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Designing an Intelligent Sustainable Supply Chain Model in the Gas Industry Using Industry 4.0 Technologies under Conditions of Uncertainty

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ABSTRACT

With the intensification of environmental pressures, volatility in energy markets, and increasing complexity in operational environments, gas industry supply chains are confronted with high levels of uncertainty and multidimensional risks. In this context, the simultaneous adoption of sustainability-oriented approaches and Industry 4.0 technologies can be considered a key strategy for enhancing efficiency, resilience, and competitiveness across the supply chain. The purpose of this study is to design and conceptualize an intelligent sustainable supply chain model for the gas industry, with an emphasis on Industry 4.0 technologies under conditions of uncertainty. The present research is applied in nature and adopts a mixed-methods (qualitative–quantitative) methodological approach. In the first stage, a systematic literature review was conducted using the PRISMA protocol to identify the initial dimensions and indicators. Subsequently, a fuzzy Delphi method was employed to validate and refine the indicators through the participation of academic and industry experts. In the next step, the weighting of criteria and sub-criteria under uncertainty was performed using the fuzzy Best–Worst Method. To reduce model complexity and focus on key factors, hierarchical clustering was applied, and the selected criteria were entered into the causal relationship analysis phase. At this stage, a fuzzy cognitive map was utilized to analyze the degree of influence and dependence among factors and to identify the system's driving variables. The results indicate that factors such as commitment to environmental sustainability, investment in intelligent technologies, and the strategic alignment of sustainability with Industry 4.0 exhibit the highest levels of centrality and driving power in enhancing the sustainable performance of the gas supply chain. The findings provide a systematic and decision-support framework for managers in the gas industry and can serve as a basis for policymaking and strategic planning aimed at developing intelligent and sustainable supply chains under conditions of uncertainty.

Keywords: *Sustainable supply chain; Industry 4.0; Uncertainty; Fuzzy multi-criteria decision-making; Fuzzy cognitive map*

1. Introduction

Sustainable supply chain management (SSCM) has moved from a peripheral corporate initiative to a strategic and institutional imperative as firms face intensifying environmental constraints, tighter regulatory regimes, and heightened stakeholder scrutiny across global value chains. Recent evidence indicates that SSCM research and practice are simultaneously expanding in scope and becoming more differentiated across world regions, reflecting differences in regulatory maturity, industrial structure, and technology readiness (Tsai et al., 2021). In parallel, operational environments have become more turbulent due to demand volatility, supply disruptions, geopolitical instability, and rapid technological shifts, forcing organizations to reconsider how sustainability objectives can be achieved without eroding cost efficiency, delivery performance, and service continuity. This tension is particularly salient in energy-intensive and high-risk sectors, where environmental externalities, safety requirements, and infrastructure complexity interact to create multi-dimensional uncertainty and systemic risk.

Within this landscape, Industry 4.0 has emerged as a foundational enabler for redesigning supply chains toward higher transparency, agility, and adaptive decision-making. The digitalization of manufacturing and logistics through cyber–physical systems, the Internet of Things (IoT), advanced analytics, artificial intelligence (AI), robotics, cloud/edge architectures, and blockchain is reshaping information flows and coordination mechanisms, transforming supply chains from linear pipelines into data-rich socio-technical systems (Haleem et al., 2023; Syed et al., 2024). Research streams emphasize that Industry 4.0 is not simply a collection of technologies but a transformation logic that alters sensing, interpretation, and response cycles in supply chain processes, strengthening visibility, accelerating feedback, and enabling real-time or near-real-time control (Bayanati, 2024; Dias et al., 2022). From a strategic viewpoint, the digital transformation of supply chains is increasingly framed as an Industry 4.0–driven reconfiguration of capabilities, governance, and inter-organizational collaboration, particularly in manufacturing supply networks under competitive and operational pressures (Khan & Emon, 2025; Singh, 2025).

At the same time, a core managerial challenge is how Industry 4.0 can be operationalized to advance sustainability outcomes rather than merely improving speed and efficiency. A growing body of work argues that sustainability performance gains depend on aligning digital technologies with environmental and social priorities, and on embedding them into organizational routines, metrics, and decision rights (Jiang et al., 2024; Lu et al., 2024). In this view, Industry 4.0 strengthens SSCM when it supports lifecycle thinking, emissions monitoring, waste minimization, responsible sourcing, and social sustainability governance through integrated data and accountability structures (Jiang et al., 2024; Ülkü et al., 2024). In humanitarian and socially oriented contexts, digital technologies are likewise reported to enhance sustainability-oriented objectives by improving traceability, coordination, and responsiveness under resource constraints, while requiring careful consideration of ethical and operational trade-offs (Ülkü et al., 2024).

A particularly influential theoretical lens for explaining performance heterogeneity in Industry 4.0–enabled SSCM is the dynamic capability perspective. Studies highlight that digital technologies deliver superior outcomes when organizations build dynamic capabilities that sense disruptions, seize opportunities, and reconfigure resources across the supply chain network (Lu et al., 2024). Empirical evidence further suggests that supply chain dynamic capabilities contribute to financial performance, and that Industry 4.0 technologies can moderate or amplify these relationships by strengthening the speed and quality of reconfiguration decisions (Eslami et al., 2024). Related work emphasizes that Industry 4.0 technology capabilities can act through resilience and incremental innovation pathways, indicating serial mediation structures in which technology capability builds resilience mechanisms that, in turn, enable adaptive improvement trajectories (Nakandala et al., 2023). These findings collectively imply that a sustainable and intelligent supply chain model must integrate both technological resources and organizational/relational capabilities.

Resilience has become a central construct at the intersection of Industry 4.0 and sustainable supply chains because sustainability objectives are difficult to maintain under disruption without robust recovery and adaptation capacity. Reviews underline the intertwined nature of supply chain resilience, Industry 4.0, and investment decisions, noting that technology adoption and resilience-building often reinforce each other but also compete for scarce capital and managerial attention (Al-Banna et al., 2023). Forward-looking analyses further indicate that Industry 4.0 will continue to enhance resilience over the coming decade, but the magnitude and direction of effects depend on how technologies are deployed, governed, and scaled across supply networks (Birkel & Müller, 2025). Comprehensive syntheses also propose strategic roadmaps for leveraging digital transformation to build resilience, stressing that resilience is not automatic; it emerges when technologies are connected to coordinated redesign of processes, data standards, and cross-firm collaboration (Ghobakhloo et al., 2025). At the operational level, visibility is repeatedly identified as a key mechanism through which Industry 4.0 strengthens resilience, particularly under environmental dynamism, by enabling faster detection of disruptions and more accurate coordination responses (Jain et al., 2024). Evidence from healthcare supply chains during crisis conditions similarly points to resilience abilities as a mediating mechanism linking Industry 4.0 adoption to performance, indicating the importance of capability development rather than purely technological acquisition (Chatterjee et al., 2023; Tortorella et al., 2024).

Another major development is the convergence of circular economy principles with Industry 4.0 in SSCM. Circular manufacturing supply chains require complex coordination of reverse flows, remanufacturing, recycling, and product-service strategies, which intensify information requirements and systemic interdependencies. Dynamic capability research shows that Industry 4.0 can enable circular manufacturing supply chains through enhanced sensing, flexible resource orchestration, and resilience-building, thereby supporting both circularity and stability under disruption (Chari et al., 2022). Conceptual and empirical work similarly argues that integrating circular economy strategies with Industry 4.0 can improve sustainability performance when organizations develop the capabilities to convert digital information into actionable circular decisions, rather than treating circularity as an isolated environmental program (Lu et al., 2024). Nonetheless, implementation barriers remain substantial, including organizational resistance, infrastructure gaps, skill shortages, and inter-organizational misalignment, which are repeatedly observed across industries and contexts (Kiani et al., 2023; Samper et al., 2022; Sharifian Jazi et al., 2024).

Implementation complexity becomes even more pronounced in emerging economies and high-volume sectors. For example, Industry 4.0 adoption challenges in fast-moving consumer goods (FMCG) have been documented as significant determinants of resilient supply chain development, reflecting the joint effects of technology readiness, workforce capability, governance constraints, and supply market fragmentation (Shakur et al., 2024). In many cases, these obstacles are not primarily technical; they arise from coordination failures, insufficient managerial commitment, limited investment capacity, and a weak institutional environment. This underscores the importance of modeling the institutional and policy layer as part of the SSCM–Industry 4.0 system, including regulatory requirements, public incentives, and multi-actor governance that shapes technology diffusion and sustainability priorities (Kiani et al., 2023; Sharifian Jazi et al., 2024).

Digital supply chains also introduce new and critical risk categories, particularly cyber supply chain risk. As connectivity increases, exposure to cyber threats, data breaches, and operational sabotage becomes more acute, potentially undermining both performance and sustainability outcomes. Research highlights that information system security practices influence cyber supply chain risk management and performance in Industry 4.0 contexts, implying that cyber governance must be integrated into the design of intelligent sustainable supply chains rather than treated as an IT afterthought (Fernando et al., 2023). Broader operations and supply chain scholarship similarly emphasizes the growing strategic importance of cybersecurity and the need for systematic research and managerial frameworks to address its operational impacts (Kumar & Mallipeddi, 2022). In sustainability-oriented systems, cyber resilience is not only about protection but also about ensuring continuity of monitoring, compliance reporting, and environmental control systems that rely on data integrity.

Collaboration and knowledge-sharing across supply chain actors constitute additional determinants of successful Industry 4.0–enabled SSCM. Empirical evidence suggests that knowledge-sharing practices affect the adoption of Industry 4.0 technologies across supply chain actors, particularly where technology deployment requires shared standards, coordinated process redesign, and mutual trust (Eslami et al., 2023). Interview-based insights also indicate that sustainable supply chain collaboration in Industry 4.0 depends on relational governance, buyer–supplier alignment, and the co-development of digital interfaces that support joint sustainability initiatives (Kunkel et al., 2022). These findings align with the broader view of "smart" supply chains as networked systems where the locus of intelligence is distributed across firms, platforms, and institutional stakeholders rather than residing within a single focal firm (Zhang et al., 2023).

Because Industry 4.0–enabled SSCM involves interdependent criteria—environmental, economic, social, technological, and risk-related—decision-making is frequently formulated as a multi-criteria problem under uncertainty. In this context, fuzzy and hybrid decision support methods have gained traction for supplier selection, technology prioritization, and resource allocation in intelligent circular supply chains (Tavana et al., 2023). Methodological work also demonstrates that integrating fuzzy multicriteria methods with optimization and machine-learning components can strengthen decision quality in complex operational contexts, suggesting a pathway toward more intelligent, data-driven, and uncertainty-aware SSCM frameworks (Paula Vidal et al., 2022; Soni et al., 2022). In the sustainability-finance interface, Industry 4.0 technology adoption is increasingly linked with new financing mechanisms and decision frameworks for sustainable supply chain finance, especially for small and medium-sized enterprises, where investment constraints and risk perceptions are central barriers (Soni et al., 2022). These decision-centric perspectives are directly relevant for energy and gas contexts, where investment in smart infrastructure must be prioritized under capital scarcity, regulatory pressures, and long asset lifecycles.

The energy and gas sector presents a particularly demanding application domain for intelligent sustainable supply chain design. It is characterized by safety-critical operations, geographically dispersed infrastructures, complex maintenance and logistics needs, strict regulatory requirements, and substantial environmental and social impacts. In such settings, the promise of Industry 4.0 lies in improving predictive maintenance, real-time monitoring of pipelines and facilities, intelligent inventory and spare parts management, and end-to-end traceability of materials and emissions-related data, while supporting compliance and stakeholder reporting. Blockchain-enabled traceability and transparency, although initially explored intensively in food supply chains, offers transferable insights for energy supply chains regarding governance, implementation impediments, and the people–process–technology alignment required for adoption (Kayikci et al., 2022). Furthermore, the linkage between digital information logistics and Industry 4.0 underscores the operational value of structuring, integrating, and distributing high-quality information across supply chain nodes to improve coordination and decision-making (Bayanati, 2024; Dias et al., 2022).

Despite the breadth of research, several gaps remain that justify a focused model-building effort. First, while many studies assess relationships between Industry 4.0 and performance outcomes, fewer integrate sustainability, resilience, institutional pressures, investment constraints, and cyber risk within a unified modeling architecture that reflects causal interdependencies. Second, evidence increasingly indicates that environmental dynamism and uncertainty shape the performance returns of Industry 4.0, suggesting the need for frameworks that explicitly incorporate uncertainty and dynamic interactions rather than treating context as a static moderator (Chatterjee et al., 2023; Jain et al., 2024). Third, much of the literature is either conceptual or sector-general, while sector-specific constraints—such as those in energy and gas—require tailored factor structures and decision logic. Finally, there is a practical need for decision-supportable models that translate complex multi-criteria evidence into actionable prioritization and scenario insights, especially under uncertainty where traditional deterministic planning may underperform (Paula Vidal et al., 2022; Tavana et al., 2023).

Accordingly, recent research has increasingly called for integrated modeling approaches that combine (a) the identification and validation of SSCM–Industry 4.0 factors, (b) prioritization under uncertainty, and (c) causal mapping to identify system drivers and leverage points for performance improvement. Empirical modeling work on enablers of Industry 4.0 in sustainable supply chains, including fuzzy hybrid approaches, reinforces the value of structured factor modeling to determine which levers should be activated first to accelerate implementation success (Qureshi, 2023; Rana & Jani, 2023; Roknoddini et al., 2023). Complementary studies emphasize that performance gains often require process innovation and technology utilization jointly, indicating that sustainability outcomes depend on coherent bundles of practices rather than isolated technology pilots (Qureshi, 2023; Rana & Jani, 2023). At the same time, the strategic management dimension of Industry 4.0—sometimes framed as "Management 4.0"—signals that managerial logics, leadership support, and governance architectures must co-evolve with technologies for transformation to be effective and sustainable (Haleem et al., 2023).

This article addresses these needs by developing an intelligent sustainable supply chain model for the gas industry that explicitly reflects uncertainty, interdependencies, and multi-stakeholder requirements, while leveraging the insights of Industry 4.0–enabled resilience, circularity, information logistics, cybersecurity, and capability-based explanations (Bayanati, 2024; Birkel & Müller, 2025; Fernando et al., 2023; Ghobakhloo et al., 2025; Lu et al., 2024). It also responds to documented implementation challenges and contextual barriers by considering the institutional and organizational conditions that shape adoption feasibility and performance outcomes (Kiani et al., 2023; Samper et al., 2022; Shakur et al., 2024; Sharifian Jazi et al., 2024). By integrating these streams, the study seeks to contribute both theoretically—through a coherent systems view of Industry 4.0–enabled SSCM under uncertainty—and practically—through a decision-oriented framework that helps managers prioritize investments and interventions aligned with sustainability and resilience objectives (Jain et al., 2024; Soni et al., 2022; Tavana et al., 2023; Tortorella et al., 2024).

The aim of this study is to design and explain an intelligent sustainable supply chain model for the gas industry that leverages Industry 4.0 technologies under conditions of uncertainty by identifying, validating, prioritizing, and causally analyzing the key drivers of sustainable supply chain performance.

2. Methods and Materials

In this study, with the aim of designing an intelligent sustainable supply chain model for the gas industry by leveraging Industry 4.0 technologies under conditions of uncertainty, a mixed-methods (qualitative–quantitative) and multi-stage approach was adopted, enabling the integrated identification, screening, weighting, and dynamic analysis of factors. In the first step, the research commenced with a systematic qualitative study. To this end, a transparent, comprehensive, and structured search was conducted in valid international scientific databases such as Scopus, Web of Science, and ScienceDirect. Keywords including Sustainable Supply Chain, Industry 4.0 Technologies, Smart Gas Supply Chain, Uncertainty, and their combinations were employed. Inclusion criteria consisted of peer-reviewed scholarly articles related to sustainable supply chains, Industry 4.0 technologies, and the energy and gas sector, while exclusion criteria included irrelevant studies, duplicate articles, and research lacking a clear analytical framework. The screening process was carried out in accordance with the PRISMA guidelines, resulting in the extraction of an initial set of factors and indicators.

In the second stage, to validate and refine the indicators extracted from the qualitative phase, the fuzzy Delphi method was utilized. For this purpose, a questionnaire comprising 35 indicators across five main dimensions (institutional environment, corporate sustainable performance, organizational culture and leadership support, supply chain integration and development, and implementation of smart Industry 4.0 technologies) was designed and administered to 10 experts from the gas industry, academia, and the policy-making domain. Expert judgments were collected using five-level linguistic variables (very low to very high) and converted into triangular fuzzy numbers. Subsequently, by calculating the fuzzy mean and defuzzifying the results, the final indicators were confirmed.

In the third step, to determine the importance and priority of criteria and sub-criteria under conditions of uncertainty, the fuzzy Best–Worst Method (Fuzzy BWM) was applied. Initially, the best and worst criteria at each level were identified by experts, followed by pairwise comparisons using a fuzzy scale. The data were aggregated using the geometric mean, and the fuzzy BWM linear optimization model was solved using Lingo 17 software. Thereafter, fuzzy weights were converted into crisp weights, and inconsistency rates were examined, all of which fell within acceptable thresholds, indicating the reliability of expert judgments.

In the fourth stage, to reduce the dimensionality of the model and select key factors for dynamic system analysis, hierarchical clustering based on the final weights of sub-criteria was employed. This stage was conducted using the Python programming language, and the sub-criteria were classified into seven importance clusters. Criteria that ranked from a “moderate to high” level of importance (14 criteria covering more than 64 percent of the total weight) were selected for entry into the subsequent stage.

In the fifth step, to analyze causal relationships, degrees of influence and dependence, and to identify key driving factors of the system, a fuzzy cognitive map (FCM) approach was applied. Accordingly, the adjacency matrix was constructed based on expert judgments within the interval [-1, 1], and indices of influence, dependence, and centrality were calculated. Moreover, the high density of the matrix (0.93) indicated a strong interdependence among factors within the intelligent gas supply chain system.

In the sixth stage, scenario development and dynamic system analysis were conducted using FCMapper software. Based on the centrality results, three key criteria—“commitment to environmental sustainability,” “provision of financial resources and technological investment,” and “strategic alignment of Industry 4.0 and sustainability”—were selected as core driving factors. Various scenarios were designed by fixing the values of these factors within the range [0, 1], and the effects of weakening or strengthening each factor on the target variable were analyzed to identify the most sensitive pathways for improving supply chain sustainability.

Overall, by integrating systematic qualitative review, fuzzy Delphi, fuzzy BWM, clustering, fuzzy cognitive mapping, and scenario analysis, the research methodology of this article provides a comprehensive, flexible, and uncertainty-oriented framework for designing an intelligent sustainable supply chain model in the gas industry, which is both scientifically robust and practically capable of supporting strategic decision-making.

3. Findings and Results

The findings of the qualitative phase of the study, which were based on a systematic literature review and content analysis of previous studies, led to the identification of the conceptual structure of an intelligent and sustainable supply chain in the gas industry. Qualitative analysis revealed that supply chain sustainability in this industry is a multidimensional and systemic concept that is not limited solely to environmental considerations, but rather encompasses the simultaneous interaction of institutional, technological, managerial, and operational factors. At this stage, five main dimensions were identified, including the institutional and policy environment, organizational sustainable performance, organizational culture and leadership support, supply chain integration and development, and the application of smart Industry 4.0 technologies. The findings indicated that legal and regulatory pressures, environmental policies, and governance requirements play a decisive role in directing firms' behavior toward sustainability. Moreover, at the organizational level, top management commitment, capable human capital, and an innovation-oriented culture were identified as prerequisites for successful digital transformation and sustainability. At the operational level, coordination among supply chain actors, information transparency, and supply network flexibility emerged as key factors. In addition, technologies such as the Internet of Things, big data analytics, artificial intelligence, and blockchain were identified as major enablers for managing uncertainty, reducing risk, and enhancing the sustainable performance of the gas industry supply chain.

In line with the framework established at this stage, conducting a transparent, systematic, and comprehensive search must be initiated. To perform a comprehensive search, the keywords as well as the inclusion and exclusion criteria of the studies must be clearly defined within the qualitative research process.

Figure 1

Factors related to the implementation of smart Industry 4.0 technologies in the supply chain

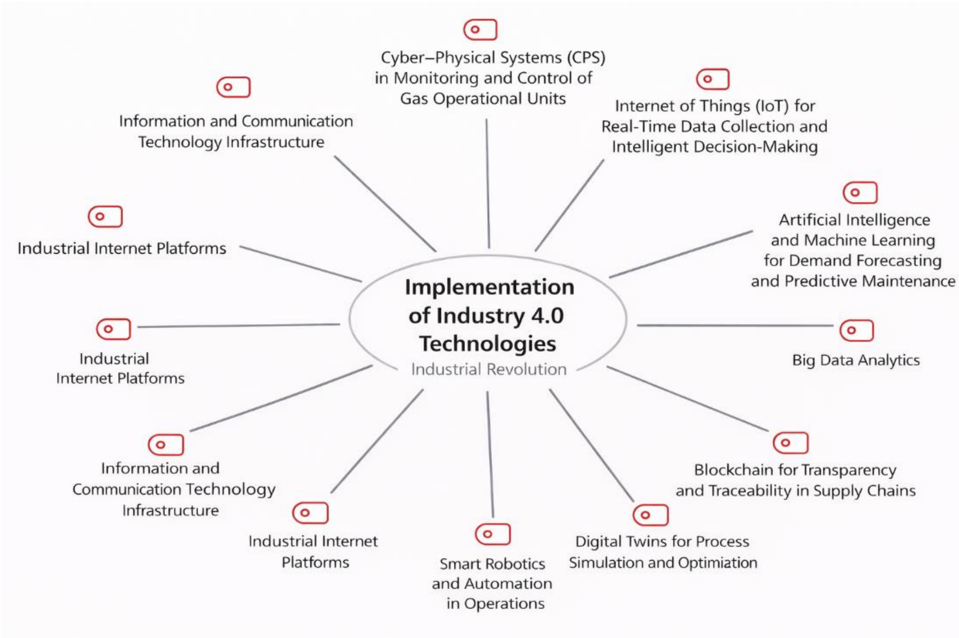
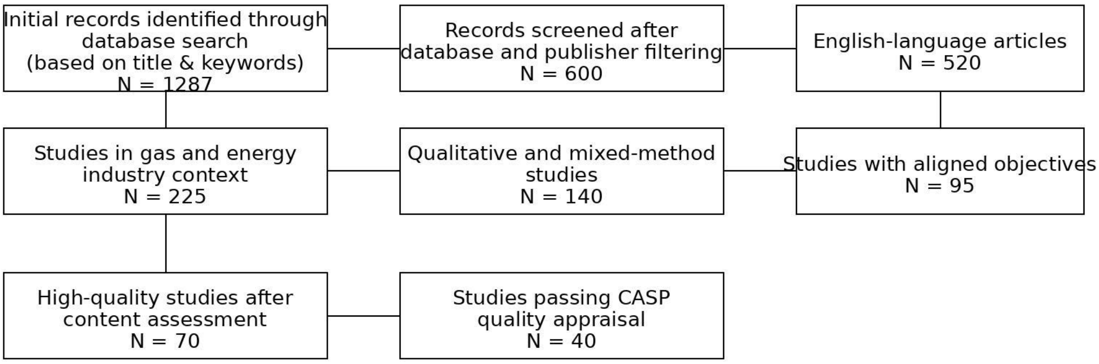


Figure 2

Process of inclusion and exclusion of texts (studies)



In this section, the fuzzy Delphi method is employed to screen and/or confirm the indicators extracted from the qualitative phase. Accordingly, a questionnaire containing 35 indicators derived from the qualitative stage was distributed to the members of the expert panel, and they were asked to express their opinions on each criterion using the linguistic variables specified in the questionnaire.

Table 1

Results of Expert Opinions in the Fuzzy Delphi Process

Criterion	Sub-criterion	Very Low	Low	Medium	High	Very High
Institutional environment	Stakeholder pressure	0	1	2	6	6
	Regulatory and legal frameworks	0	0	2	2	11
	Government–industry–university interaction in policymaking for emerging technologies	0	1	1	4	9
	Government support policies for digital projects and supply chain integration and development	0	1	2	3	9
	Compliance with regulations and standards	0	0	0	9	6
Corporate sustainable performance	Environmental and energy management and efficiency	0	1	9	3	2
	Design and implementation of sustainable performance evaluation frameworks	0	2	1	5	7
	Implementation of waste management and recycling strategies	0	0	4	1	10
	Corporate social responsibility (toward employees and society)	0	1	1	6	7
	Commitment to environmental sustainability	0	0	1	5	9
Organizational culture and leadership support	Strategic alignment of Industry 4.0 and sustainability	0	0	1	3	11
	Redesign of innovative industrial systems	0	1	3	5	6
	Research and development	0	0	1	7	7
	Training and empowerment of human resources	0	0	3	2	10
	Intra-organizational communication to facilitate innovation and digitalization	0	1	3	4	7
	Establishment of a flexible and network-based organizational structure for sustainable performance	1	0	6	8	0
	Promotion of an innovation culture and organizational learning	0	0	3	4	8
	Top management commitment and support for digital transformation and sustainability	0	0	3	4	8
Supply chain integration and development	Interaction and collaboration among supply chain stakeholders	0	0	1	7	7
	Transparency and information sharing in the supply chain	0	2	1	4	8

Implementation of smart Industry 4.0 technologies in the supply chain	Optimization of logistics flows using real-time data and digital technologies	0	1	2	4	8
	Design of flexible and resilient supply chain networks	1	0	2	4	8
	Shared data exchange and decision-making platforms	0	0	6	3	6
	Provision of financial resources and technological investment	0	0	0	2	13
	Implementation of clean technologies and supply chain integration and development	1	3	5	6	0
	Development of technical and operational infrastructures	0	0	1	3	11
	Advanced communication infrastructure, cloud and edge networks for operational data	0	4	5	5	1
	Interoperability among intelligent systems	0	1	1	6	7
	Cybersecurity and data protection	0	0	2	3	10
	Robotics, drones, and automation in gas distribution and maintenance operations	0	1	8	4	2
	Cyber–physical systems (CPS) for monitoring and control of gas operational units	0	0	1	7	7
	Blockchain for tracking shipments, contracts, and supply chain transparency	0	0	2	2	11
	Big data analytics	0	4	7	4	0
	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0	0	1	3	11
	Internet of Things for real-time monitoring of pipelines, equipment, and warehouses	0	0	0	5	10

The counts of expert judgments for the research indicators are reported above. First, a fuzzy mean is calculated from the collected scores, and then the fuzzy mean is defuzzified into a crisp value. The results of all fuzzification calculations in the first round of the Delphi process are presented. For example, for the indicator in Row 1, the fuzzy Delphi calculations are as follows.

Zero experts assigned a very low score, one expert assigned a low score, two experts assigned a medium score, six experts assigned a high score, and six experts assigned a very high score. Accordingly, the fuzzy and non-fuzzy (crisp) scores for this indicator are calculated as follows:

Fuzzy score

$$\text{Fuzzy score} = \frac{0 \times (0,0,0.25) + 1 \times (0,0.25,0.5) + 2 \times (0.25,0.5,0.75) + 6 \times (0.5,0.75,1) + 6 \times (0.75,1,1)}{15} = (0.533,0.783,0.933)$$

Crisp score

$$\text{Crisp score} = \frac{0.533 + 0.783 + 0.933}{3} = 0.75$$

Based on this procedure, six indicators did not achieve the required threshold score and were eliminated, while 29 indicators were finally confirmed.

Table 2

Results of the Fuzzy Delphi Method

Criterion	Sub-criterion	Fuzzy score	Crisp score	Status
Institutional environment	Stakeholder pressure	(0.533, 0.783, 0.933)	0.750	Confirmed
	Regulatory and legal frameworks	(0.650, 0.900, 0.967)	0.839	Confirmed
	Government–industry–university interaction in policymaking for emerging technologies	(0.600, 0.850, 0.950)	0.800	Confirmed
	Government support policies for digital projects and supply chain integration and development	(0.583, 0.833, 0.933)	0.783	Confirmed

	Compliance with regulations and standards	(0.600, 0.850, 1.000)	0.817	Confirmed
Corporate sustainable performance	Environmental and energy management and efficiency	(0.350, 0.600, 0.817)	0.589	Rejected
	Design and implementation of sustainable performance evaluation frameworks	(0.533, 0.783, 0.917)	0.744	Confirmed
	Implementation of waste management and recycling strategies	(0.600, 0.850, 0.933)	0.794	Confirmed
	Corporate social responsibility (toward employees and society)	(0.567, 0.817, 0.950)	0.778	Confirmed
	Commitment to environmental sustainability	(0.633, 0.883, 0.983)	0.833	Confirmed
Organizational culture and leadership support	Strategic alignment of Industry 4.0 and sustainability	(0.667, 0.917, 0.983)	0.856	Confirmed
	Redesign of innovative industrial systems	(0.517, 0.767, 0.917)	0.733	Confirmed
	Research and development	(0.600, 0.850, 0.983)	0.811	Confirmed
	Training and empowerment of human resources	(0.617, 0.867, 0.950)	0.811	Confirmed
	Intra-organizational communication to facilitate innovation and digitalization	(0.533, 0.783, 0.917)	0.744	Confirmed
	Establishment of a flexible and network-based organizational structure for sustainable performance	(0.367, 0.600, 0.850)	0.606	Rejected
	Promotion of an innovation culture and organizational learning	(0.583, 0.833, 0.950)	0.789	Confirmed
	Top management commitment and support for digital transformation and sustainability	(0.583, 0.833, 0.950)	0.789	Confirmed
Supply chain integration and development	Interaction and collaboration among supply chain stakeholders	(0.600, 0.850, 0.983)	0.811	Confirmed
	Transparency and information sharing in the supply chain	(0.550, 0.800, 0.917)	0.756	Confirmed
	Optimization of logistics flows using real-time data and digital technologies	(0.567, 0.817, 0.933)	0.772	Confirmed
	Design of flexible and resilient supply chain networks	(0.567, 0.800, 0.917)	0.761	Confirmed
	Shared data exchange and decision-making platforms	(0.500, 0.750, 0.900)	0.717	Confirmed
Implementation of smart Industry 4.0 technologies in the supply chain	Provision of financial resources and technological investment	(0.717, 0.967, 1.000)	0.894	Confirmed
	Implementation of clean technologies and supply chain integration and development	(0.283, 0.517, 0.767)	0.522	Rejected
	Development of technical and operational infrastructures	(0.667, 0.917, 0.983)	0.856	Confirmed
	Advanced communication infrastructure, cloud and edge networks for operational data	(0.300, 0.550, 0.783)	0.544	Rejected
	Interoperability among intelligent systems	(0.567, 0.817, 0.950)	0.778	Confirmed
	Cybersecurity and data protection	(0.633, 0.883, 0.967)	0.828	Confirmed
	Robotics, drones, and automation in gas distribution and maintenance operations	(0.367, 0.617, 0.833)	0.606	Rejected
	Cyber–physical systems (CPS) for monitoring and control of gas operational units	(0.600, 0.850, 0.983)	0.811	Confirmed
	Blockchain for tracking shipments, contracts, and supply chain transparency	(0.650, 0.900, 0.967)	0.839	Confirmed
	Big data analytics	(0.250, 0.500, 0.750)	0.500	Rejected
	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	(0.667, 0.917, 0.983)	0.856	Confirmed
	Internet of Things for real-time monitoring of pipelines, equipment, and warehouses	(0.667, 0.917, 1.000)	0.861	Confirmed

In this section, the fuzzy Best–Worst Method (fuzzy BWM) is used to weight and prioritize the study factors.

In the first step of the Best–Worst Method, the most important (best) and the least important (worst) indicators must be identified. In this study, based on expert judgments obtained and quantified through the fuzzy Delphi process, the most important (best) and the least important (worst) indicators were determined, as reported in the table below.

Table 3

Best and Worst Criteria (Fuzzy BWM Inputs)

Criterion	Sub-criterion	Sub-criterion symbol	Best/Worst
Institutional environment	Stakeholder pressure	A1	Least important
	Regulatory and legal frameworks	A2	Most important
	Government–industry–university interaction in policymaking for emerging technologies	A3	—
	Government support policies for digital and green projects	A4	—
	Compliance with regulations and standards	A5	—
Corporate sustainable performance	Design and implementation of sustainable performance evaluation frameworks	B1	Least important
	Implementation of waste management and recycling strategies	B2	—
	Corporate social responsibility	B3	—
	Commitment to environmental sustainability	B4	Most important
Organizational culture and leadership support (top management)	Strategic alignment of Industry 4.0 and sustainability	C1	Most important
	Redesign of innovative industrial systems	C2	Least important
	Research and development	C3	—
	Training and empowerment of human resources	C4	—
	Intra-organizational communication to facilitate innovation and digitalization	C5	—
	Promotion of an innovation culture and organizational learning	C6	—
	Top management commitment and support for digital transformation and sustainability	C7	—
Supply chain integration and development (least important main criterion)	Interaction and collaboration among supply chain stakeholders	D1	Most important
	Transparency and information sharing in the supply chain	D2	—
	Optimization of logistics flows using real-time data and digital technologies	D3	—
	Design of flexible and resilient supply chain networks	D4	—
	Shared data exchange and decision-making platforms	D5	Least important
Implementation of smart Industry 4.0 technologies in the supply chain (most important main criterion)	Provision of financial resources and technological investment	E1	Most important
	Development of technical and operational infrastructures	E2	—
	Interoperability among intelligent systems	E3	Least important
	Cybersecurity and data protection	E4	—
	Cyber–physical systems (CPS) for monitoring and control of gas operational units	E5	—
	Blockchain for tracking shipments, contracts, and supply chain transparency	E6	—
	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	E7	—
	Internet of Things for real-time monitoring of pipelines, equipment, and warehouses	E8	—

In this step, pairwise comparisons are conducted for the best criterion relative to the other criteria (BO) and for the other criteria relative to the worst criterion (OW). In this study, pairwise comparison matrices were first constructed and distributed to 10 experts, who were asked to determine the degree of preference in each pairwise comparison using the five-point fuzzy scale. After data collection, the pairwise comparisons were aggregated using the geometric mean, as reported below.

$$\mu = 1 - ((1-0.9)^{0.1051} \times (1-0.75)^{0.1051} \times (1-0.5)^{0.1051} \times (1-0.75)^{0.1051} \times (1-0.5)^{0.074} \times (1-0.75)^{0.074} \times (1-0.5)^{0.1051} \times (1-0.5)^{0.074} \times (1-0.75)^{0.1262} \times (1-0.5)^{0.1262}) = 0.682$$

$$\nu = ((0.1)^{0.1051} \times (0.2)^{0.1051} \times (0.45)^{0.1051} \times (0.2)^{0.1051} \times (0.45)^{0.074} \times (0.2)^{0.074} \times (0.45)^{0.1051} \times (0.45)^{0.074} \times (0.2)^{0.1262} \times (0.45)^{0.1262}) = 0.275$$

$$\pi = 1 - 0.682 - 0.275 = 0.042$$

Next, the intuitionistic fuzzy number is converted into a crisp value as follows:

$$\text{Crisp} = \frac{(0.682 - 0.275 + 1)}{2} = 0.703$$

Table 4

Pairwise Comparison of Main Criteria (Aggregated Fuzzy BO and OW Vectors)

	A	B	C	D	E
Best criterion (D)	(1.085, 1.516, 2.038)	(1.114, 1.382, 1.663)	(0.828, 1.000, 1.208)	—	(2.991, 3.497, 4.002)
Worst criterion (E)	(0.874, 1.260, 1.778)	(1.291, 1.741, 2.316)	(1.799, 2.297, 2.885)	—	—

Table 5

Pairwise Comparison of Institutional Environment Sub-criteria (A) (Aggregated Fuzzy BO and OW Vectors)

	A1	A2	A3	A4	A5
Best criterion (A2)	(1.840, 2.352, 2.860)	—	(1.007, 1.420, 1.947)	(1.063, 1.294, 1.546)	(1.469, 1.940, 2.495)
Worst criterion (A1)	—	—	(0.763, 1.097, 1.563)	(1.611, 2.095, 2.681)	(1.028, 1.260, 1.512)

Table 6

Pairwise Comparison of Corporate Sustainable Performance Sub-criteria (B) (Aggregated Fuzzy BO and OW Vectors)

	B1	B2	B3	B4
Best criterion (B4)	(2.672, 3.189, 3.700)	(1.243, 1.689, 2.229)	(1.100, 1.528, 2.060)	—
Worst criterion (B1)	—	(0.874, 1.149, 1.491)	(0.784, 1.149, 1.661)	—

Table 7

Pairwise Comparison of Organizational Culture and Leadership Support Sub-criteria (C) (Aggregated Fuzzy BO and OW Vectors)

	C1	C2	C3	C4	C5	C6	C7
Best criterion (C1)	—	(2.991, 3.497, 4.002)	(1.768, 2.264, 2.794)	(1.312, 1.540, 1.771)	(2.182, 2.693, 3.200)	(1.243, 1.689, 2.229)	(1.840, 2.352, 2.860)
Worst criterion (C2)	—	—	(0.874, 1.097, 1.365)	(1.611, 1.910, 2.248)	(0.806, 1.047, 1.356)	(0.851, 1.203, 1.673)	(0.763, 1.047, 1.431)

Table 8

Pairwise Comparison of Supply Chain Integration and Development Sub-criteria (D) (Aggregated Fuzzy BO and OW Vectors)

	D1	D2	D3	D4	D5
Best criterion (D1)	—	(1.512, 1.993, 2.525)	(1.294, 1.755, 2.282)	(1.201, 1.644, 2.180)	(3.059, 3.565, 4.070)
Worst criterion (D5)	—	(1.035, 1.294, 1.589)	(0.840, 1.158, 1.591)	(0.976, 1.320, 1.752)	—

Table 9

Pairwise Comparison of Smart Industry 4.0 Technology Implementation Sub-criteria (E) (Aggregated Fuzzy BO and OW Vectors)

	E1	E2	E3	E4	E5	E6	E7	E8
Best criterion (E1)	—	(1.161, 1.600, 2.131)	(2.925, 3.431, 3.936)	(1.226, 1.528, 1.849)	(1.085, 1.516, 2.038)	(1.485, 1.962, 2.522)	(1.252, 1.582, 1.964)	(1.512, 1.993, 2.525)
Worst criterion (E3)	—	(0.922, 1.260, 1.685)	—	(1.156, 1.516, 1.971)	(0.704, 1.047, 1.552)	(1.003, 1.260, 1.562)	(1.320, 1.587, 1.871)	(0.874, 1.149, 1.491)

Table 10

Final Weight and Rank of the Main Criteria

Code	Criterion	Fuzzy weight	Crisp weight	Rank
A	Institutional environment	(0.137, 0.150, 0.198)	0.156	4
B	Corporate sustainable performance	(0.183, 0.194, 0.247)	0.201	3
C	Organizational culture and leadership support	(0.238, 0.245, 0.299)	0.253	2
D	Supply chain integration and development	(0.092, 0.092, 0.109)	0.095	5
E	Implementation of smart Industry 4.0 technologies in the supply chain	(0.285, 0.285, 0.332)	0.293	1

The fuzzy weights were obtained directly from solving the model in Lingo. These fuzzy weights were then converted to crisp weights using the defuzzification formula $R(\tilde{a}_i) = (l_i + 4m_i + u_i)/6$. For example, the fuzzy weight of the institutional environment criterion is (0.137, 0.150, 0.198), and its crisp weight equals $(0.137 + 4 \times 0.150 + 0.198)/6 = 0.156$. Accordingly, the criterion "implementation of smart Industry 4.0 technologies in the supply chain" achieved the first rank with a weight of 0.293. The criterion "organizational culture and leadership support" achieved the second rank with a weight of 0.253, and "corporate sustainable performance" achieved the third rank with a weight of 0.201. The priority ordering of the remaining criteria is also shown in Figure 4-12.

Similarly, for the sub-criteria, a linear optimization model was constructed and solved using the software, as presented below.

Among the institutional environment sub-criteria, "regulatory and legal frameworks" achieved the first rank with a weight of 0.290. "Government support policies for digital and green projects" with a weight of 0.254 and "government–industry–university interaction in policymaking for emerging technologies" with a weight of 0.178 achieved the second and third ranks, respectively.

Table 11

Weight and Rank of Institutional Environment Sub-criteria

Code	Sub-criterion	Fuzzy weight	Crisp weight	Rank
A1	Stakeholder pressure	(0.107, 0.141, 0.143)	0.136	5
A2	Regulatory and legal frameworks	(0.232, 0.301, 0.301)	0.290	1
A3	Government–industry–university interaction in policymaking for emerging technologies	(0.139, 0.184, 0.190)	0.178	3
A4	Government support policies for digital and green projects	(0.199, 0.265, 0.265)	0.254	2
A5	Compliance with regulations and standards	(0.116, 0.147, 0.147)	0.142	4

Among the corporate sustainable performance sub-criteria, "commitment to environmental sustainability" achieved the first rank with a weight of 0.420. "Corporate social responsibility" achieved the second rank with a weight of 0.224, and "implementation of waste management and recycling strategies" achieved the third rank with a weight of 0.206.

Table 12

Weight and Rank of Corporate Sustainable Performance Sub-criteria

Code	Sub-criterion	Fuzzy weight	Crisp weight	Rank
B1	Design and implementation of sustainable performance evaluation frameworks	(0.124, 0.152, 0.157)	0.148	4
B2	Implementation of waste management and recycling strategies	(0.167, 0.211, 0.227)	0.206	3
B3	Corporate social responsibility	(0.178, 0.229, 0.249)	0.224	2
B4	Commitment to environmental sustainability	(0.363, 0.431, 0.431)	0.420	1

Among the organizational culture and leadership support sub-criteria, “strategic alignment of Industry 4.0 and sustainability” achieved the first rank with a weight of 0.258. “Training and empowerment of human resources” achieved the second rank with a weight of 0.185, and “promotion of an innovation culture and organizational learning” achieved the third rank with a weight of 0.129.

Table 13

Weight and Rank of Organizational Culture and Leadership Support Sub-criteria

Code	Sub-criterion	Fuzzy weight	Crisp weight	Rank
C1	Strategic alignment of Industry 4.0 and sustainability	(0.251, 0.251, 0.293)	0.258	1
C2	Redesign of innovative industrial systems	(0.080, 0.080, 0.095)	0.083	7
C3	Research and development	(0.115, 0.115, 0.137)	0.119	4
C4	Training and empowerment of human resources	(0.180, 0.180, 0.207)	0.185	2
C5	Intra-organizational communication to facilitate innovation and digitalization	(0.100, 0.107, 0.136)	0.111	6
C6	Promotion of an innovation culture and organizational learning	(0.114, 0.124, 0.161)	0.129	3
C7	Top management commitment and support for digital transformation and sustainability	(0.105, 0.111, 0.142)	0.115	5

Among the supply chain integration and development sub-criteria, “interaction and collaboration among supply chain stakeholders” achieved the first rank with a weight of 0.352. “design of flexible and resilient supply chain networks” achieved the second rank with a weight of 0.185, and “transparency and information sharing in the supply chain” achieved the third rank with a weight of 0.182.

Table 14

Weight and Rank of Supply Chain Integration and Development Sub-criteria

Code	Sub-criterion	Fuzzy weight	Crisp weight	Rank
D1	Interaction and collaboration among supply chain stakeholders	(0.343, 0.343, 0.398)	0.352	1
D2	Transparency and information sharing in the supply chain	(0.177, 0.177, 0.206)	0.182	3
D3	Optimization of logistics flows using real-time data and digital technologies	(0.152, 0.162, 0.208)	0.168	4
D4	Design of flexible and resilient supply chain networks	(0.170, 0.180, 0.220)	0.185	2
D5	Shared data exchange and decision-making platforms	(0.107, 0.107, 0.127)	0.110	5

Among the sub-criteria of implementing smart Industry 4.0 technologies in the supply chain, “provision of financial resources and technological investment” achieved the first rank with a weight of 0.241. “cyber–physical systems (CPS) for monitoring and control of gas operational units” achieved the second rank with a weight of 0.123, and “cybersecurity and data protection” achieved the third rank with a weight of 0.121.

Table 15

Weight and Rank of Smart Industry 4.0 Technology Implementation Sub-criteria

Code	Sub-criterion	Fuzzy weight	Crisp weight	Rank
E1	Provision of financial resources and technological investment	(0.210, 0.247, 0.247)	0.241	1
E2	Development of technical and operational infrastructures	(0.095, 0.120, 0.129)	0.117	5
E3	Interoperability among intelligent systems	(0.068, 0.083, 0.085)	0.081	8
E4	Cybersecurity and data protection	(0.107, 0.124, 0.124)	0.121	3
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	(0.099, 0.125, 0.136)	0.123	2
E6	Blockchain for tracking shipments, contracts, and supply chain transparency	(0.083, 0.102, 0.108)	0.100	6
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	(0.102, 0.121, 0.122)	0.118	4
E8	Internet of Things for real-time monitoring of pipelines, equipment, and warehouses	(0.083, 0.101, 0.106)	0.099	7

Table 16

Inconsistency Rate of Pairwise Comparisons

Factor	ξ	$\tilde{\xi}^*$	Inconsistency rate
Main criteria	8.04	0.380	0.047
Institutional environment (A)	8.04	0.213	0.026
Corporate sustainable performance (B)	8.04	0.355	0.044
Organizational culture and leadership support (C)	8.04	0.346	0.043
Supply chain integration and development (D)	8.04	0.359	0.045
Smart Industry 4.0 technology implementation in the supply chain (E)	8.04	0.458	0.057

The final weights of sub-criteria are obtained by multiplying the weight of each main criterion by the relative weight of its sub-criteria. Based on this, product quality achieved the first rank among all sub-criteria, rapid responsiveness to customer needs achieved the second rank, and risk management achieved the third rank.

Table 17

Final Weights of Sub-criteria

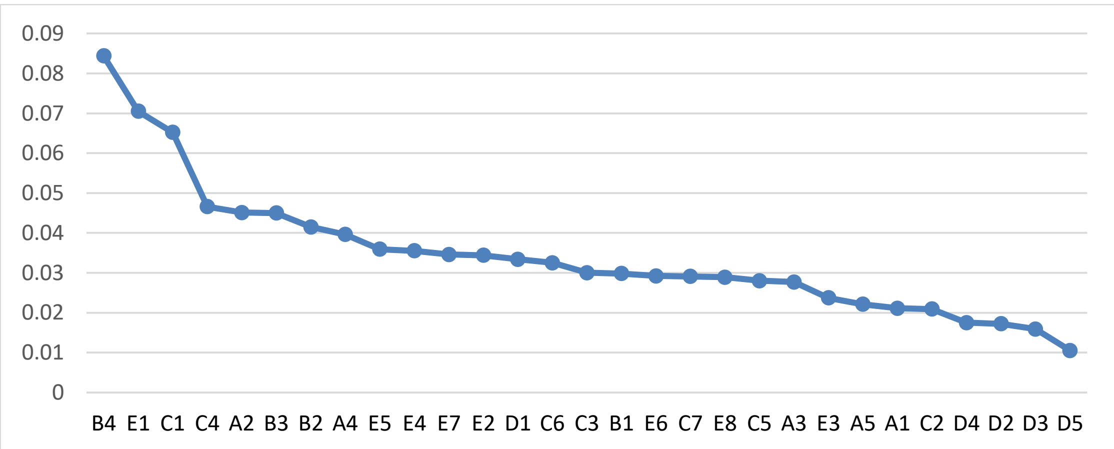
Criterion	Criterion weight	Sub-criterion	Relative sub-criterion weight	Final sub-criterion weight	Final sub-criterion rank
Institutional environment	0.156	Stakeholder pressure	0.136	0.0211	24
		Regulatory and legal frameworks	0.290	0.0451	5
		Government–industry–university interaction in policymaking for emerging technologies	0.178	0.0277	21
		Government support policies for digital and green projects	0.254	0.0396	8
		Compliance with regulations and standards	0.142	0.0221	23
Corporate sustainable performance	0.201	Design and implementation of sustainable performance evaluation frameworks	0.148	0.0298	16
		Implementation of waste management and recycling strategies	0.206	0.0415	7
		Corporate social responsibility	0.224	0.0450	6
		Commitment to environmental sustainability	0.420	0.0844	1
Organizational culture and leadership support (top management)	0.253	Strategic alignment of Industry 4.0 and sustainability	0.258	0.0652	3
		Redesign of innovative industrial systems	0.083	0.0209	25
		Research and development	0.119	0.0300	15
		Training and empowerment of human resources	0.185	0.0466	4
		Intra-organizational communication to facilitate innovation and digitalization	0.111	0.0280	20

		Promotion of an innovation culture and organizational learning	0.129	0.0325	14
		Top management commitment and support for digital transformation and sustainability	0.115	0.0291	18
Supply chain integration and development (least important main criterion)	0.095	Interaction and collaboration among supply chain stakeholders	0.352	0.0334	13
		Transparency and information sharing in the supply chain	0.182	0.0172	27
		Optimization of logistics flows using real-time data and digital technologies	0.168	0.0159	28
		Design of flexible and resilient supply chain networks	0.185	0.0175	26
		Shared data exchange and decision-making platforms	0.110	0.0105	29
Smart Industry 4.0 technology implementation in the supply chain (most important main criterion)	0.293	Provision of financial resources and technological investment	0.241	0.0705	2
		Development of technical and operational infrastructures	0.117	0.0344	12
		Interoperability among intelligent systems	0.081	0.0237	22
		Cybersecurity and data protection	0.121	0.0355	10
		Cyber–physical systems (CPS) for monitoring and control of gas operational units	0.123	0.0359	9
		Blockchain for tracking shipments, contracts, and supply chain transparency	0.100	0.0292	17
		Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0.118	0.0346	11
		Internet of Things for real-time monitoring of pipelines, equipment, and warehouses	0.099	0.0289	19

To implement the fuzzy cognitive map, a subset of important criteria must be identified, and the fuzzy inference system should be developed based on those criteria. Because using all criteria is neither logical nor practical in the FCM model due to the large matrix size, the most important criteria must be selected and the FCM model executed accordingly. Therefore, an agglomerative clustering algorithm was applied, placing the criteria into seven clusters. For clustering, a line chart was first plotted based on the final weights obtained from the fuzzy BWM method, as shown in the figure below.

Figure 3

Priority of sub-criteria based on final weights



Hierarchical clustering was then performed in Python based on the sub-criteria sorted by their final weights; the corresponding code is provided in the appendix. As shown in Figure 4, the sub-criteria were divided into seven clusters, and their names and categories were specified. For selecting criteria for the FCM stage, sub-criteria up to Cluster 4—namely those that achieved "moderate-to-high" importance or above—were selected. This set includes 14 criteria and accounts for more than 64% of the total importance.

Figure 4

Hierarchical clustering of sub-criteria

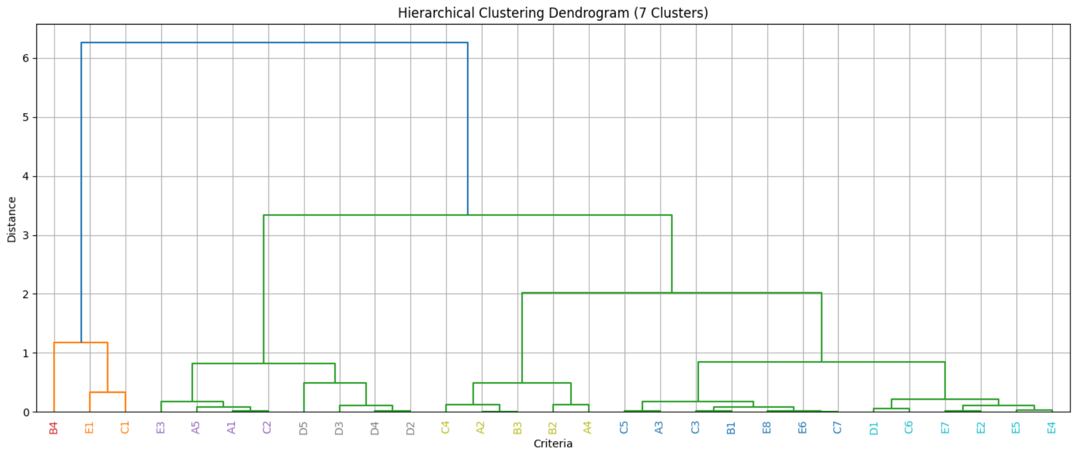


Table 18

Sub-criteria Names and Cluster Membership

Symbol	Criterion name	Weight	Cluster code	Cluster name
B4	Commitment to environmental sustainability	0.0844	1	Very high importance
E1	Provision of financial resources and technological investment	0.0705	2	High importance
C1	Strategic alignment of Industry 4.0 and sustainability	0.0652	2	High importance
C4	Training and empowerment of human resources	0.0466	3	High importance
A2	Regulatory and legal frameworks	0.0451	3	High importance
B3	Corporate social responsibility	0.0450	3	High importance
B2	Implementation of waste management and recycling strategies	0.0415	3	High importance
A4	Government support policies for digital and green projects	0.0396	3	High importance
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	0.0359	4	Moderate-to-high importance
E4	Cybersecurity and data protection	0.0355	4	Moderate-to-high importance
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0.0346	4	Moderate-to-high importance
E2	Development of technical and operational infrastructures	0.0344	4	Moderate-to-high importance
D1	Interaction and collaboration among supply chain stakeholders	0.0334	4	Moderate-to-high importance
C6	Promotion of an innovation culture and organizational learning	0.0325	4	Moderate-to-high importance
C3	Research and development	0.0300	5	Moderate importance
B1	Design and implementation of sustainable performance evaluation frameworks	0.0298	5	Moderate importance
E6	Blockchain for tracking shipments, contracts, and supply chain transparency	0.0292	5	Moderate importance
C7	Top management commitment and support for digital transformation and sustainability	0.0291	5	Moderate importance
E8	Internet of Things for real-time monitoring of pipelines, equipment, and warehouses	0.0289	5	Moderate importance
C5	Intra-organizational communication to facilitate innovation and digitalization	0.0280	5	Moderate importance

A3	Government–industry–university interaction in policymaking for emerging technologies	0.0277	5	Moderate importance
E3	Interoperability among intelligent systems	0.0237	6	Low importance
A5	Compliance with regulations and standards	0.0221	6	Low importance
A1	Stakeholder pressure	0.0211	6	Low importance
C2	Redesign of innovative industrial systems	0.0209	6	Low importance
D4	Design of flexible and resilient supply chain networks	0.0175	7	Very low importance
D2	Transparency and information sharing in the supply chain	0.0172	7	Very low importance
D3	Optimization of logistics flows using real-time data and digital technologies	0.0159	7	Very low importance
D5	Shared data exchange and decision-making platforms	0.0105	7	Very low importance

Next, the relationships among the 14 selected factors identified through clustering were analyzed using the fuzzy cognitive map (FCM) approach. First, a questionnaire (matrix) was designed to assess the mutual effects among criteria within the interval [-1, 1] and was completed by experts; it is presented in Table 19 as the adjacency matrix. In this table, values fall within the interval [-1, 1]; a positive value indicates a positive effect, whereas a negative value indicates a negative effect.

Table 19

Adjacency Matrix of the Criteria

	B4	E1	C1	C4	A2	B3	B2	A4	E5	E4	E7	E2	D1	C6
B4	0.00	0.48	0.69	0.35	0.63	0.67	0.79	0.56	0.44	0.43	0.42	0.51	0.58	0.48
E1	0.61	0.00	0.70	0.57	0.55	0.44	0.44	0.72	0.73	0.68	0.77	0.87	0.63	0.55
C1	0.70	0.65	0.00	0.52	0.72	0.55	0.61	0.71	0.59	0.53	0.59	0.65	0.69	0.60
C4	0.41	0.49	0.52	0.00	0.42	0.45	0.34	0.42	0.59	0.52	0.61	0.53	0.62	0.80
A2	0.63	0.55	0.72	0.42	0.00	0.51	0.48	0.81	0.52	0.60	0.52	0.62	0.52	0.47
B3	0.65	0.44	0.55	0.44	0.49	0.00	0.61	0.45	0.33	0.37	0.35	0.37	0.61	0.46
B2	0.74	0.44	0.57	0.34	0.48	0.61	0.00	0.41	0.35	0.34	0.34	0.44	0.49	0.36
A4	0.57	0.70	0.71	0.42	0.82	0.45	0.42	0.00	0.60	0.52	0.57	0.77	0.55	0.47
E5	0.44	0.73	0.59	0.61	0.51	0.34	0.34	0.59	0.00	0.79	0.77	0.81	0.60	0.55
E4	0.43	0.68	0.51	0.52	0.59	0.35	0.31	0.53	0.84	0.00	0.67	0.66	0.49	0.49
E7	0.42	0.77	0.59	0.61	0.51	0.34	0.34	0.57	0.77	0.72	0.00	0.66	0.57	0.65
E2	0.53	0.87	0.65	0.53	0.61	0.37	0.44	0.77	0.81	0.66	0.66	0.00	0.64	0.55
D1	0.58	0.63	0.69	0.62	0.54	0.61	0.50	0.55	0.59	0.49	0.57	0.64	0.00	0.64
C6	0.48	0.55	0.60	0.76	0.47	0.46	0.36	0.47	0.55	0.49	0.65	0.55	0.64	0.00

The intensity measures of influence, dependence, and centrality for the criteria are also reported. Moreover, the criteria were ranked based on centrality. Centrality refers to the sum of a criterion's influence and dependence and indicates that "provision of financial resources and technological investment" (E1) is ranked first. In addition, the matrix fill rate (density) is 93%.

Table 20

Strength of Variables Based on Influence, Dependence, and Centrality

Code	Criterion name	Influence	Dependence	Centrality
B4	Commitment to environmental sustainability	7.03	7.19	14.22
E1	Provision of financial resources and technological investment	8.26	7.98	16.24
C1	Strategic alignment of Industry 4.0 and sustainability	8.11	8.09	16.20
C4	Training and empowerment of human resources	6.72	6.71	13.43
A2	Regulatory and legal frameworks	7.37	7.34	14.71
B3	Corporate social responsibility	6.12	6.15	12.27
B2	Implementation of waste management and recycling strategies	5.91	5.98	11.89
A4	Government support policies for digital and green projects	7.57	7.56	15.13
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	7.67	7.71	15.38
E4	Cybersecurity and data protection	7.07	7.14	14.21
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	7.52	7.49	15.01
E2	Development of technical and operational infrastructures	8.09	8.08	16.17
D1	Interaction and collaboration among supply chain stakeholders	7.65	7.63	15.28
C6	Promotion of an innovation culture and organizational learning	7.03	7.07	14.10

Density: 0.93

In scenario design within FCMapper, several considerations must be taken into account. One of these is that the software defines a baseline (default) scenario in which the system's steady state is computed; this scenario indicates where the system will converge if all factors remain unchanged. Therefore, the scenarios proposed by the researchers are compared against this baseline scenario. Another point is that, in FCMapper scenario design, the interval [0, 1] is used to fix the value of a target factor. In this way, the selected factor is held constant at a predefined value, and the internal relational effects that would otherwise decrease or increase that factor are blocked. In this study, for scenario development, the three criteria ranked first to third in importance were selected, namely commitment to environmental sustainability (B4), provision of financial resources and technological investment (E1), and strategic alignment of Industry 4.0 and sustainability (C1).

The criterion "commitment to environmental sustainability" (B4) was considered the target criterion. The input factors affecting this criterion were identified by examining the fuzzy cognitive map, and by assigning a value of zero to each of these factors separately, the magnitude of changes in the target factor (commitment to environmental sustainability) was computed. The results indicate that B2 is the most influential factor on the target criterion, as shown in the table below.

Table 21

Sensitivity of the Target Criterion: Commitment to Environmental Sustainability (B4)

Code	Input factors to the criterion "commitment to environmental sustainability"	Change in the factor "commitment to environmental sustainability"
B4	Commitment to environmental sustainability	—
E1	Provision of financial resources and technological investment	0.00007807
C1	Strategic alignment of Industry 4.0 and sustainability	0.00011275
C4	Training and empowerment of human resources	0.00018909
A2	Regulatory and legal frameworks	0.00021066
B3	Corporate social responsibility	0.00075211
B2	Implementation of waste management and recycling strategies	0.00112312
A4	Government support policies for digital and green projects	0.00014464
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	0.00009172
E4	Cybersecurity and data protection	0.00015758
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0.00010793
E2	Development of technical and operational infrastructures	0.00007626
D1	Interaction and collaboration among supply chain stakeholders	0.00014130
C6	Promotion of an innovation culture and organizational learning	0.00019380

At this stage, the input factors to "implementation of waste management and recycling strategies" (B2) were determined based on the fuzzy cognitive map. The value of each input factor was set to zero, and the resulting changes in B2 are reported in the following table.

Table 22

Sensitivity of Criterion B2

Code	Input factors to criterion B2	Change in factor B2
B4	Commitment to environmental sustainability	0.00030496
E1	Provision of financial resources and technological investment	0.00006989
C1	Strategic alignment of Industry 4.0 and sustainability	0.00008701
C4	Training and empowerment of human resources	0.00018228
A2	Regulatory and legal frameworks	0.00014767
B3	Corporate social responsibility	0.00066105
B2	Implementation of waste management and recycling strategies	—
A4	Government support policies for digital and green projects	0.00009753
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	0.00006944
E4	Cybersecurity and data protection	0.00011860
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0.00008360
E2	Development of technical and operational infrastructures	0.00006324
D1	Interaction and collaboration among supply chain stakeholders	0.00011346
C6	Promotion of an innovation culture and organizational learning	0.00013615
C15	Financial stability	0.00030496

At this stage, the input factors to "corporate social responsibility" (B3) were determined based on the fuzzy cognitive map. The value of each input factor was set to zero, and the resulting changes in B3 are reported in the table below.

Table 23

Sensitivity of Criterion B3

Code	Input factors to criterion B3	Change in factor B3
B4	Commitment to environmental sustainability	0.00025500
E1	Provision of financial resources and technological investment	0.00006993
C1	Strategic alignment of Industry 4.0 and sustainability	0.00008310
C4	Training and empowerment of human resources	0.00024869
A2	Regulatory and legal frameworks	0.00015162
B3	Corporate social responsibility	—
B2	Implementation of waste management and recycling strategies	0.00078359
A4	Government support policies for digital and green projects	0.00010938
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	0.00006483
E4	Cybersecurity and data protection	0.00013115
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0.00008656
E2	Development of technical and operational infrastructures	0.00005129
D1	Interaction and collaboration among supply chain stakeholders	0.00015076
C6	Promotion of an innovation culture and organizational learning	0.00018343
C15	Financial stability	0.00025500

At this stage, the input factors to B2 were determined based on the fuzzy cognitive map, the value of each input factor was set to zero, and the resulting changes in B2 are reported (as a sensitivity analysis).

Table 24

Final Sensitivity of Criterion B2

Code	Input factors to criterion B2	Change in factor B2
B4	Commitment to environmental sustainability	0.00030496
E1	Provision of financial resources and technological investment	0.00006989
C1	Strategic alignment of Industry 4.0 and sustainability	0.00008701
C4	Training and empowerment of human resources	0.00018228
A2	Regulatory and legal frameworks	0.00014767
B3	Corporate social responsibility	0.00066105
B2	Implementation of waste management and recycling strategies	—
A4	Government support policies for digital and green projects	0.00009753
E5	Cyber–physical systems (CPS) for monitoring and control of gas operational units	0.00006944
E4	Cybersecurity and data protection	0.00011860
E7	Artificial intelligence and machine learning for demand forecasting and predictive maintenance	0.00008360
E2	Development of technical and operational infrastructures	0.00006324
D1	Interaction and collaboration among supply chain stakeholders	0.00011346
C6	Promotion of an innovation culture and organizational learning	0.00013615
C15	Financial stability	0.00030496

In the first scenario, the corporate social responsibility indicator is introduced as the main driver and the starting point of the sustainability pathway. This choice suggests that the first influential factor in shaping a sustainable supply chain is the adoption and strengthening of socially responsible practices by firms operating in the gas industry. In practice, institutional pressures, local community expectations, legal requirements, and the need to improve firms' public environmental image encourage organizations to enhance their corporate social responsibility initiatives. Interpreting this structure implies that action in the corporate social responsibility domain creates the necessary foundation for implementing more operational policies. Accordingly, the second step of the scenario—implementing waste management and recycling strategies—follows corporate social responsibility. Strengthening corporate social responsibility is typically accompanied by requirements to reduce environmental impacts; thus, firms initially move toward reducing waste, recycling gaseous and solid residues, and using smart waste monitoring technologies. These measures are particularly important in the gas industry, where a substantial share of pollution arises from gas leaks, flaring emissions, and process residues. The final stage of this scenario—commitment to environmental sustainability—indicates that the organization reaches a higher level of sustainability maturity. At this level, the organization moves beyond ad hoc initiatives and formulates macro-level and long-term environmental protection policies. Such commitment may include reducing pollutants, complying with environmental, social, and governance standards, investing in clean energy, and using Industry 4.0 technologies such as smart sensors for real-time emissions monitoring. Overall, Scenario 1 has an environment-centered orientation and shows that attention to corporate social responsibility and waste management ultimately drives the organization toward a structural and sustained commitment to environmental protection. This scenario is suitable for companies exposed to environmental and social pressures and in need of improving their environmental performance.

In the second scenario, the starting point is again the corporate social responsibility indicator, but the pathway ends at a different final point. According to this scenario, corporate social responsibility initiatives and the implementation of waste management programs create the need and motivation within the organization to secure financial resources and invest in advanced technologies. Implementing waste management strategies is typically costly and, in many gas companies, requires new equipment and technologies. Consequently, the economic pressures associated with meeting environmental requirements push the firm toward mobilizing financial resources, attracting investment, and allocating budgets for Industry 4.0 technologies. Technologies such as the Internet of Things, artificial intelligence, industrial robotics, and big data analytics are powerful tools for pollution control, energy consumption optimization, and precise waste management; however, without targeted investment, their adoption is not feasible. The movement toward indicator E1 in this scenario reflects a growth-oriented and technology-driven structure. In this case, the organization not only acts to reduce environmental impacts but also transforms sustainability into an economic and technological opportunity. In other words, waste management in this scenario increases demand for technology and financing, and the company moves along a digital development trajectory.

The third scenario also begins with corporate social responsibility and waste management, but its final stage is strategic alignment of Industry 4.0 and sustainability, which reflects the organization reaching a level of digital and managerial maturity in which Industry 4.0 technologies are not merely operational tools but are treated as a core pillar for achieving sustainability objectives. In this scenario, waste management serves as a leading domain into which Industry 4.0 technologies are first introduced, thereby playing a driving role. Technologies such as smart waste monitoring sensors, sorting robots, digital material tracking systems, and real-time data analytics constitute the starting point for aligning digitalization and sustainability. The entry of technology into this domain pushes the organization toward integrating digital and environmental strategies. Reaching indicator C1 signifies that the organization moves beyond tactical actions and, at the strategic level, seeks coordination between its digital transformation agenda and sustainability agenda. At this level, Industry 4.0 technologies are regarded as an integral part of the organization's macro-level policymaking related to environmental protection, energy productivity, and supply chain resilience. This approach enables the organization to build greater flexibility and agility under uncertainty by relying on data-driven capabilities.

4. Discussion and Conclusion

The findings of this study provide a comprehensive and system-oriented understanding of how an intelligent sustainable supply chain can be designed for the gas industry under conditions of uncertainty through the integration of Industry 4.0 technologies, institutional factors, and organizational capabilities. The prioritization results obtained from the fuzzy Best–Worst Method indicate that the implementation of smart Industry 4.0 technologies constitutes the most influential main criterion in enhancing sustainable supply chain performance, followed by organizational culture and leadership support, corporate sustainable performance, the institutional environment, and finally supply chain integration and development. This hierarchy underscores that technological advancement alone is insufficient unless it is embedded within supportive organizational and institutional structures, a conclusion that aligns with recent arguments emphasizing the socio-technical nature of digital transformation in supply chains (Ghobakhloo et al., 2025; Singh, 2025).

The dominance of Industry 4.0 implementation as the top-ranked criterion highlights the critical role of digital infrastructures, advanced analytics, and intelligent automation in managing uncertainty and complexity in gas supply chains. Technologies such as cyber–physical systems, artificial intelligence, and the Internet of Things enable real-time monitoring, predictive maintenance, and data-driven decision-making, which are particularly vital in safety-critical and geographically dispersed gas operations. This result is consistent with prior studies showing that Industry 4.0 base technologies significantly enhance supply chain resilience, visibility, and responsiveness, especially in turbulent environments (Birkel & Müller, 2025; Jain et al., 2024; Khan & Emon, 2025). Moreover, the high centrality of financial resources and technological investment among sub-criteria suggests that without adequate capital allocation, the transformative potential of Industry 4.0 cannot be fully realized. This finding corroborates evidence that investment capacity mediates the relationship between digitalization and performance, particularly in capital-intensive industries (Al-Banna et al., 2023; Eslami et al., 2024).

The second-ranked criterion, organizational culture and leadership support, emphasizes that intelligent sustainable supply chains are deeply dependent on managerial commitment, strategic alignment, and human capital development. Among its sub-criteria, the strategic alignment of Industry 4.0 and sustainability emerged as one of the most influential drivers, indicating that organizations must integrate digital transformation objectives with sustainability goals at the strategic level rather than treating them as parallel or competing agendas. This result aligns with dynamic capability theory, which posits that sustained performance under uncertainty depends on the ability of top management to sense opportunities, seize them through coherent strategies, and reconfigure organizational resources accordingly (Lu et al., 2024; Nakandala et al., 2023). Empirical research further supports that leadership commitment and workforce empowerment significantly shape the success of Industry 4.0 adoption and its sustainability outcomes (Eslami et al., 2023; Haleem et al., 2023).

Corporate sustainable performance, ranked third, reflects the operational manifestation of sustainability strategies within firms. The finding that commitment to environmental sustainability is the highest-priority sub-criterion within this dimension indicates that environmental considerations remain the cornerstone of sustainability in the gas industry. This is unsurprising given the sector's environmental footprint, regulatory scrutiny, and societal expectations. Prior research consistently demonstrates that environmental commitment drives the adoption of cleaner technologies, waste management practices, and emissions reduction initiatives, thereby reinforcing sustainable supply chain outcomes (Qureshi, 2023; Rana & Jani, 2023). The prominence of corporate social responsibility and waste management strategies further supports the view that social legitimacy and environmental stewardship are mutually reinforcing in shaping sustainable supply chain performance (Jiang et al., 2024; Samper et al., 2022).

The institutional environment, although not the top-ranked criterion, plays a pivotal enabling role by shaping incentives, constraints, and legitimacy conditions for supply chain transformation. The high ranking of regulatory and legal frameworks among institutional sub-criteria indicates that clear, stable, and enforceable regulations are essential for motivating firms to invest in sustainable and intelligent supply chain practices. This finding aligns with studies highlighting the importance of institutional pressures, public policies, and government support mechanisms in accelerating the diffusion of Industry 4.0 and circular economy practices in supply chains (Kiani et al., 2023; Sharifian Jazi et al., 2024). In regulated industries such as gas, compliance requirements not only impose constraints but also create opportunities for innovation by encouraging firms to adopt advanced monitoring and reporting technologies (Ülkü et al., 2024; Zhang et al., 2023).

Supply chain integration and development, while ranked lowest among the main criteria, remains an important complementary factor. The relatively lower weight of this dimension does not imply irrelevance but suggests that integration benefits are contingent on the prior establishment of technological, organizational, and institutional foundations. The prominence of stakeholder interaction and collaboration within this dimension supports the argument that intelligent supply chains function as networked systems requiring coordinated action among multiple actors (Kunkel et al., 2022; Zhang et al., 2023). However, the lower overall weight may reflect the challenges of achieving deep integration in gas supply chains characterized by fragmented ownership structures, legacy infrastructures, and asymmetric power relations.

The fuzzy cognitive mapping results further enrich these insights by revealing the causal structure and dynamic interactions among the most important factors. The high centrality values of financial and technological investment, strategic alignment of Industry 4.0 and sustainability, and commitment to environmental sustainability indicate that these factors act as key system drivers. This finding is consistent with resilience-oriented studies showing that investment in digital capabilities and strategic coherence amplifies the positive effects of Industry 4.0 on supply chain performance and sustainability under uncertainty (Birkel & Müller, 2025; Ghobakhloo et al., 2025). The high density of the cognitive map suggests strong interdependencies among factors, reinforcing the notion that piecemeal interventions are unlikely to yield substantial improvements unless coordinated across multiple dimensions.

The scenario analysis offers additional interpretive depth by illustrating alternative development pathways toward sustainability. The first scenario, which emphasizes corporate social responsibility and waste management as precursors to environmental commitment, reflects a compliance- and legitimacy-driven pathway. This pathway resonates with research highlighting that social and environmental pressures often trigger incremental sustainability initiatives that later evolve into more comprehensive strategies (Jiang et al., 2024; Tsai et al., 2021). The second scenario, which channels early sustainability actions into financial and technological investment, represents a growth- and innovation-oriented pathway where sustainability becomes a driver of digital transformation. This perspective aligns with studies arguing that Industry 4.0 can convert sustainability challenges into economic and technological opportunities when supported by adequate investment (Eslami et al., 2024; Soni et al., 2022). The third scenario, culminating in the strategic alignment of Industry 4.0 and sustainability, reflects the highest level of organizational maturity, where digital technologies are fully embedded in sustainability governance and supply chain decision-making. This pathway echoes the concept of "Management 4.0," which emphasizes the co-evolution of leadership, strategy, and technology in achieving sustainable competitive advantage (Haleem et al., 2023; Lu et al., 2024).

Overall, the results of this study support and extend existing literature by providing an integrated, uncertainty-aware model that captures the complex interplay among technology, organization, institution, and performance in the gas industry supply chain. Unlike prior studies that often focus on isolated relationships, the present findings demonstrate that sustainable supply chain performance emerges from a configuration of mutually reinforcing factors, consistent with systems and dynamic capability perspectives (Chari et al., 2022; Nakandala et al., 2023). By combining fuzzy multi-criteria decision-making with causal mapping, the study offers a robust analytical approach for prioritizing interventions and understanding their systemic implications in volatile and high-risk industrial contexts.

Despite its contributions, this study has several limitations. First, the findings are based on expert judgments and methodological modeling, which, although systematic and rigorous, may reflect subjective perceptions shaped by the specific industrial and institutional context studied. Second, the cross-sectional nature of the analysis limits the ability to capture temporal dynamics and learning effects associated with long-term Industry 4.0 and sustainability implementation. Third, the study focuses on the gas industry, which may constrain the generalizability of the results to other sectors with different technological, regulatory, or market characteristics.

Future research could extend this work by conducting longitudinal empirical studies to examine how intelligent sustainable supply chain capabilities evolve over time and how causal relationships change as digital maturity increases. Comparative studies across different energy sub-sectors or across countries with varying institutional environments could also enhance generalizability. Additionally, integrating quantitative performance data with expert-based modeling could strengthen validation and provide richer insights into the financial, environmental, and social impacts of intelligent supply chain transformation under uncertainty.

From a managerial perspective, the results suggest that practitioners should prioritize strategic investment in Industry 4.0 technologies while simultaneously fostering leadership commitment, workforce capabilities, and cultural readiness for sustainability-oriented digital transformation. Policymakers and regulators can support this transition by providing stable regulatory frameworks, targeted incentives, and collaborative platforms that reduce uncertainty and encourage long-term investment. Finally, managers should adopt a systemic view of supply chain transformation, recognizing that sustainability and intelligence are achieved through coordinated action across technological, organizational, and institutional domains rather than through isolated initiatives.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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