry. *Operations Management Research, 15*(1), 166–178.

Chowdhury, P., Paul, S., Kaisar, S., & Moktadir, M. (2021). COVID-19 pandemic related supply chain studies: A systematic review. *Transportation Research Part E: Logistics and Transportation Review, 148*, 102271.

Coopmans, I., Jo, B., Marchand, F., Mathijs, E., Messely, L., Rogge, E., & Wauters, E. (2021). COVID-19 impacts on Flemish food supply chains and lessons for agri-food system resilience. *Agricultural Systems, 190*, 103136.

Cuong, B. C. (2013). Picture fuzzy sets first results. Part 1, Seminar neuro-fuzzy systems with applications, Preprint 03/2013, Institute of Mathematics, Hanoi.

Dorcheh, F., Razavi Hajiagha, S., Rahbari, M., Jafari-Sadeghi, V., & Amoozad Mahdiraji, H. (2021). Identifying, analysing and improving red meat supply chain strategies considering the impact of COVID-19 pandemic: A hybrid SWOT-QSPM approach in an emerging economy. *British Food Journal, 123*(12), 4194–4223.

Duan, W., Ma, H., & Xu, D. (2021). Analysis of the impact of COVID-19 on the coupling of the material flow and capital flow in a closed-loop supply chain. *Advances in Production Engineering and Management, 16*(1), 5–22.

Garousi Mokhtarzadeh, N., Amoozad Mahdiraji, H., Jafari-Sadeghi, V., Soltani, A., & Abbasi Kamardi, A. (2020). A product-technology portfolio alignment approach for food industry: A multi-criteria decision making with z-numbers. *British Food Journal, 122*(12), 3947–3967.

Ghadir, A. H., Vandchali, H. R., Fallah, M., & Tirkolaee, E. B. (2022). Evaluating the impacts of COVID-19 outbreak on supply chain risks by modified failure mode and effects analysis: A case study in an automotive company. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04651-1

Ghomi-Avili, M., Naeini, S. G. J., Tavakkoli-Moghaddam, R., & Jabbarzadeh, A. (2018). A fuzzy pricing model for a green competitive closed-loop supply chain network design in the presence of disruptions. *Journal of Cleaner Production, 188*, 425–442.

Gupta, R., Rathore, B., & Biswas, B. (2022). Impact of COVID-19 on supply chains: Lessons learned and future research directions. *International Journal of Quality and Reliability Management, 39*(10), 2400–2423.

Hameed, I. A. (2011). Using Gaussian membership functions for improving the reliability and robustness of students' evaluation systems. *Expert Systems with Applications, 38*(6), 7135–7142.

Hao J., Bose B.K. (2002). Evaluation of membership functions for fuzzy logic controlled induction motor drive. In: 28th Annual IEEE conference of the industrial electronics society, Sevilla, Spain.

Herold, D., Nowicka, K., Pluta-Zaremba, A., & Kummer, S. (2021). COVID-19 and the pursuit of supply chain resilience: Reactions and "lessons learned" from logistics service providers (LSPs). *Supply Chain Management, 26*(6), 702–714.

Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research Part E: Logistics and Transportation Review, 136*, 101922.

Ivanov, D., & Das, A. (2020). Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: A research note. *International Journal of Integrated Supply Management, 13*(1), 90–102.

Karunathilake, K. (2020). Positive and negative impacts of COVID-19, an analysis with special reference to challenges on the supply chain in South Asian countries. *Journal of Social and Economic Development, 23*(Suppl 3), 568–581.

Khan, S. A. R., & Ponce, P. (2022). Investigating the effects of the outbreak of COVID-19 on perishable food supply chains: An empirical study using PLS-SEM. *The International Journal of Logistics Management, 33*(3), 773–795.

Kumar, A., & Dixit, G. (2018). An analysis of barriers affecting the implementation of e-waste management practices in India: A novel ISM-DEMATEL approach. *Sustainable Production and Consumption, 14*, 36–52.

Kumar, A., Zavadskas, E., Mangla, S., Agrawal, V., Sharma, K., & Gupta, D. (2019). When risks need attention: Adoption of green supply chain initiatives in the pharmaceutical industry. *International Journal of Production Research, 57*(11), 3554–3576.

Kumar, P., & Kumar Singh, R. (2022). Strategic framework for developing resilience in agri-food supply chains during COVID-19 pandemic. *International Journal of Logistics Research and Applications, 25*(11), 1401–1424.

Love, D., Allison, E., Asche, F., Belton, B., Cottrell, R., Froehlich, H., & Zhang, W. (2021). Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. *Global Food Security, 28*, 100494.

Luckstead, J., Nayga, R. M., Jr., & Snell, H. A. (2021). Labor issues in the food supply chain amid the COVID-19 pandemic. *Applied Economic Perspectives and Policy, 43*(1), 382–400.

Magableh, G. M. (2021). Supply chains and the COVID-19 pandemic: A comprehensive framework. *European Management Review, 18*(3), 363–382.

Mahdiraji, H. A., Govindan, K., Yaftiyan, F., Garza-Reyes, J. A., & Hajiagha, S. H. R. (2023). Unveiling coordination contracts' roles considering circular economy and eco-innovation toward pharmaceutical supply chain resiliency: Evidence of an emerging economy. *Journal of Cleaner Production, 382*, 135135.

Mahdiraji, H. A., Yaftiyan, F., Abbasi-Kamardi, A., & Garza-Reyes, J. A. (2022). Investigating potential interventions on disruptive impacts of industry 4.0 technologies in circular supply chains: Evidence from SMEs of an emerging economy. *Computers and Industrial Engineering, 174*, 108753.

Mehrjerdi, Y. Z., & Shafiee, M. (2021). A resilient and sustainable closed-loop supply chain using multiple sourcing and information-sharing strategies. *Journal of Cleaner Production, 289*, 125141.

Mishra, R., Singh, R. K., & Subramanian, N. (2022). Impact of disruptions in agri-food supply chain due to COVID-19 pandemic: Contextualised resilience framework to achieve operational excellence. *The International Journal of Logistics Management, 33*(3), 926–954.

Mohit, H., & Sadeghi, J. K. (2021). Data mining application for crisis management during major disruptions, association for information systems, AIS Electronic Library (AISeL), ICIS (2021), TREOs. 74.

Mondal, A., & Roy, S. (2021). Multi-objective sustainable opened-and closed-loop supply chain under mixed uncertainty during COVID-19 pandemic situation. *Computers and Industrial Engineering, 159*, 107453.

Narasimha, P., Jena, P., & Majhi, R. (2021). Impact of COVID-19 on the Indian seaport transportation and maritime supply chain. *Transport Policy, 110*, 191–203.
Nasrollahi, M., Fathi, M., Sobhani, S., Khosravi, A., & Noorbakhsh, A. (2021). Modelling resilient supplier selection criteria in desalination supply chain based on fuzzy DEMATEL and ISM. *International Journal of Management Science and Engineering Management, 16*(4), 264–278.
Nikian, A., Khademi Zare, H., Lotfi, M. M., & Fallah Nezhad, M. S. (2022). Redesign of a sustainable and resilient closed-loop supply chain network under uncertainty and disruption caused by sanctions and COVID-19. *Operations Management Research, 16*(2), 1019–1042.
Paul, A., Shukla, N., & Trianni, A. (2023). Modelling supply chain sustainability challenges in the food processing sector amid the COVID-19 outbreak. *Socio-Economic Planning Sciences, 87*, 101535.
Paul, S. K., Chowdhury, P., Chakrabortty, R. K., Ivanov, D., & Sallam, K. (2022). A mathematical model for managing the multi-dimensional impacts of the COVID-19 pandemic in supply chain of a high-demand item. *Annals of Operations Research*. https://doi.org/10.1007/s10479-022-04650-2
Pereira, M. M. O., Silva, M. E., & Hendry, L. C. (2021). Supply chain sustainability learning: The COVID-19 impact on emerging economy suppliers. *Supply Chain Management: An International Journal, 26*(6), 715–736.
Poursoltan, L., Seyed-Hosseini, S. M., & Jabbarzadeh, A. (2021). Green closed-loop supply chain network under the COVID-19 pandemic. *Sustainability, 13*(16), 9407.
Princy, S., & Dhenakaran, S. S. (2016). Comparison of triangular and trapezoidal fuzzy membership function. *Journal of Computer Science and Engineering, 2*(8), 46–51.
Queiroz, M. M., Ivanov, D., Dolgui, A., & Fosso Wamba, S. (2022). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research, 319*(1), 1159–1196.
Razavi Hajiagha, S., Alaei, S., Amoozad Mahdiraji, H., & Yaftiyan, F. (2021). International collaboration formation in entrepreneurial food industry: Evidence of an emerging economy. *British Food Journal, 124*(7), 2012–2038.
Roy, S. (2020). Economic impact of Covid-19 pandemic. *A Preprint*, 1–29.
Rukasha, T., Nyagadza, B., Pashapa, R., & Muposhi, A. (2021). Covid-19 impact on Zimbabwean agricultural supply chains and markets: A sustainable livelihoods perspective. *Cogent Social Sciences, 7*(1), 1928980.
Rutkowska, A. (2016). Influence of membership function's shape on portfolio optimization results. *Journal of Artificial Intelligence and Soft Computing Research, 6*(1), 45–54.
Sadollah, A. (2018). Introductory chapter: which membership function is appropriate in fuzzy system? In: *Fuzzy logic based in optimization methods and control systems and its applications*. IntechOpen.
Sajjad, A. (2021). The COVID-19 pandemic, social sustainability and global supply chain resilience: A review. *Corporate Governance, 21*(6), 1142–1154.
Scala, B., & Lindsay, C. (2021). Supply chain resilience during pandemic disruption: Evidence from healthcare. *Supply Chain Management, 26*(6), 672–688.
Scopus. (2021, October 15). Retrieved from analyze search results.
Senapati, T., & Yager, R. R. (2020). Fermatean fuzzy sets. *Journal of Ambient Intelligence and Humanized Computing, 11*, 663–674.
Sharma, J., Tyagi, M., & Bhardwaj, A. (2021). Exploration of COVID-19 impact on the dimensions of food safety and security: A perspective of societal issues with relief measures. *Journal of Agribusiness in Developing and Emerging Economies, 11*(5), 452–471.
Sharma, M., Luthra, S., Joshi, S., & Kumar, A. (2020). Developing a framework for enhancing survivability of sustainable supply chains during and post-COVID-19 pandemic. *International Journal of Logistics Research and Applications, 25*(4–5), 433–453.
Shen, Z. M., & Sun, Y. (2021). Strengthening supply chain resilience during COVID-19: A case study of JD.com. *Journal of Operations Management, 69*(3), 359–383.
Singh, S., Kumar, R., Panchal, R., & Tiwari, M. (2021). Impact of COVID-19 on logistics systems and disruptions in food supply chain. *International Journal of Production Research, 56*(7), 1993–2008.
Torra, V. (2010). Hesitant fuzzy sets. *International Journal of Intelligent Systems, 25*, 529–539.
Trivedi, A., Jakhar, S. K., & Sinha, D. (2021). Analyzing barriers to inland waterways as a sustainable transportation mode in India: A DEMATEL-ISM based approach. *Journal of Cleaner Production, 295*, 126301.
Udofia, E., Adejare, B., Olaore, G., & Udofia, E. (2021). Supply disruption in the wake of COVID-19 crisis and organisational performance: Mediated by organisational productivity and customer satisfaction. *Journal of Humanities and Applied Social Sciences, 3*(5), 319–338.
Van Barneveld, K., Quinlan, M., Kriesler, P., Junor, A., Baum, F., Chowdhury, A., & Rainnie, A. (2020b). The COVID-19 pandemic: Lessons on building more equal and sustainable societies. *The Economic and Labour Relations Review, 31*(2), 133–157.

Velayutham, A., Rahman, A., Narayan, A., & Wang, M. (2021). Pandemic turned into pandemonium: The effect on supply chains and the role of accounting information. *Accounting, Auditing and Accountability Journal, 34*(6), 1404–1415.
World Health Organization. (2021). Retrieved from WHO Coronavirus (COVID-19) Dashboard: https://covid19.who.int/.
Xu, S., Zhang, X., Feng, L., & Yang, W. (2020). Disruption risks in supply chain management: A literature review based on bibliometric analysis. *International Journal of Production Research, 58*(11), 3508–3526.
Xu, Z., Pokharel, S., & Elomri, A. (2023). An eco-friendly closed-loop supply chain facing demand and carbon price uncertainty. *Annals of Operations Research, 320*(2), 1041–1067.
Yaftiyan, F., Rassaf, M., Borchalouei, M. N., & Ghahremani, H. (2023). Unveiling factors propelling start-ups towards entrepreneurial internationalisation: A fuzzy multi-layer decision-making approach. In: *Decision-making in international entrepreneurship: Unveiling cognitive implications towards entrepreneurial internationalisation* (pp. 137–165). Emerald Publishing Limited.
Yager, R. R. (2013). Pythagorean fuzzy subsets. In: *2013 joint IFSA world congress and NAFIPS annual meeting (IFSA/NAFIPS)* (pp. 57–61). IEEE.
Yavari, M., & Zaker, H. (2019). An integrated two-layer network model for designing a resilient green-closed loop supply chain of perishable products under disruption. *Journal of Cleaner Production, 230*, 198–218.
Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*(3), 338–356.
Zahraee, S. M., Shiwakoti, N., & Stasinopoulos, P. (2022). Agricultural biomass supply chain resilience: COVID-19 outbreak vs. sustainability compliance, technological change, uncertainties, and policies. *Cleaner Logistics and Supply Chain, 4*, 100049.

Authors and Affiliations

Hannan Amoozad Mahdiraji[1] · Fatemeh Yaftiyan[2] · Jose Arturo Garza-Reyes[3,4] · Seyed Hossein Razavi Hajiagha[5] · Yigit Kazancoglu[6]

✉ Hannan Amoozad Mahdiraji
h.m.amoozad@bham.ac.uk

Fatemeh Yaftiyan
Fatemeh.yaftiyan@ut.ac.ir

Jose Arturo Garza-Reyes
J.Reyes@derby.ac.uk

Seyed Hossein Razavi Hajiagha
h.razavi@khatam.ac.ir

Yigit Kazancoglu
yigit.kazancoglu@yasar.edu.tr

1 Birmingham Business School, University of Birmingham, Birmingham, UK

2 Faculty of Management, University of Tehran, Tehran, Iran

3 Centre for Supply Chain Improvement, University of Derby, Kedleston Road Campus, Derby DE22 1GB, UK

4 Department of Management Studies, Graphic Era Deemed to Be University, Dehradun, India

5 Faculty of Management and Finance, Khatam University, Tehran, Iran

6 Department of Logistics Management, Yasar University, Izmir, Turkey