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Assessing Stakeholder Preferences in Carbon Credit Systems with Neutrosophic DELPHI and DEMATEL

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Abstract

The global carbon credit market has evolved into a key mechanism for mitigating climate change, yet challenges persist regarding transparency, stakeholder trust, and market efficiency. Vietnam is in the early stages of establishing its Carbon Credit Systems (CCS), guided by its commitment to achieving net-zero emissions by 2050. Despite regulatory developments, the Vietnamese carbon market remains fragmented, with concerns over pricing disparities, market liquidity, verification standards, and stakeholder engagement. This study assesses stakeholder preferences in Vietnam's CCS using an advanced Multi-Criteria Decision-Making (MCDM) approach-based Neutrosophic Sets (NS) integrating Delphi and DEMATEL methods. Unlike traditional fuzzy logic-based models, NS provides a more nuanced representation of uncertainty by incorporating truth, indeterminacy, and falsity, allowing for more accurate stakeholder preference modeling. The NS Delphi method is applied to refine expert consensus, while NS DEMATEL identifies interdependencies among key stakeholder concerns, including policy alignment, financial incentives, verification mechanisms, and market accessibility. Findings reveal that regulatory transparency, price stability, and cross-border certification are critical factors shaping market participation. Moreover, private sector involvement and financial institutions play a pivotal role in market development, requiring stronger incentives and risk mitigation measures. The results contribute to both theoretical advancements in decision science and practical policymaking by offering structured recommendations to enhance Vietnam's carbon trading system. By integrating stakeholder perspectives with uncertainty modeling, this study provides a strategic foundation for developing a more transparent, efficient, and scalable carbon credit framework in Vietnam, ensuring alignment with global carbon pricing mechanisms and fostering long-term sustainability.

Keywords: Carbon credit market, Stakeholder preferences, Neutrosophic sets, Multi-criteria decision-making, Sustainability.

1 | Introduction

The global carbon credit market has become a key mechanism for addressing climate change through market-based emissions reductions. As of 2024, the market was valued at USD 114.8 billion and is expected to grow

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to USD 474.2 billion by 2034, driven by regulatory policies, ESG commitments, and digital innovations such as blockchain and AI that improve transparency [1]. Carbon credits are traded in both compliance markets (e.g., EU ETS, RGGI, Korea ETS) and voluntary markets, enabling organizations to offset emissions by funding certified reduction projects [2], [3]. However, the market faces persistent challenges related to offset legitimacy, double counting, greenwashing, and disparities in governance and credit quality [3], [4]. These concerns are amplified in voluntary markets, which lack centralized oversight [5]. While tokenized carbon credits offer efficiency, they also raise regulatory risks [3]. Article 6 of the Paris Agreement aims to standardize international credit transfers, yet implementation barriers remain due to fragmented standards and divergent stakeholder priorities [6]. Ultimately, stakeholder trust, transparency, and accountability are critical for ensuring the long-term credibility and effectiveness of carbon markets [4], [7].

Vietnam is gradually developing its carbon credit market as part of its 2050 net-zero commitment [8]. Under Decision No. 232/QD-TTg, a phased roadmap outlines a pilot phase (2025–2028) focused on regulatory frameworks and infrastructure, before full-scale implementation post-2029 [9]. The market will operate through a dual system of emission quotas and certified carbon credits [10]. Yet, several challenges persist: absence of a mandatory trading system, limited market liquidity, and large price discrepancies—Vietnamese credits trade at $5–10 per ton, while EU credits exceed $100 [11]. In addition, Vietnam lacks centralized verification standards, hindering international recognition. However, the country holds significant potential in forest-based credits, exemplified by the $51.5 million deal under the Forest Carbon Partnership Facility [8]. To fully realize this potential, Vietnam must strengthen its MRV systems and align more closely with international carbon markets [10].

Beyond technical design, the success of Vietnam's carbon market depends on the active engagement of stakeholders—businesses, policymakers, financial institutions, and local communities. Without strong participation from the private sector, particularly major emitters and multinational firms, the system risks fragmentation. Carbon trading must be seen not only as a compliance tool but also as a pathway to access green finance and improve corporate sustainability. Financial institutions are critical enablers, providing capital and risk-sharing mechanisms to support participation [12]. At the same time, robust regulatory frameworks are essential to incentivize emission reductions and build market trust. Local communities, especially in forest-based projects, must be included to ensure co-benefits and equity [13]. As Vietnam nears full implementation in 2028, understanding and aligning stakeholder preferences with market design is key to building a credible, scalable, and equitable Carbon Credit Systems (CCS).

Despite increasing global attention on carbon credit markets, Vietnam's CCS remains underdeveloped and understudied. Most existing research has focused on sector-specific applications, such as carbon pricing in the construction sector [14], green credit policies [15], and forestry-based sequestration [16]. However, there is a lack of a comprehensive analysis that examines stakeholder roles, interactions, and preferences across the entire Vietnamese carbon credit ecosystem. While studies on Voluntary Carbon Markets (VCMs), Emission Trading Systems (ETS), and cap-and-trade mechanisms exist for other countries [17], [18], Vietnam-specific research remains fragmented and does not provide a unified framework for stakeholder engagement in CCS development. The challenge extends beyond market structure to the very foundation of stakeholder participation, as recent studies on climate finance in Vietnam indicate that willingness to engage is driven by perceived benefits, trust, and transparency [19]. The application of Multi-Criteria Decision-Making (MCDM) methods in carbon credit market research has been well-documented, with various studies employing approaches such as Analytical Hierarchy Process (AHP), Fuzzy AHP, DEMATEL, and hybrid models to address decision-making complexities [20–22]. However, these conventional MCDM approaches often struggle to effectively model the inherent uncertainty and vagueness in stakeholder preferences, regulatory compliance, and market dynamics. Traditional fuzzy set-based models, while valuable, impose structural constraints that fail to accommodate real-world indeterminacy, where multiple conflicting perspectives coexist [23]. Neutrosophic Sets (NS), as an extension of fuzzy logic, provide a powerful alternative by incorporating three independent membership functions—truth, indeterminacy, and falsity—allowing for a more granular representation of uncertainty. While Fuzzy MCDM methods (Fuzzy AHP, Fuzzy DEMATEL) attempt to address uncertainty, they limit decision-making flexibility by forcing membership functions into predefined distributions, such as Triangular Fuzzy Numbers (TFNs), which do not fully capture hesitation or contradictions in stakeholder assessments [24]. In contrast, NS extend traditional fuzzy logic by introducing three independent membership degrees—truth, indeterminacy, and falsity—allowing for more nuanced and realistic modeling [24]. Unlike Intuitionistic Fuzzy Sets (IFS), which only account for truth and falsity but ignore indeterminacy, or Pythagorean and Spherical Fuzzy Sets, which impose summation constraints that restrict adaptability, Neutrosophic logic offers unparalleled flexibility in capturing conflicting viewpoints and incomplete information [24]. This is particularly relevant in Vietnam's carbon credit market, where stakeholder perceptions of policy effectiveness, credit pricing, and regulatory trust are often contradictory and evolving. Recent studies have demonstrated the effectiveness of NS in addressing complex decision-making scenarios, particularly in sustainability assessments, supply chain management, and financial risk evaluation [24]. By integrating NS with MCDM techniques such as DEMATEL and Delphi, researchers have successfully improved the accuracy and reliability of decision models, reduced loss of information and mitigating the limitations of traditional fuzzy-based approaches.

By addressing the complexities of stakeholder preferences and incorporating expert judgment into the analysis, this research aims to provide a more strategic and informed foundation for policy recommendations in the U.S. CCS. To achieve this goal, the primary objective is to explore and answer the following central research questions:

I. What are the key stakeholder preferences in the Vietnam's CCS?

II. How do these preferences interact and influence one another within the system?

III. How can policy recommendations be formulated to account for uncertainty and stakeholder interdependence?

As a consequence of these research questions, this study will strive to achieve the following objectives:

I. Identify and assess stakeholder preferences in Vietnam's CCS.

II. Analyze the interdependencies among these preferences using Neutrosophic DEMATEL.

III. Provide policy recommendations based on the findings, incorporating uncertainty into the decision-making process.

This research contributes significantly to both theoretical and practical aspects of carbon credit policy design. Theoretically, it advances decision-making methodologies by integrating Neutrosophic theory with the DEMATEL framework, allowing for a more precise evaluation of uncertainty and complexity in stakeholder preferences—factors often overlooked in traditional models. Methodologically, this study enhances the analytical rigor of stakeholder assessment by employing expert-driven techniques (Delphi) alongside causal analysis (DEMATEL), offering a structured approach for prioritizing stakeholder concerns. Practically, the findings will provide valuable insights for policymakers, helping to design more effective and adaptive CCS that reflect diverse stakeholder interests. By bridging the gap between theory and practice, this study aims to support the development of robust and sustainable carbon credit market strategy in the Vietnam market context.

This paper is structured as follows. Section 2 reviews existing literature on CCS and stakeholder engagement. Section 3 outlines the research methodology, detailing the use of Neutrosophic DELPHI and DEMATEL. Section 4 presents the findings and analysis, while Section 5 discusses the implications, limitations, and potential avenues for future research.

2|Literature Review

2.1| Literature Review in Carbon Credit Systems

Climate change stems from various causes, primarily global warming driven by human activities like deforestation and fossil fuel use. Earth's surface temperature has risen by about 0.8°C, with over 90% certainty that humans are the main contributors [25]. Greenhouse gases—including CO_2 (9–26%), methane, and ozone—trap heat, causing a natural warming effect of 33°C. Rapid population growth and reliance on chemical fuels since the 18th century have further escalated emissions. In May 2024, CO_2 levels reached 426.7 ppm—well above the 350-ppm safety threshold and the highest since records began. These rising emissions led to global agreements like the Kyoto Protocol (1997) [26] and Paris Agreement (2015) [27], which set reduction targets and promoted carbon pricing and credit markets to curb emissions and fund green initiatives [28]. The table below highlights key milestones in global climate policy development.

Table 1. Landmarks in the emergence of the climate change regime.

No	Conferences	Date	Key Notes	Reference
1	Kyoto Protocol	1997	Limit greenhouse gases based on national capacity, in line with UNFCCC.	[26]
2	REDD+ (Reducing emissions from deforestation and forest degradation in developing countries)	2005	Encourage developing countries to protect forests by valuing carbon storage or avoiding emissions.	[27]
3	EU ETS (European Union Emissions Trading System)	2005	Reduce emissions cost-effectively.	[29]
4	Doha Commitment (COP - 18)	2012	Kyoto II, Durban progress, climate finance, and loss/damage.	[30]
5	California Cap-and-Trade Program	2013	Cap and trade emission rights.	[31]
6	Paris Agreement	2015	From binding Kyoto targets to voluntary Paris pledges Global Stocktake (GST) to track emission progress	[32]
7	COP - 24	2018	Adoption of Paris Rulebook guidelines for measuring, reporting, and evaluating emission reductions.	[32]
8	Decision No. 1055/QD-TTg	2020	Resilience, adaptation, and sustainability.	[32]
9	COP - 26	2021	Phase out fossil fuel subsidies and accelerate net-zero actions	[32]
10	Decree No. 06/2022/ND-CP in Vietnam	2022	Roadmap for developing and operating Vietnam's carbon credit market.	[33]
11	Decree No. 107/2022/ND-CP	2022	Forest carbon trading pilot in North Central Vietnam.	[34]
12	COP - 29	2024	Climate finance for low-carbon transition in developing countries	[35]

The global climate regime began with the Kyoto Protocol (1997)[26], requiring developed countries to reduce emissions [26] REDD+ (2005) followed, encouraging forest protection in developing countries by valuing stored carbon [26]. That same year, the EU ETS enabled Europe to cut emissions via carbon markets [29] COP-18 (2012) expanded Kyoto targets and emphasized climate finance California's Cap-and-Trade (2013) became a model for regional carbon trading [30], [31]. The Paris Agreement (2015) marked a global shift toward voluntary commitments and progress tracking COP-24 (2018) introduced the Paris Rulebook to guide implementation [32]. Vietnam joined with Decision 1055/QĐ-TTg (2020) for adaptation and sustainable growth [36]. COP-26 (2021) urged cuts in fossil fuel subsidies [32], [36], followed by Vietnam's Decrees 06/2022 and 107/2022 on carbon and forest credit markets [33], [34]. Most recently, COP-29 (2024) prioritized climate finance for developing nations [35].

To improve global coordination, Common Carbon Market Systems (CCMS) were introduced to connect countries with similar emission profiles, enhance transparency, and cut reduction costs—addressing Kyoto's limitations [29]. Linking national ETSs could increase efficiency but reduces regulatory autonomy [37]. Mechanisms like "exchange rates" for carbon units have been suggested [38] though differences in policy and standards remain barriers [39], [40]. Despite these, studies show benefits from linking systems like the EU and U.S. markets [40]. The Clean Development Mechanism (CDM), under Kyoto, allows entities to offset emissions by funding projects in developing countries, though concerns remain over additionality and actual impact [41]. Similarly, California's Compliance Offset Mechanism under AB32 (2006) enables large emitters to use certified credits for compliance, regulated for rigor and permanence [22], [42]. VCMs offer flexibility for non-mandated actors, with projects ranging from forest conservation to CO_2 removal—though transparency and governance issues persist [43].

Carbon credit allocation methods—free allocation and auctioning—significantly affect ETS fairness and efficiency. Free allocation helps ease transition, especially in emission-heavy sectors, but may lead to windfall profits [39]. Auctioning promotes fairness, government revenue, and investment in clean technology, as adopted increasingly in the EU ETS [44]. The success of CCS depends on collaboration among four key groups: policymakers, industry, NGOs, and academia [40], [45]. Policymakers design and monitor frameworks aligned with global goals [46], [47]. Industry must comply with regulations and often invests in CCS or VCMs NGOs ensure transparency and public engagement while researchers provide models, analysis, and education to guide policy [25], [28], [46, 48, 49]. Effective cooperation among these actors is key to long-term CCS success.

2.2 | Key Factors Impacting Stakeholder Preferences in CCS

Stakeholders in CCS, encompassing parent companies, governments, businesses, institutional investors, financial entities, research and development institutions, and environmental NGOs, are defined as groups or organizations capable of influencing carbon emission reduction objectives [50–53]. Identifying the factors influencing stakeholder preferences helps determine their needs and priorities in the development and construction of the CCS. The Stakeholder theory, originating from the work of Flak and Rose [54], suggests that addressing the needs of various stakeholders enhances both profitability and long-term sustainability of an organization. This theory also posits that the success of complex governance agreements depends on active participation, trust, and satisfaction of different stakeholder groups, each with their own interests and levels of influence. The Emissions Trading System (ETS) theory, provides a market-based framework for managing greenhouse gas emissions [55]. As Flak and Rose [54] highlighted in their study of Stakeholder theory applied to e-Government, businesses and governments fundamentally differ in their goals, with businesses prioritizing profitability and sustainability, while governments focus on policy formulation, regulation, service provision, and regional development. In the carbon credit market, stakeholder preferences are influenced by interconnected factors such as system design, governance, market transparency, and technology [24], [54], [56]. These differing goals shape stakeholders' priorities within the CCS

, requiring a balance between financial efficiency and environmental integrity based on the preferences and needs of the parties involved in the carbon emissions market. In this context, establishing quantitative emission levels, allocating tradable permits or credits, and allowing market-driven trading mechanisms create a flexible and cost-effective approach to achieving environmental goals [57].

While the ETS theory explains the operations of the market, it also assumes a stable Institutional Environment (IE) [57]. Institutional theory emphasizes that markets function effectively only when shaped by both formal and informal institutions through reliable, predictable legal and regulatory frameworks that provide legitimacy and reduce uncertainty [58]. Allocation methods, such as auctions versus reserve mechanisms, affect fairness and efficiency while equitable credit distribution across sectors fosters trust [59]. Ensuring transparency at the project level is crucial for building credibility and reinforcing market trust [60]. To ensure the reliability and sustainability of the trading system, institutional governance frameworks and enforcement mechanisms that support market legitimacy have been established based on institutional theory [58]. Effective institutions help mitigate information asymmetry, reduce uncertainty, and foster stakeholder trust, thereby enhancing liquidity and market efficiency in the carbon credit market. Yunjing Wang et al. [61], based on Stakeholder theory, Institutional theory, the Natural Resource-Based View (NRBV), and Low-Carbon Strategic Cost Management, developed a new four-dimensional framework and proposed a carbon reduction roadmap for companies, focusing on participation in the ETS, green technology adoption, strengthening corporate governance, and maintaining cash flow to support the transition to low-carbon operations [61]. The application of blockchain, AI, and IoT in the carbon credit market also marks a fundamental shift in the way emissions are tracked, reported, and verified [62]. These technologies have the potential to enhance market efficiency and reinforce the credibility of carbon trading systems. The integration of these foundational theories allows our paper to identify the key factors influencing stakeholder priorities in a successful CCS. Based on the theories of stakeholders, institutions and ETS, we build an analytical framework for the factors affecting the preferences of stakeholders in the CCS. Combining these theories, we propose 5 dimensions with 50 factors, as presented in *Table 2*, to help identify the needs and priorities of stakeholders in the process of developing a CCS.

Table 2. List of key factors effect stakeholder preferences in Carbon Credit System.

No	Dimensions	Code	Barrier Name	Definition	References
1	System Design and Operation (SDO)	SDO1	Method of initial credit allocation	How carbon credits are distributed at the start (e.g., free allocation, auction)	[63]
2		SDO2	Equity in allocation among sectors/regions	Fair distribution of credits across industries and regions	[59], [64]
3		SDO3	Adjustment mechanisms for allocation over time	Mechanisms to modify credit allocation based on changing conditions	[64]
4		SDO4	Treatment of new entrants and exiting companies	Rules for credit allocation to new businesses and handling exiting ones	[65]
5		SDO5	Allocation based on performance or efficiency	Assigning credits based on emissions efficiency and sustainability efforts.	[64]
6		SDO6	Price determination mechanism	How carbon credit prices are set (market-driven or regulated).	[66]
7		SDO7	Price stability and volatility management	Strategies to control extreme price fluctuations.	[67]
8		SDO8	Banking and borrowing of credits	Allowing firms to save or borrow credits for future use.	[68], [69]
9		SDO9	Market power and competition issues	Ensuring no firm dominates carbon trading unfairly.	[70]
10		SDO10	Liquidity of the market	The ease of buying and selling carbon credits.	[71], [72]
11	Transparency and Accountability (TA)	TA1	Public access to credit issuance and retirement data	Availability of credit issuance and retirement information.	[73]
12		TA2	Transparency in credit trading platforms	Openness in transaction records and market operations.	[73]
13		TA3	Disclosure of company-specific emission data	Disclosure of firms' emissions levels.	[74]

Table 2. Continued.

No	Dimensions	Code	Barrier Name	Definition	References
14	Transparency and Accountability (TA)	TA4	Independent auditing of the system	The involvement of third-party auditors to verify emissions reductions and ensure compliance.	[75]
15		TA5	Mechanisms for public participation and feedback	the public to express preferences, provide feedback, and voice concerns about the CCS, ensuring its legitimacy and social acceptance.	[76]
16		TA6	Robustness of monitoring methodologies	Reliability of emission tracking systems.	[77]
17		TA7	Frequency and accuracy of emission measurements	Frequency and precision of emissions data collection.	[78]
18		TA8	Independent third-party verification	Independent validation of emission reductions.	[31]
19		TA9	Transparency in verification reports	Public availability of audit and compliance results.	[79]
20		TA10	Handling of uncertainties and errors	Errors and fraud in credit systems.	[80]
21	Impact and Effectiveness (IE)	IE1	Overall cap on emissions and its stringency	The total limit on emissions and its enforcement level.	[81]
22		IE2	Achievement of emission reduction targets	How well the system meets emission reduction goals.	[82]
23		IE3	Additionality of emission reductions	Ensuring reductions wouldn't happen without the system.	[83]
24		IE4	Permanence of emission reductions	Long-term sustainability of emission reductions.	[84]
25		IE5	Avoidance of double counting	Avoiding multiple claims on the same emission reduction.	[85]
26		IE6	Impact on jobs and livelihoods	Effects of carbon trading on employment.	[86]
27		IE7	Distributional effects across socioeconomic groups	How benefits and costs are spread across groups.	[87]
28		IE8	Impact on economic growth and competitiveness	Influence on national and industrial competitiveness.	[88]
29		IE9	Support for vulnerable communities	Ensuring benefits reach disadvantaged populations.	[89]
30		IE10	Equity in system design and implementation	Fair treatment of all stakeholders in policy and practice.	[59]

Table 2. Continued.

No	Dimensions	Code	Barrier Name	Definition	References
31	Governance and International Relations (GIR)	GIR1	Regulatory oversight and enforcement mechanisms	Carbon credit governance and regulatory oversight	[89]
32		GIR2	Legal framework and stability	Legal framework and stability in carbon markets	[90]
33		GIR3	Role of government agencies in system management	Role of government agencies in carbon credit management	[91]
34		GIR4	International compatibility and recognition	International compatibility of carbon trading systems	[92]
35		GIR5	Adaptive management and policy updates	Adaptive management and carbon policy updates	[93]
36		GIR6	Recognition of international credits	Recognition of international carbon credits	[94]
37		GIR7	Linkages with other carbon markets	Linkages between carbon markets worldwide	[95]
38		GIR8	Compliance with international climate agreements	Compliance with international climate agreements and carbon credits	[83]
39		GIR9	Harmonization of standards and methodologies	Harmonization of carbon credit standards and methodologies	[96]
40		GIR10	Participation in global carbon pricing initiatives	Global carbon pricing initiatives and participation	[97]
41	Offsets and Innovation (OI)	OI1	Eligibility criteria for offsets	Eligibility criteria for carbon offsets	[98]
42		OI2	Types of projects eligible for offsets	Types of projects eligible for carbon offset programs	[83]
43		OI3	Additionality and permanence requirements for offsets	Additionality and permanence requirements in carbon offsets	[99]
44		OI4	Limits on the use of offsets	Limits on carbon offset usage in credit systems	[100]
45		OI5	Transparency in offset project information	Transparency in carbon offset project information	[60]
46		OI6	Incentives for emission reduction technologies	Incentives for emission reduction technologies	[101]
47		OI7	Support for research and development	Support for research and development in carbon reduction	[102]
48		OI8	Encouragement of low-carbon innovation	Encouraging low-carbon technology and innovation	[103]
49		OI9	Technology transfer mechanisms	Technology transfer mechanisms for carbon reduction	[104]
50		OI10	Compatibility with emerging technologies	Compatibility of carbon credits with emerging technologies	[62]

2.3 | Previous Studies

MCDM techniques have proven effective in various carbon credit applications. Wei et al. [105] built a framework to assess barriers in forest carbon sink projects in China, while Chen et al. [106] examined challenges in Taiwan's offset projects. Wu et al. [107] ranked Chinese pilot cities for carbon finance, and Florindo et al. [108] evaluated emission reduction strategies in Brazilian beef exports based on impact. These studies show how MCDM helps prioritize influencing factors in CCS. To understand stakeholder preferences in CCS, it's essential to review how past research has applied diverse decision-making tools. Prior studies have addressed how policies, financial models, market design, and regulation shape stakeholder views. For instance, Su et al. [109] highlighted key implementation challenges in Africa, such as finance access, policy gaps, and limited expertise. Gujba et al. [110] emphasized price volatility and unclear policy as major market barriers. *Table 3* summarizes studies using tools like Delphi, AHP, Fuzzy Delphi, and DEMATEL to explore CCS-related preferences. These works underline the value of participatory approaches, expose key market barriers, and offer strategic paths to foster effective CCS. Synthesizing these insights helps identify research gaps and suitable methodological combinations to support stakeholder involvement and inform CCS policymaking.

Table 3. Summary of articles and methods related to stakeholder preferences in carbon credit system.

No	Articles	Methods	Applications
1	[111]	Delphi	Emphasizes the government's role, the need for inclusive participatory processes, and enhancing the role of NGOs in the decision/evaluation process.
2	[112]	WINGS, AHP-EWM	Assess and prioritize factors influencing carbon emissions reduction in agriculture, helping policy makers develop effective emissions reduction strategies.
3	[113]	Delphi, Fuzzy AHP	Emphasizes the need for strong political support, economic incentives, and environmental regulations to accelerate green finance development.
4	[48]	AHP	Applying AHP method to identify and rank sustainable development issues at regional level, focusing on stakeholder groups and specific issues in Goa region, India.
5	[23]	Fuzzy Delphi, Fuzzy DEMATEL	Explore the critical barriers to developing the green bond market, including policy, market, financial, capacity, and awareness challenges. Provides insights and recommendations for overcoming these barriers, enhancing green finance practices in Vietnam and other emerging economies.
6	[22]	Fuzzy Delphi, Fuzzy DEMATEL	Provides a structured framework for understanding the relationships between various factors such as policy and regulation, economic market conditions, financial institutions, and behavioral aspects.
7	[114]	Delphi-AHP, Fuzzy TOPSIS	Emphasize the importance of wind energy... offering a practical tool for government agencies and stakeholders to guide energy investments and resource development in line with Pakistan's sustainability goals.
8	[115]	Fuzzy AHP, Fuzzy VIKOR, TOPSIS	Highlights the importance of involving diverse stakeholders (government, NGOs, academia, industry, and local representatives) to ensure that the sustainability index reflects a broad range of perspectives.

Table 3 summarizes recent studies applying advanced decision-making methods to CCS. While prior research addresses market design, credit allocation, and verification, few have explored how different stakeholders—such as policymakers, industries, NGOs, and researchers—prioritize key system components. For example, Taylan et al. [115] used a hybrid Fuzzy AHP–VIKOR–TOPSIS model to rank eight energy systems in Saudi Arabia based on nine criteria. Solar PV emerged as the top choice, but the study lacked consideration of social impacts. Similarly, Solangi et al. [114] integrated Delphi, AHP, and Fuzzy TOPSIS to rank renewable energy options in Pakistan using four criteria and 20 sub-criteria. Wind energy was found most viable, though the long-term economic effects remained unexamined.

In India, Kwatra et al. [48] applied AHP to rank sustainability issues in Goa. They involved stakeholders across sectors and found local concerns like waste and governance ranked higher than global issues. However, the study didn't offer concrete policy solutions. Focusing on carbon emission reduction, Zhang et al. [112] used an FNS–WINGS–AHP-EWM framework in agriculture. Policy and technology were found most influential, though system complexity limited the model's comprehensiveness. Li et al. [111] combined Delphi and Fuzzy AHP to study green finance in China, identifying political factors like climate commitment as most impactful. Yet, their findings remained vulnerable to policy shifts. In Vietnam, Nguyen et al. [24] applied Fuzzy Delphi, DEMATEL, and DANP to identify 38 green bond market barriers across five dimensions. Weak regulations and unclear guidelines were top obstacles, though global market risks were not fully assessed. Dong and Huo [22] also used Fuzzy Delphi–DEMATEL to explore financial barriers to energy efficiency in SMEs. Inefficient trading mechanisms and limited incentives were key issues, but the study overlooked awareness and behavioral barriers. Combining Neutrosophic Delphi and DEMATEL in studying issues related to carbon credit is not popular. In this paper, we will use the combination of Neutrosophic Delphi and DEMATEL methods to identify factors influencing the preferences of stakeholders in a CCS. Delphi reduces uncertainty and expert bias, while DEMATEL uncovers causal relationships and influence levels among factors. This integrated approach enhances the accuracy of stakeholder preference analysis and supports better policy design.

2.4|Literature Review on Methods

2.4.1|The importance of MCDM in evaluating carbon credit systems and Delphi-DEMATEL method

MCDM is an effective framework for tackling complex problems with conflicting criteria by integrating qualitative and quantitative data [116]. Since the adoption of the Paris Agreement and SDGs in 2015, numerous climate policies have emerged [113], [117]. MCDM has been widely applied in the CCS field to address financial constraints, policy risks, and market volatility [109]. Hybrid methods such as Fuzzy Delphi and DEMATEL support policy and risk evaluation [105] while Fuzzy COCOSO and CRITIC improve financial risk analysis [118]. Delphi also assists in forecasting and strategic planning [119]. Li et al. [111] found political factors key to green finance in China using Delphi and Fuzzy AHP. Zhang et al. [112] proposed an FNS-WINGS-AHP-EWM model to assess agricultural emission reduction, highlighting technology's role. In India, Kwatra et al. [48] applied AHP to rank local sustainability priorities like waste and governance. These studies confirm MCDM's flexibility in supporting transparency and effective carbon credit policy.

The Delphi method, developed by RAND in the 1950s, aims to build expert consensus through iterative surveys with controlled feedback [120], [121]. It is widely used to identify managerial and supply chain risks Khan et al. [122] with anonymity reducing bias [123]. Though qualitative, Delphi is effective for extracting expert insights [123]. Li et al. [113] used Delphi to identify 6 key and 26 sub-factors for green finance. The Fuzzy Delphi method refines this by applying fuzzy logic and TFNs, enabling single-round consensus and minimizing biased judgments [22]. DEMATEL, developed in the 1970s by Battelle Memorial Institute, analyzes causal relationships between criteria through pairwise comparisons, visualizing them via matrices or graphs [124], [125]. It is particularly useful in complex decision contexts [126]. In green supply chains, DEMATEL identified carbon information management and training as key influencers in supplier [126]. Kazemi et al. [127] found energy efficiency to be the most impactful CO_2 reduction strategy. DEMATEL's ability to map cause-effect relationships distinguishes it from AHP and ISM, offering deeper insight into variable interdependence [128].

2.4.2|The Neutrosophic set

Indeterminacy stems from the inherent complexity of real-world situations—just as there are infinite shades between black and white or millions of decimals between zero and one—therefore, analytical methods must be sufficiently flexible and adaptable to handle incomplete, inconsistent, and indeterminate data without neglecting any part of its [129]. *Fig. 1* shows the geometric representation between Fuzzy Sets (FS), IFS, Pythagorean Fuzzy Sets (PFS) and NS. The three axes in space include α (truth), β (falsity), and γ (indeterminacy). FS, developed by Zadeh [130] in 1965, allows the representation $\alpha \in [0;1]$ to handle ambiguity in information, but only reflects the degree of consensus without expressing disagreement or hesitation, making it limited in complex and multidimensional decision-making contexts such as environmental policy. While FS are considered the foundation for ambiguity theories, in more complex cases—where uncertainty is not simply a linear path between true and false—FS is quite limited. To overcome the limitations of FS, IFS added a falsity component in addition to the truth, in which each element is described by two functions f and t with the constraint $f + t \leq 1$, and the remaining part represents the hesitation level to more intuitively reflect the lack of certainty in human judgment [131]. However, a notable limitation of IFS is the constraint that the sum of the confidence and negation values does not exceed 1, which reduces the flexibility when it is necessary to simultaneously represent both high confidence and negation levels in complex situations.

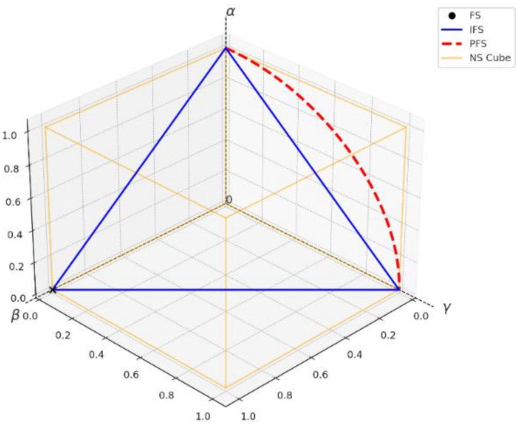

Fig. 1. Geometric representations of Fuzzy and Neutrosophic numbers.

PFSs developed to overcome the limitations of IFSs allow the sum of squares of the consensus (t) and dissent (f) levels to not exceed 1 ($t^2 + f^2 \leq 1$) instead of the linear constraint as in IFSs ($t + f \leq 1$), thereby expanding the representation space and increasing flexibility in reflecting conflicting assessments with high consensus and dissent levels at the same time, but still does not allow determining the indecisive component (i) independently but only indirectly inferring from the other two components [132]. NSs allow the three main components – truth, falsity, and indeterminacy – to vary independently between 0 and 1 without being constrained by a total limit, thereby significantly expanding the ability to represent highly uncertain judgments in situations where experts cannot clearly determine right or wrong or when market information is lacking [133]. Viewed from a three-dimensional perspective, NSs not only generalizes traditional FS both geometrically and conceptually but also provides a necessary methodological foundation for this study by enabling more practical and comprehensive evaluation contexts in characterized by conflicting, ambiguous, or hard-to-define data—especially common in analyzing stakeholder behavior, preferences, and expectations within the climate sector.

2.4.3 | Integration of Neutrosophic Delphi-DEMATEL

Although Zadeh [130] introduced FS in 1965 and later developed interval-valued FS (1975), these models still struggle with uncertainty under incomplete information [134]. To address this, Atanassov proposed IFS by adding non-membership values, and later, with, extended IFS into interval form [134]. Smarandache developed NS with three independent components—truth (T), indeterminacy (I), and falsity (F)—to handle incomplete, conflicting, and uncertain data [135]. Wang introduced single-valued NSs for decision-making in situations with conflicting information.

Nguyen et al. [24] applied Neutrosophic-Z (NZN) combined with Delphi and DEMATEL to analyze barriers to sustainable fashion consumption in Vietnam. NZN handled uncertainty in consumer behavior, Delphi gathered expert opinions, and DEMATEL identified cause-effect relationships. Similarly, Abdel-Basset integrated Neutrosophic, Delphi, and AHP to assess green building sustainability—an MCDM problem under uncertainty. While AHP is widely used in MCDM [136], [137], it has limitations under uncertain conditions. Therefore, for evaluating CCS, combining Neutrosophic Delphi with DEMATEL is more suitable—DEMATEL reveals cause-effect links between factors like credit allocation, market transparency, and emission reduction, while Neutrosophic logic improves decision reliability under uncertainty.

3 | Methods

3.1 | Preliminaries

The NS theory builds upon the IFS theory by introducing a more flexible approach to handling incomplete information [138]. Unlike IFS, where the sum of membership degrees must equal 1, NS theory allows for independent assignment of truth (T), falsity (F), and indeterminacy (I) degrees, with their total sum reaching up to 3. This enables a more nuanced representation of uncertainty.

Formally, let N be a set of elements, where each element $n \in N$ is characterized by an NS O defined through three membership functions:

Truth-membership function: $T_O(n)$

Indeterminacy-membership function: $I_O(n)$

Falsity-membership function: $F_O(n)$

These functions take values within the extended range $]0^-,1^+[$, meaning they can slightly exceed the conventional limits of 0 and 1, offering a more comprehensive way to model uncertainty.

Specifically:

$T_O(n): N \rightarrow]0-,1+[$

$I_O(n): N \rightarrow]0-,1+[$

$F_O(n): N \rightarrow]0-,1+[$

In the NS framework, there is no strict requirement that the sum of truth, indeterminacy, and falsity values must follow a fixed rule. However, the maximum possible sum of these values must remain within the range of 0 to 3, expressed mathematically as:

0^-≤ supT_O(n) + supI_O(n) + supF_O(n) ≤ 3^+.

This structure provides greater flexibility in managing uncertainty, truth, and falsity within a system, as it is not bound by rigid constraints, allowing for a more adaptable representation of imprecise or incomplete information.

Definition 2. Let N be a set of objects, where each object is represented by n [139]. A Single-Valued Neutrosophic Set (SVNS), denoted as Ö is defined as follows:

$$\ddot{O} = \{ (n, T_{\ddot{o}}(n), I_{\ddot{o}}(n), F_{\ddot{o}}(n) : n \in N \}. \quad (1)$$

When an object n belongs to the SVNS, it is referred to as a Single-Valued Neutrosophic Number (SVNN). For simplicity, this can be expressed as:

$$n = \left(T_{\ddot{o}}(n), I_{\ddot{o}}(n), F_{\ddot{o}}(n)\right).$$

Definition 3. Consider two SVNNs, denoted as $x = (T_x, I_x, F_x)$ and $y = (T_y, I_y, F_y)$ where $z > 0$ is a positive constant. The following mathematical operations can be applied to these numbers.

$$x \supseteq y \Leftrightarrow T_x \geq T_y, I_x \leq I_y, F_x \leq F_y. \quad (2)$$

$$x = y \Leftrightarrow x \supseteq y \text{ and } y \supseteq x. \tag{3}$$

$$x \cup y = \langle T_x \vee T_y, I_x \wedge I_y, F_x \wedge F_y \rangle. \tag{4}$$

$$x \cap y = \langle T_x \wedge T_y, I_x \vee I_y, F_x \vee F_y \rangle. \tag{5}$$

$$x\text{^}i = \langle F\_x, 1 - I\_x, T\_x \rangle \text{ (Complement of x)}. \tag{6}$$

Addition of Two SVNNs:

$$x \oplus y = \left(T_x + T_y - T_x T_y, I_x I_y, F_x F_y\right). \tag{7}$$

This operation merges the truth, indeterminacy, and falsity values of both x and y. Multiplication of Two SVNNs:

$$x \otimes y = \left(T_x T_y, I_x + I_y - I_x I_y, F_x + F_y - F_x F_y\right). \tag{8}$$

This operation computes the product of the truth values while appropriately modifying the indeterminacy and falsity values. Scaling an SVNN by a positive constant z:

$$zx = (1 - (1 - Tx)z, Ixz, Fxz). \tag{9}$$

This operation adjusts the truth, indeterminacy, and falsity values of aa based on the constant z. Raising an SVNN to the power of z:

$$xz = (T_x z, 1 - (1 - I_x)z, 1 - (1 - F_x)z). \tag{10}$$

In this operation, each component of x is exponentiated by z.

Definition 4. This describes the process of aggregating multiple SVNNs using a weighted approach. Consider a set of SVNNs, represented.

$\ddot{O}_r = (T_{\ddot{O}_r}, I_{\ddot{O}_r}, F_{\ddot{O}_r})$ and r = 1, 2,…, n. Each SVNN consists of three components: truth, indeterminacy, and falsity membership functions. The Single-Valued Neutrosophic Weighted Aggregation Arithmetic (SVNWAA) operator for these SVNNs is computed as follows:

$$\begin{aligned} \text{SVNWAA}(\bar{A}_1, \bar{A}_2, \dots, \bar{A}_n) &= \sum_{j=1}^{n} w_j \bar{A}_j \\ &= \left[1 - \prod_{j=1}^{n}\left(1 - T_{\bar{A}_j}\right)^{w_j}, \prod_{j=1}^{n}\left(I_{\bar{A}_j}\right)^{w_j}, \prod_{j=1}^{n}\left(F_{\bar{A}_j}\right)^{w_j}\right]. \end{aligned} \tag{11}$$

The Single-Valued Neutrosophic Weighted Aggregation Geometric (SVNWAG) operator for these SVNNs is determined using the following formula:

$$\begin{aligned} \text{SVNWAG}(\tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n) &= \prod_{j=1}^{n} (\tilde{A}_j)^{w_j} \\ &= \left[\prod_{j=1}^{n}\left(T_{\bar{A}_j}\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - I_{\bar{A}_j}\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1 - F_{\bar{A}_j}\right)^{w_j}\right]. \end{aligned} \tag{12}$$

In this formula:

w_r denotes the weight assigned to each SVNN $\ddot{O}_r$ with the condition that $w_r > 0$ and the weights sum to 1.

The truth component $T_{\ddot{O}_r}$ is aggregated using a complement product-based approach.

The indeterminacy $I_{\ddot{O}_r}$ and falsity $F_{\ddot{O}_r}$ components are computed using weighted geometric means.

Definition 5. This defines the process of deneutrosophication, which simplifies a SVNN by transforming it into a real number.

Given an SVNN, Ö is represented as:

$$\ddot{O} = \{ (n, T_{\ddot{o}}(n), I_{\ddot{o}}(n), F_{\ddot{o}}(n)) : n \in N \}.$$

The objective is to reduce this set to a single real number by applying the following computation:

$$E(\ddot{O}) = \frac{3 + T_{\ddot{o}} - 2I_{\ddot{o}} - F_{\ddot{o}}}{4}. \quad (13)$$

Illustrative example 1: let us work with two SVNNs: x = (0.7, 0.2, 0.25) and y = (0.5, 0.4, 0.35), z = 0.6, wx = 0.55 and wy = 0.45 an example of *Eqs. (2)–(7)* are shown below:

x ⊕ y = (0.7, 0.2, 0.25) ⊕ (0.5, 0.4, 0.35) = (0.85, 0.08, 0.15)

x ⊗ y = (0.7, 0.2, 0.25) ⊗ (0.5, 0.4, 0.35) = (0.35, 0.52, 0.575)

zx = 0.6 · (0.7, 0.2, 0.25) = (0.5832, 0.3200, 0.4168)

xz = (0.7748, 0.1360, 0.2252)

$SVNWAA$ (x, y) = (0.6458, 0.2880, 0.3452)

$SVNWAG$ (x, y) = (0.6285, 0.3156, 0.3764)

$$E(x, y) = \frac{3 + 0.6458 - 2 \cdot 0.2880 - 0.3452}{4} = 0.68115.$$

3.2 | Research Flowchart

The proposed model includes two consecutive stages—NS Delphi and NS DEMATEL—each targeting distinct elements involved in assessing and overcoming obstacles to WMPs in SRL, as depicted in *Fig. 2.*

Phase 1 focused on identifying and validating important factors that influence stakeholder preferences in the CCS. An expert panel of researchers, policy makers, and business representatives in the environmental and carbon finance fields was assembled to assess the importance of each factor. The Neutrosophic Delphi method was applied to synthesize expert opinions, ensure consensus, and eliminate factors with weak influence. The result of this phase is a list of the most important factors, which serves as the basis for analyzing the causal relationship between them.

Phase 2 used the Neutrosophic DEMATEL method to assess the level of mutual influence between barriers to stakeholder preferences in the CCS. Based on the validated factors from Phase 1, the experts continued to analyze the level of impact of each factor on other factors, determining the causal relationship between them. This process involves gathering expert opinions on the strength of influence between factors, using the Neutrosophic set theory to handle the uncertainty in the assessment. From there, a direct impact matrix is built and standardized to identify the cause factors and the affected factors (effect factors). The results of this stage help clarify the dependency relationship between factors, identify key barriers with strong spillover effects, and propose priority strategies to improve the CCS. The calculation of impact weights supports the decision-making process, helping to focus on the factors that have the greatest impact on the priorities of stakeholders.

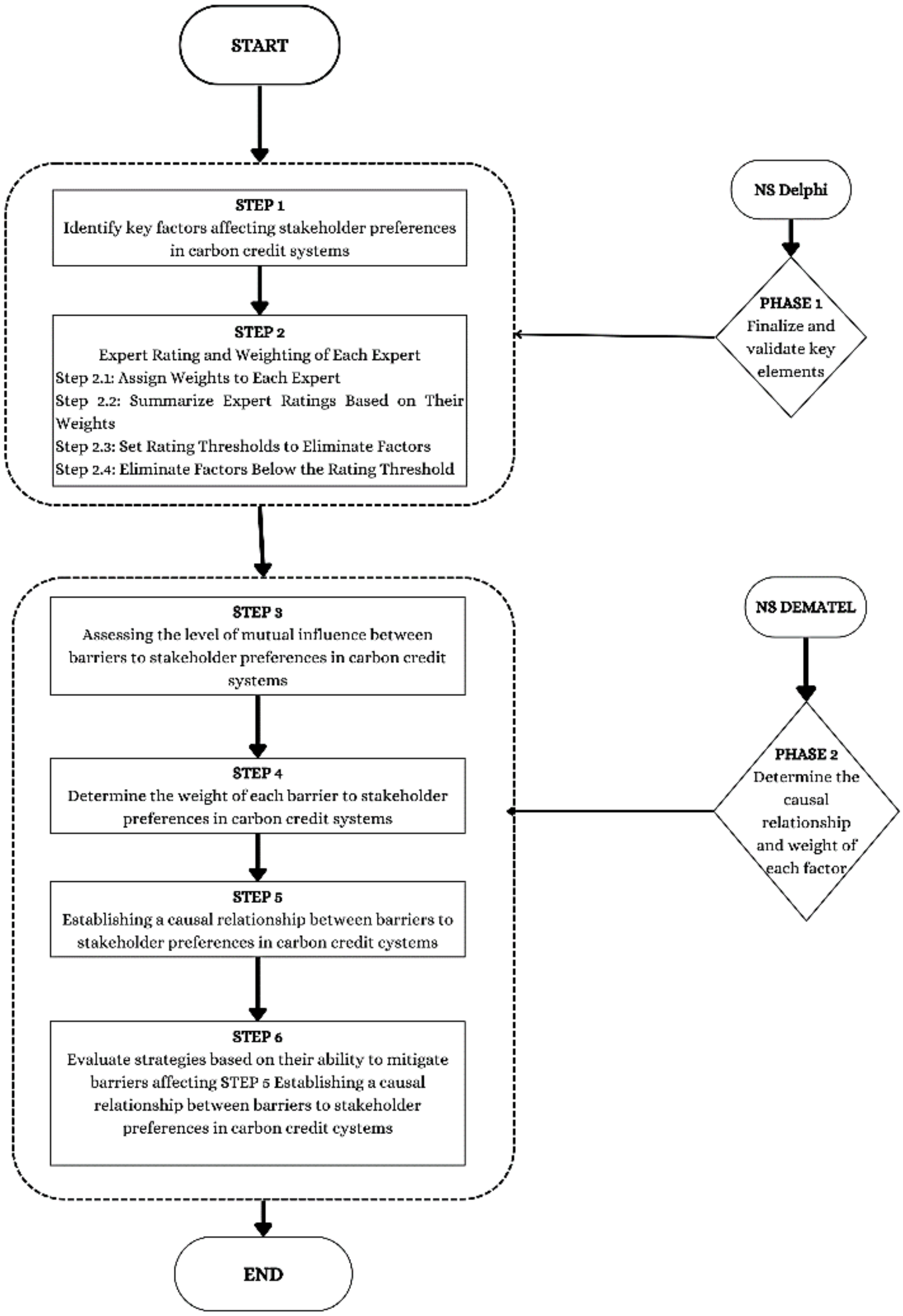

Fig. 2. Research flowchart.

3.3 | NS Delphi Method

In the assessment process, m experts evaluate l factors, assigning significance to each factor using a linguistic scale. These linguistic evaluations are then transformed into NS numbers, allowing for the handling of uncertainty in expert opinions.

Step 1. Calculating the expert weight.

The weight assigned to each expert is determined using NS numbers, considering two key criteria:

Professional experience (measured by the number of years working in the relevant field).

Educational background (academic qualifications and research expertise).

Each expert is assessed based on these two criteria and assigned corresponding values in the Neutrosophic framework. These values are then combined using *Eq. (2)* to compute the preliminary expert weight. This weight is further refined and converted into a precise numerical score through *Eq. (7)*.

The final weight reflects the reliability of each expert's judgment in the evaluation process. *Table 4* presents the expert-level assessment criteria alongside the corresponding linguistic scale [140].

Table 4. Expert rating scale.

Education	Experience	Linguistic Scale	Code	NS Number
Doctor	Over 20 years	Extremely high	EH	(0.8,0.15,0.2)
Master	From 10 to 20 years	High	H	(0.6,0.35,0.4)
Bachelor	From 5 to 10 years	Medium	M	(0.4,0.65,0.6)
Under Bachelor	Under five years	Low	L	(0.2,0.85,0.8)
		Extremely low	EL	(0,1,1)

For example, Expert 1 holds a master's degree and possesses between 5 to 10 years of professional experience. Given these credentials, their weight is assessed as high (H) for qualifications and medium (M) for experience. These assessments are represented using NS as follows:

Qualifications: (0.6, 0.35, 0.4)

Experience: (0.4, 0.65, 0.6).

The two NS evaluations are integrated using *Eq. (7)*, and the resulting value is then transformed into a crisp number using *Eq. (13)*. Accordingly, the final evaluation for Expert 1 is:

$$(0.6, 0.35, 0.4) \oplus (0.4, 0.65, 0.6) = (0.76, 0.2275, 0.24).$$

By applying *Eq. (13)* to convert the NS number (0.76, 0.2275, 0.24) into a crisp value, the resulting score is 0.76625.

To determine the evaluation values for m experts, we derive a set of m scores, represented as SM, where: $\mathrm{sm_x} = \{\mathrm{sm_1},\ \mathrm{sm_2},\ \mathrm{sm_3}, \dots \mathrm{sm_m}\}$. The weight assigned to each expert, denoted as SW, is expressed as: $\mathrm{sw_x} = \{\mathrm{sw_1},\ \mathrm{sw_2},\ \mathrm{sw_3}, \dots \mathrm{sw_x}\}$. This weighting is calculated using the formula provided in *Eq. (14)*.

$$\mathrm{sw_x} = \frac{\mathrm{sm_x}}{\sum_{x=1}^{m} \mathrm{sm_x}}. \quad (14)$$

This formula determines each expert's weight by dividing their evaluation score $\mathrm{sm_x}$ by the sum of all experts' scores. This calculation yields the relative weight, representing the expert's significance in comparison to others within the group.

Step 2. Construct a weighted expert evaluation matrix.

Experts assess the significance of l factors. Their initial evaluations, expressed in linguistic terms, are then converted into NS numbers and structured into a matrix:

$$\otimes\ \mathrm{FM} = [\mathrm{f_{hx}}]_{\mathrm{lxm}},$$

where:

l is the number of factors being evaluated.

m is the number of participating experts.

The linguistic evaluation scale and corresponding NS values are outlined in *Table 5* [140], [141].

Each element f_{hx} within the matrix represents the evaluation score assigned by expert x for factor h. This conversion process translates qualitative assessments into a structured quantitative format, facilitating a systematic analysis of factor importance across the expert group [139].

Table 5. Linguistic Importance Scale in NS Delphi.

Linguistic Scale	Code	Membership Function		
		T	I	F
Extremely high	EH	0.8	0.15	0.2
High	H	0.6	0.35	0.4
Medium	M	0.4	0.65	0.6
Low	L	0.2	0.85	0.8
Extremely low	EL	0	1	1

The weighted expert evaluation matrix, denoted as: $\otimes FMW = [fw_{hx}]_{lxm}$ is calculated using *Eq. (15)* below:

$$fw_{hx} = fw_{hx} \otimes sw_x, \tag{15}$$

where:

h = 1,2, … , l represents the factors being evaluated.

x = 1,2, … , m denotes the participating experts.

sw_x is the weight assigned to expert x, expressed as a set $\{sw_1, sw_2, sw_3, \dots, sw_x\}$.

This step ensures that each expert's evaluation is weighted appropriately, reflecting their relative importance in the assessment process.

Step 3. Determining the threshold and validating factors.

Each factor is evaluated by m experts. The individual expert assessments are aggregated using *Eq. (6)*, producing a consolidated evaluation for each of the l factors, represented in Normalized NS format.

Next, the aggregated evaluations are converted into crisp scores using *Eq. (13)*, resulting in a set of l evaluation values.

$$xp_h = \{xp_1, xp_2, \dots, xp_l\}.$$

To establish the acceptance threshold, the threshold value γ is computed using *Eq. (16)*.

$$\gamma = \frac{\sum_{h=1}^{l} xp_h}{l}. \tag{16}$$

A factor h is considered acceptable if its evaluation score xp_h meets or exceeds the threshold γ. Conversely, if xp_h is below γ, the factor is eliminated.

3.4 | NS DEMATEL Method

Suppose there are m experts, each assigned a specific weight wb, assessing the mutual influence of l factors. Initially, the ratings are expressed in linguistic terms and then converted into NS. The rating scale and the corresponding NS values are provided in *Table 6*.

Table 6. Linguistic importance scale in NS DEMATEL.

Linguistic Scale	Code	Membership Function		
		T	I	F
Absolute influence	AI	0.8	0.15	0.2
Strong influence	SI	0.6	0.35	0.4
Fair influence	FI	0.4	0.65	0.6
Weak influence	WI	0.2	0.85	0.8
No influence	NI	0	1	1

Once the assessments are transformed into NS, the data will be processed through the DEMATEL method. The steps for the calculations are detailed below [142].

Step 1. Creating the direct relationship matrix $\otimes$ P.

The evaluations of the mutual influence among l factors (where factor h affects factor g) from m experts, denoted as p_{hg}^{m}, are converted into NS with their corresponding expert weights wb_k. These evaluations are then consolidated using *Eq. (17)*, resulting in the direct influence matrix $\otimes P = [\otimes p_{hg}]_{l\times l}$, where:

$$p = SVNWA(p_{hg}^{1}, p_{hg}^{2}, \dots, p_{hg}^{m}) = \sum_{k=1}^{m} wb_k p_{hg}^{m}. \tag{17}$$

Here, h = 1, 2, ..., q, g = 1, 2, ..., q, and k = 1, 2, ..., m. The notation $\otimes p_{hg}$ is defined as (p_{hg}^{α}, p_{hg}^{β}, p_{hg}^{γ}). It is important to note that the diagonal elements of this matrix are 0, i.e., meaning $\otimes$ p = 0, when h = g.

Then, *Eq. (13)* is applied to convert the matrix $\otimes$ P into crisp scores.

Step 2. Calculate the normalized direct relationship matrix $\otimes$ Q.

The matrix

$\otimes Q = [\otimes q_{hg}]_{l\times l}$ will undergo normalization to produce the matrix using *Eqs. (18)-(20)*:

$$\otimes Q = [\otimes q_{hg}]_{l\times l} = \begin{bmatrix} \otimes\theta\cdot p_{11} & \otimes\theta\cdot p_{12} & \cdots & \otimes\theta\cdot p_{1g} & \cdots & \otimes\theta\cdot p_{1l} \\ \otimes\theta\cdot p_{21} & \otimes\theta\cdot p_{22} & \cdots & \otimes\theta\cdot p_{2g} & \cdots & \otimes\theta\cdot p_{2l} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \otimes\theta\cdot p_{h1} & \otimes\theta\cdot p_{h2} & \cdots & \otimes\theta\cdot p_{hg} & \cdots & \otimes\theta\cdot p_{hl} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \otimes\theta\cdot p_{l1} & \otimes\theta\cdot p_{l2} & \cdots & \otimes\theta\cdot p_{lg} & \cdots & \otimes\theta\cdot p_{ll} \end{bmatrix}_{lxl}. \tag{18}$$

$$\otimes q\_hg = \theta. p\_hg. \tag{19}$$

With:

$$\theta = \frac{1}{\max 1\le r\le l \left(\sum_{h=1}^{l} p_{hg}\right)}. \tag{20}$$

Here, h = g = 1, 2, 3, …, l.

Step 3. Determining the total influence matrix $\otimes$ E.

To compute the total influence matrix $\otimes$ E, the normalized direct relationship matrix $\otimes$ Q is integrated using *Eq. (21)* and *Eq. (22)*, which summarize all direct and indirect influence interactions from the first to infinite power.

$$\otimes \mathrm{E} = \left[\otimes \mathrm{e}_{\mathrm{hg}}\right]_{\mathrm{l\times l}} = \begin{bmatrix} \otimes \mathrm{e}_{11} & \otimes \mathrm{e}_{12} & \cdots & \otimes \mathrm{e}_{1\mathrm{g}} & \cdots & \otimes \mathrm{e}_{1\mathrm{l}} \\ \otimes \mathrm{e}_{21} & \otimes \mathrm{e}_{22} & \cdots & \otimes \mathrm{e}_{2\mathrm{g}} & \cdots & \otimes \mathrm{e}_{2\mathrm{l}} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \otimes \mathrm{e}_{\mathrm{h}1} & \otimes \mathrm{e}_{\mathrm{h}2} & \cdots & \otimes \mathrm{e}_{\mathrm{hg}} & \cdots & \otimes \mathrm{e}_{\mathrm{hl}} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \otimes \mathrm{e}_{\mathrm{l}1} & \otimes \mathrm{e}_{\mathrm{l}2} & \cdots & \otimes \mathrm{e}_{\mathrm{lg}} & \cdots & \otimes \mathrm{e}_{\mathrm{ll}} \end{bmatrix}_{\mathrm{l\times l}}, \tag{21}$$

where: h = g = 1, 2, 3, …, l.

$$\begin{aligned} \otimes \mathrm{E} &= \otimes \mathrm{Q} + \otimes \mathrm{Q}^2 + \cdots + \otimes \mathrm{Q}^{\infty} \\ &= \otimes \mathrm{Q}(\mathrm{I} + \otimes \mathrm{Q} + \otimes \mathrm{Q}^2 + \cdots + \otimes \mathrm{Q}^{\infty-1}) \\ &= \otimes \mathrm{Q}(\mathrm{M} - \otimes \mathrm{Q}^{\infty})(\mathrm{M} - \otimes \mathrm{Q})^{-1} = \otimes \mathrm{Q}(\mathrm{M} - \otimes \mathrm{Q})^{-1} \end{aligned}, \tag{22}$$

where $\otimes \mathrm{Q}^{\infty} = [0]_{\mathrm{lxl}}$ and M is the identity matrix.

The elements of matrix $\otimes$ E in the form of neutrosophic are converted to crisp neutrosophic using *Eq. (13)*, resulting in the matrix $\otimes \mathrm{E}^* = \left[\mathrm{e}^*_{\mathrm{hg}}\right]_{\mathrm{l\times l}}$.

Step 4. Formulating a cause and effect map.

The value $\otimes$ f is derived by summing the rows of the total influence matrix $\otimes \mathrm{E}^*$, while $\otimes$ d is obtained by summing the columns of matrix $\otimes \mathrm{E}^*$.

$$\otimes \mathrm{f} = [\otimes \mathrm{f}_{\mathrm{h}}]_{\mathrm{l\times 1}} = \left(\otimes \mathrm{f}_1, \otimes \mathrm{f}_2, \dots, \otimes \mathrm{f}_{\mathrm{h},}, \dots, \otimes \mathrm{f}_{\mathrm{l}}\right). \tag{23}$$

$$[\otimes \mathrm{f}_{\mathrm{h}}]_{\mathrm{l\times 1}} = \left[\sum_{\mathrm{j}=1}^{\mathrm{h}} \otimes \mathrm{e}^*_{\mathrm{hg}}\right]_{\mathrm{l\times 1}}. \tag{24}$$

$$\otimes \mathrm{d} = [\otimes \mathrm{d}_{\mathrm{h}}]_{1\times \mathrm{l}} = \left(\otimes \mathrm{d}_1, \otimes \mathrm{d}_2, \dots, \otimes \mathrm{d}_{\mathrm{g}}, \dots, \otimes \mathrm{d}_{\mathrm{l}}\right)^{\mathrm{E}}. \tag{25}$$

$$\left[\otimes \mathrm{d}_{\mathrm{g}}\right]_{1\times \mathrm{l}} = \left[\sum_{\mathrm{h}=1}^{\mathrm{l}} \otimes \mathrm{e}^*_{\mathrm{gh}}\right]_{1\times \mathrm{l}} = [\otimes \mathrm{d}_{\mathrm{h}}]^{\mathrm{E}}_{\mathrm{l\times 1}}. \tag{26}$$

The combined influence index, represented by $\otimes \mathrm{f}_{\mathrm{h}} + \otimes \mathrm{d}_{\mathrm{h}}$, measures the total strength of influence given and received. The difference $\otimes \mathrm{f}_{\mathrm{h}} - \otimes \mathrm{d}_{\mathrm{h}}$ signifies the net influence. A larger value of $\otimes \mathrm{f}_{\mathrm{h}} + \otimes \mathrm{d}_{\mathrm{h}}$ implies that factor h has a significant impact on the evaluation system. A positive $\otimes \mathrm{f}_{\mathrm{h}} - \otimes \mathrm{d}_{\mathrm{h}}$ indicates that indicator h exerts considerable influence on other indicators, while a negative $\otimes \mathrm{f}_{\mathrm{h}} - \otimes \mathrm{d}_{\mathrm{h}}$ value suggests that other indicators affect indicator h more.

The overall impact of an indicator on the system is reflected in $\otimes \mathrm{f}_{\mathrm{h}} - \otimes \mathrm{d}_{\mathrm{h}}$. Thus, *Eq. (27)* will calculate the indicator's impact weight.

$$\sigma_{\mathrm{h}} = \frac{(\mathrm{f}_{\mathrm{h}} + \mathrm{d}_{\mathrm{h}})}{\sum_{\mathrm{h}=1}^{\mathrm{l}} (\mathrm{f}_{\mathrm{h}} + \mathrm{d}_{\mathrm{h}})}. \tag{27}$$

4 | Results

4.2 | Results of NS DEMATEL Technique

4.2.1 | NS DEMATEL results of 5 dimensions

Following the NS Delphi phase, five primary dimensions were validated and employed to analyze their mutual influence and the cause-effect relationships within the context of smart reverse logistics in Vietnam. These dimensions include Sustainable Development Orientation (SDO), Technology Application (TA), IE, Governmental Incentives and Regulations (GIR), and Organizational Internal Implementation (OI).

Initially, to determine the mutual impact relationships among dimensions, experts assessed each pairwise interaction using linguistic terms ranging from "No influence" to "Absolutely influence". These evaluations were then converted into Neutrosophic fuzzy values to establish the NS direct-relation matrix, with expert weights integrated to ensure robust accuracy. Based on these, the aggregated direct-influence matrix was generated (*Table 7*), representing the inter-dimensional relationships in terms of influence intensity.

Table 7. Aggregated-direct-influence-matrix of 5 dimensions.

	SDO	**TA**	**IE**	**GIR**	**OII**
SDO	(0; 0; 0)	(0.403; 0.632; 0.597)	(0.456; 0.579; 0.544)	(0.486; 0.538; 0.514)	(0.345; 0.703; 0.655)
TA	(0.399; 0.64; 0.601)	(0; 0; 0)	(0.473; 0.552; 0.527)	(0.452; 0.58; 0.548)	(0.406; 0.637; 0.594)
IE	(0.47; 0.555; 0.53)	(0.467; 0.562; 0.533)	(0; 0; 0)	(0.343; 0.702; 0.657)	(0.378; 0.661; 0.622)
GIR	(0.452; 0.575; 0.547)	(0.412; 0.624; 0.588)	(0.482; 0.542; 0.518)	(0; 0; 0)	(0.493; 0.528; 0.507)
OII	(0.488; 0.533; 0.512)	(0.483; 0.533; 0.517)	(0.522; 0.501; 0.478)	(0.431; 0.604; 0.569)	(0; 0; 0)

Following this, the neutrosophic values were defuzzified to generate crisp scores. The total relation matrix was derived after normalization and further computations (not shown here for brevity). Values for $\mathrm{Ri}, \mathrm{Ci}, \mathrm{Ri} + \mathrm{Ci}, \mathrm{Ri} - \mathrm{Ci}$ were computed and presented in *Table 8*.

Table 8. NS DEMATEL results of five dimensions.

	Ri	**Ci**	**Ri+Ci**	**Ri-Ci**	**Check**
SDO	4.3848	4.20575	8.5905	0.1790	Cause
TA	4.3830	4.16825	8.5513	0.2148	Cause
IE	4.4600	4.754	9.2140	-0.2940	Effect
GIR	4.3933	4.04025	8.4335	0.3530	Cause
OII	4.7388	5.1915	9.9303	-0.4528	Effect

Based on the $\otimes ri - \otimes ci$ values, the five dimensions were classified into cause and effect groups. The cause group—comprising SDO, TA, and GIR—demonstrates positive causality, indicating that these dimensions exert a stronger influence on others rather than being influenced. Notably, GIR recorded the highest causality degree (0.3530), suggesting it plays a central role in shaping other factors within smart reverse logistics.

Conversely, IE and OI fall into the effect group, marked by negative $\otimes ri - \otimes ci$ values. These dimensions are more influenced by other variables and reflect outcomes of systemic interactions. Particularly, OII shows the lowest causality score (-0.4528), implying it is the most impacted dimension and likely to improve if influential cause factors are properly addressed.

This classification provides a strategic roadmap for enhancing warehouse management in reverse logistics. Targeting improvements in GIR, TA, and SDO can effectively uplift the overall system by indirectly impacting dependent dimensions like IE and OI.

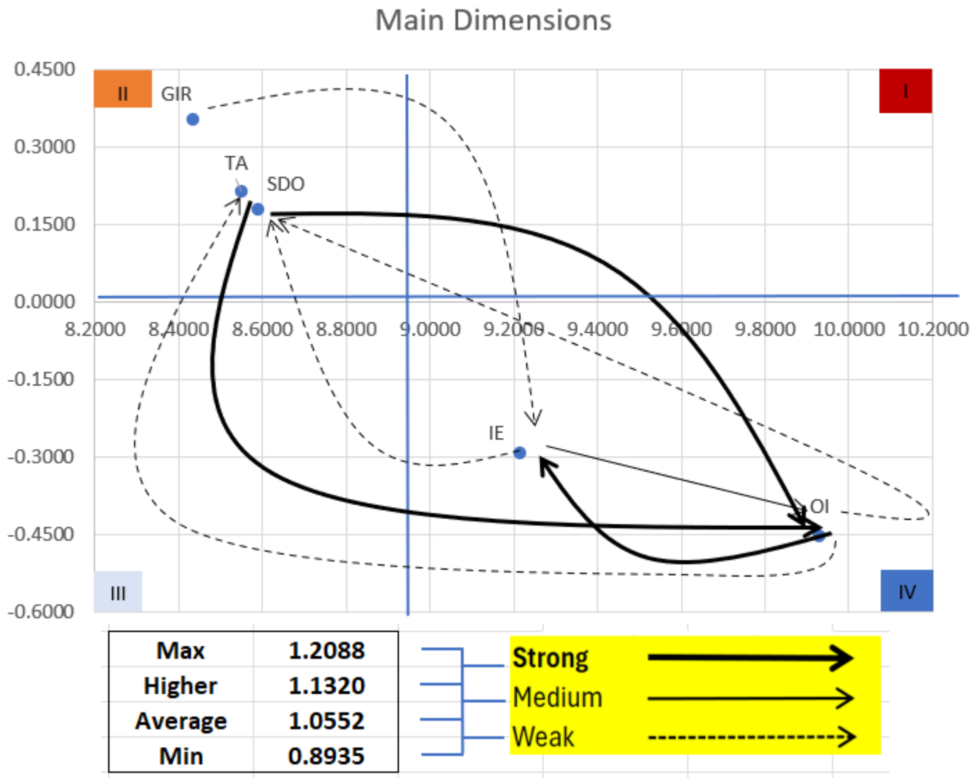

Fig. 2. Impact-relation map main dimension.

4.2.2 | NS DEMATEL results of sub dimensions

NS DEMATEL results of system design and operation

The NS-DEMATEL analysis for the System Design and Operation (SDO) dimension highlights a distinct division between driving and reactive sub-dimensions. Among these, certain factors exhibit significant causal influence, while others function more as outcomes within the system's structural dynamics.

As shown in *Table 9*, sub-dimensions SDO2 (equity in allocation) and SDO3 (adjustment mechanisms for allocation) exhibit the highest net influence values (Ri−Ci = 0.4418 and 0.3890, respectively). These figures underline their capacity as key system drivers, with strong interaction intensity and proactive influence on other components.

Table 9. NS DEMATEL results of SDO sub-dimensions.

	Ri	Ci	Ri+Ci	Ri-Ci	Check
SDO1	11.7468	11.5985	23.3453	0.1482	Cause
SDO2	11.7890	11.34725	23.1363	0.4418	Cause
SDO3	11.9453	11.55625	23.5015	0.3890	Cause
SDO6	11.7090	11.36925	23.0783	0.3397	Cause
SDO7	10.7808	11.50575	22.2865	-0.7250	Effect
SDO8	11.2238	11.718	22.9418	-0.4943	Effect
SDO9	11.7028	11.598	23.3008	0.1047	Cause
SDO10	11.5063	11.7105	23.2168	-0.2043	Effect

Alongside SDO2 and SDO3, other sub-dimensions such as SDO1, SDO6, and SDO9 also demonstrate positive RI−CI scores, reaffirming their roles as cause factors. These elements serve as the technical and structural backbone of reverse logistics, contributing to system resilience and operational optimization.

Conversely, SDO7, SDO8, and SDO10 are positioned as effect sub-dimensions, showing negative RI−CI values. Notably, SDO7 (−0.7250) and SDO8 (−0.4943) indicate strong susceptibility to external influence. These factors represent systemic outcomes rather than initiators of change, and are more responsive to upstream improvements.

Although SDO10 registers a high total interaction value (Ri+Ci = 23.2168), its negative net influence (−0.2043) further reinforces its classification as a dependent factor. This highlights the importance of enhancing upstream drivers to stimulate downstream performance.

In summary, prioritizing improvements in equitable allocation (SDO2), dynamic adjustment mechanisms (SDO3), and overall system design will likely produce positive ripple effects across the entire reverse logistics structure—particularly in reactive components like market liquidity and price stability. These insights offer strategic guidance for fortifying the operational core of smart reverse logistics systems in Vietnam.

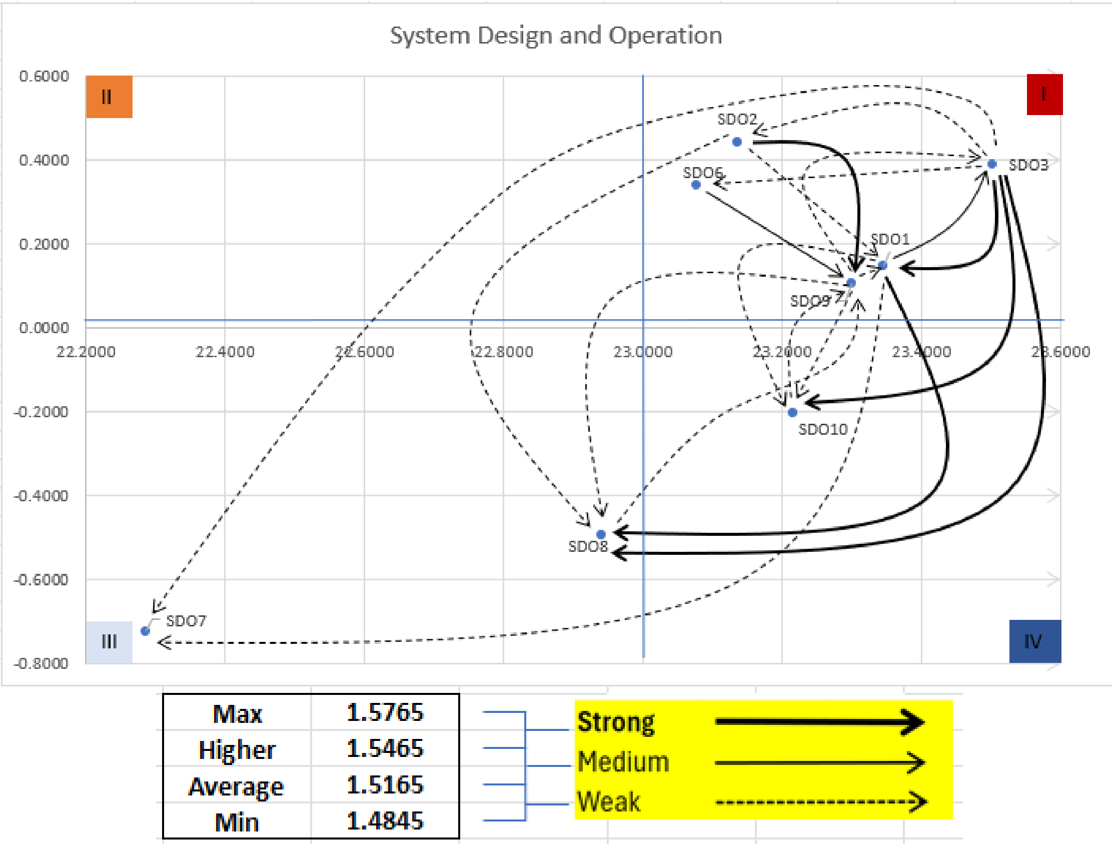

Fig. 3. Impact-relation system design and operation dimension.

NS DEMATEL results of transparency and accountability

The NS-DEMATEL analysis of the Transparency and Accountability (TA) dimension reveals a system predominantly composed of reactive sub-dimensions, with only a few factors demonstrating meaningful causal influence. This distribution suggests that while the TA structure is responsive, it lacks strong internal drivers capable of independently initiating systemic improvements.

Among the sub-dimensions, TA3 (monitoring and evaluation mechanisms) emerges as the most prominent cause factor, registering the highest net influence (Ri−Ci = 1.2033). This indicates that improvements in accountability frameworks can exert broad systemic effects, shaping transparency outcomes across multiple operational areas. Similarly, TA2 (clear reporting and disclosure requirements) also acts as a key driver, with a net influence of 0.7680. Both sub-dimensions are situated in Quadrant I, reinforcing their proactive role in the structure.

Table 10. NS DEMATEL Results of TA Sub-Dimensions.

	Ri	Ci	Ri+Ci	Ri-Ci	Check
TA1	11.1378	11.8245	22.9623	-0.6868	Effect
TA2	11.6835	10.9155	22.5990	0.7680	Cause
TA3	11.7310	10.52775	22.2588	1.2033	Cause
TA6	11.3248	11.801	23.1258	-0.4763	Effect
TA7	11.3700	12.10125	23.4713	-0.7313	Effect
TA8	11.4813	11.6265	23.1078	-0.1452	Effect
TA9	11.3110	11.24275	22.5538	0.0683	Cause

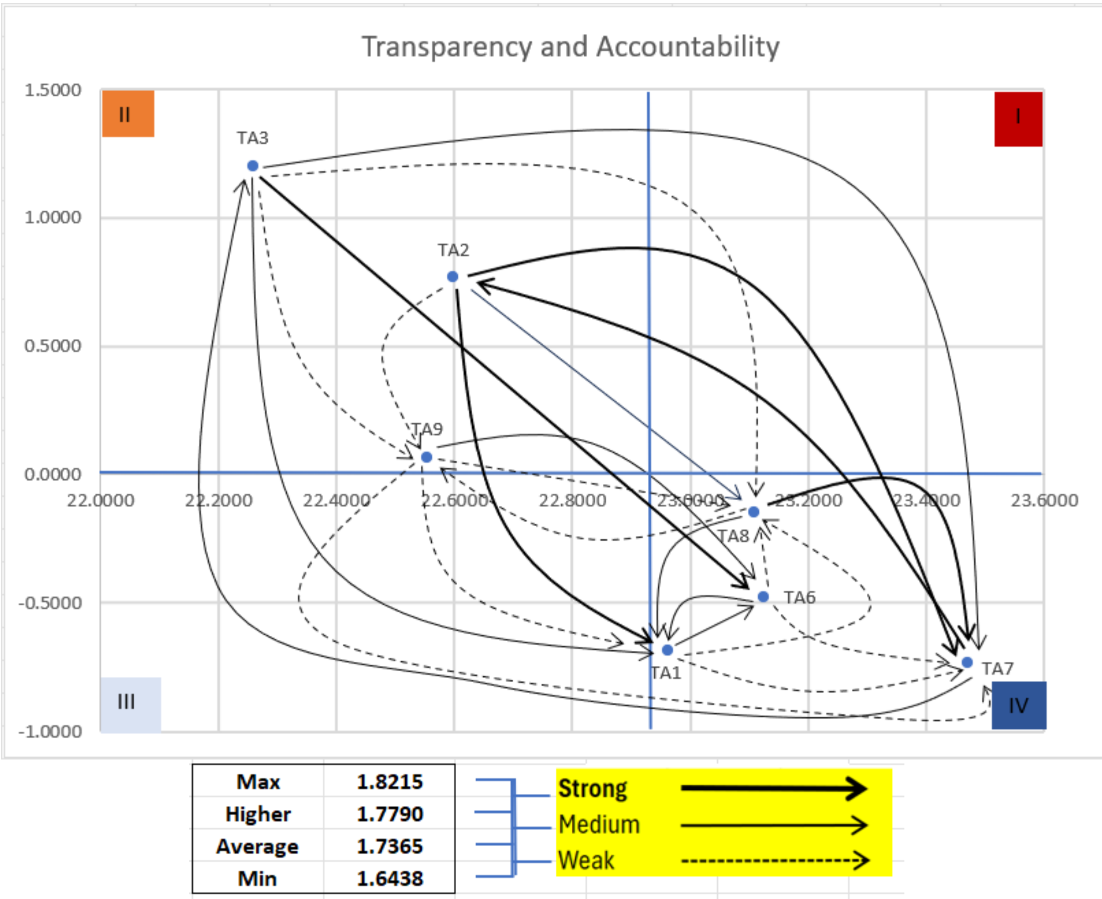

Fig. 4. Impact-relation transparency and accountability dimension.

In addition to TA3 and TA2, TA9 (institutional commitment to transparency) also exhibits a positive Ri−Ci value, albeit marginal (0.0683). Its classification as a causal factor reflects its foundational role in upholding transparency standards, even if its influence is less pronounced.

Conversely, the remaining sub-dimensions—TA1, TA6, TA7, and TA8—are all characterized by negative net influence scores. These elements are positioned as effect dimensions, indicating their responsiveness to changes in more dominant upstream components. TA7 (consumer trust and perception) holds the most negative net value (−0.7313), suggesting it is highly sensitive to system-wide changes and dependent on other factors for improvement.

Although TA8 (real-time data sharing platforms) is among the most interactive elements in the system in terms of total influence (Ri+Ci = 23.1078), its slightly negative Ri−Ci score (−0.1452) underscores its status as a reactive element, likely to benefit only after structural reinforcements in monitoring and disclosure have been made.

In conclusion, building a robust and transparent reverse logistics ecosystem requires strategic attention to core drivers like TA3 and TA2. By enhancing these foundational mechanisms, organizations can trigger systemic improvements thet alevate not only operational transparency but also public confidence and institutional accountability.

NS DEMATEL results of impact and effectiveness

The NS-DEMATEL analysis of the Impact and Effectiveness (IE) dimension reveals a relatively balanced configuration between driving and responsive elements. While most sub-dimensions demonstrate reactive characteristics, a few stand out as critical levers for systemic change. Most notably, IE8 (integration of circular economy goals) emerges as the strongest cause factor with a net influence of 0.3207. Its central role underscores the importance of embedding sustainability principles within system operations to maximize reverse logistics effectiveness. Complementing this driver, both IE1 (measurement of reverse logistics performance) and IE5 (sustainability-oriented KPIs) also function as causal sub-dimensions, albeit with more moderate Ri−Ci scores (0.1475 and 0.0925, respectively). These findings emphasize the foundational importance of robust performance tracking and metric-based governance.

The sub-dimension statistics supporting these interpretations are presented in *Table 11* below.

Table 11. NS DEMATEL results of IE sub-dimensions.

	Ri	Ci	Ri+Ci	Ri-Ci	Check
IE1	5.7665	5.619	11.3855	0.1475	Cause
IE2	5.7973	5.834	11.6313	-0.0368	Effect
IE3	5.4293	5.71725	11.1465	-0.2880	Effect
IE4	5.5615	5.709	11.2705	-0.1475	Effect
IE5	5.6318	5.53925	11.1710	0.0925	Cause
IE7	5.3028	5.39125	10.6940	-0.0885	Effect
IE8	5.8130	5.49225	11.3053	0.3207	Cause

In contrast, IE2, IE3, IE4, and IE7 all display negative Ri−Ci values and are thus classified as effect sub-dimensions. Among these, IE3 (delays in feedback loops) and IE4 (lack of outcome evaluation) are particularly passive, reflecting weaknesses in the system’s responsiveness to ongoing performance. Interestingly, IE2 (limited evidence of environmental benefit)—while showing the highest total interaction score (Ri+Ci = 11.6313)—still bears a slightly negative net influence. This highlights its dependence on improvements in upstream evaluation design and strategic alignment, rather than functioning as an independent driver. In summary, strengthening strategic goal-setting (IE8), refining performance measurement systems (IE1), and integrating sustainability-focused KPIs (IE5) will likely yield widespread improvements in the effectiveness and adaptability of reverse logistics systems. These enhancements can, in turn, help overcome inertia in more reactive components, fostering a more results-oriented and resilient operational framework.

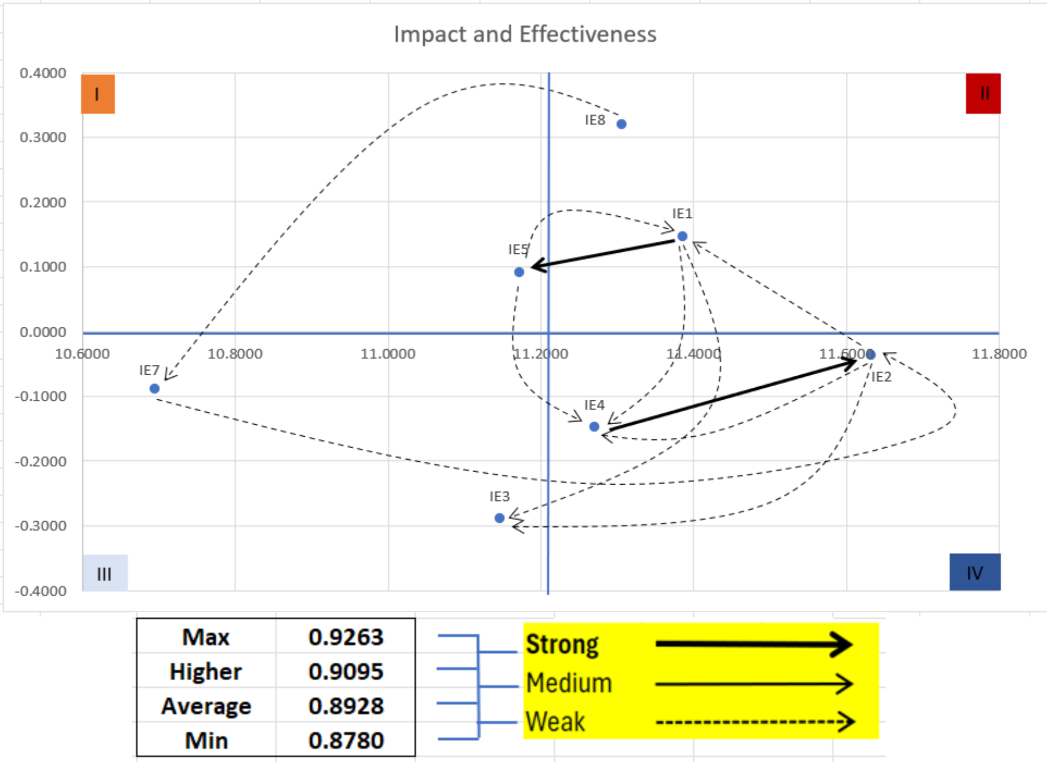

Fig. 5. Impact-relation impact and effectiveness dimension.

NS DEMATEL results of governance and international relations

The NS-DEMATEL analysis of the Governance and International Relations (GIR) dimension illustrates a structure dominated by reactive sub-dimensions, though a select group of elements stands out as potential levers for initiating systemic improvements. These findings offer important insights into the regulatory and institutional dynamics that influence the effectiveness of reverse logistics frameworks.

At the forefront is GIR8 (global partnerships and compliance standards), which emerges as the most influential cause factor with a net influence score of 0.5323. Its role emphasizes the necessity of aligning domestic logistics practices with international standards, enabling both credibility and cross-border compatibility within the system. Complementing this driver are GIR4 (policy alignment across sectors) and GIR2 (clarity in roles and responsibilities), which, although less dominant in magnitude (Ri−Ci = 0.0487 and 0.0225, respectively), still function as structural catalysts that foster institutional coherence and regulatory clarity.

These distinctions are clearly reflected in *Table 12* below.

Table 12. NS DEMATEL Results of GIR Sub-Dimensions.

	Ri	Ci	Ri+Ci	Ri-Ci	Check
GIR1	7.9395	8.02425	15.9638	-0.0847	Effect
GIR2	7.9420	7.9195	15.8615	0.0225	Cause
GIR3	7.8188	8.0715	15.8903	-0.2528	Effect
GIR4	7.6418	7.593	15.2348	0.0487	Cause
GIR5	7.9475	8.0255	15.9730	-0.0780	Effect
GIR7	7.8213	7.88925	15.7105	-0.0680	Effect
GIR8	7.9983	7.466	15.4643	0.5323	Cause
GIR10	7.9798	8.09975	16.0795	-0.1200	Effect

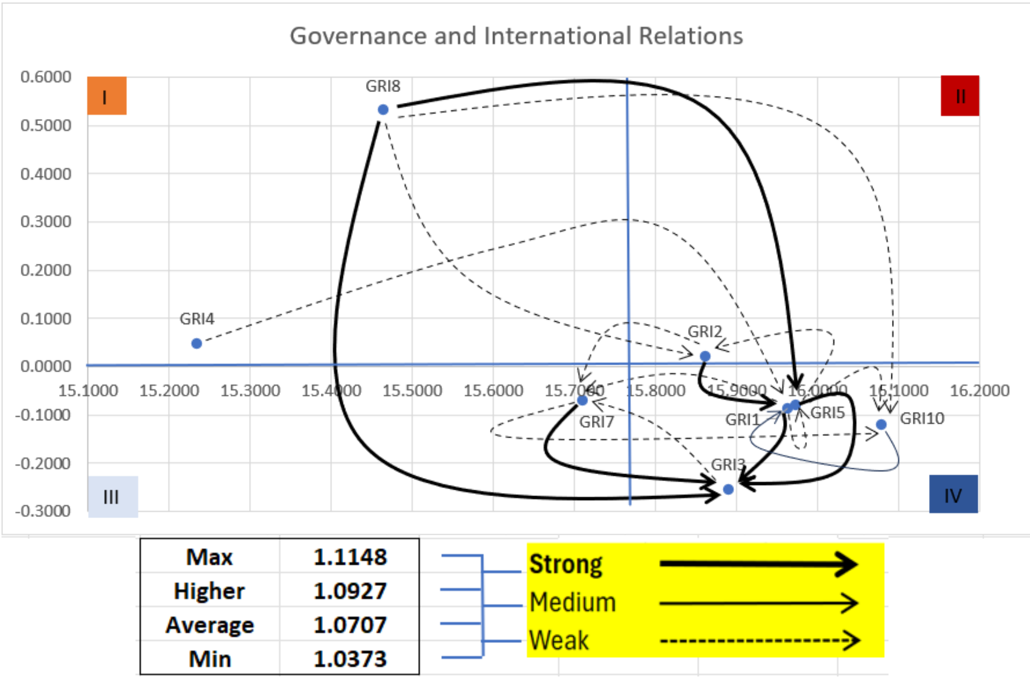

Fig. 6. Impact-relation governance and international relations dimension.

In contrast, the majority of GIR sub-dimensions—including GIR1, GIR3, GIR5, GIR7, and GIR10—are identified as effect dimensions due to their negative RI−CI scores. These components are typically shaped by shifts in policy coordination or international alignment rather than initiating change themselves. Particularly, GIR3 (administrative complexity in cross-border logistics) and GIR10 (monitoring & enforcement mechanisms) exhibit more pronounced negative values, indicating their susceptibility to systemic bottlenecks and institutional inertia.

It is noteworthy that GIR10, despite showing the highest overall interaction level (Ri+Ci = 16.0795), holds a negative net influence, reaffirming its status as a reactive rather than a proactive element within the governance system.

In summary, strategic efforts to strengthen reverse logistics governance should begin with bolstering global cooperation (GIR8), ensuring inter-agency coordination (GIR2), and enhancing policy alignment across sectors (GIR4). These cause factors form the institutional backbone necessary for establishing a credible, adaptive, and internationally aligned logistics governance model.

NS DEMATEL results of offsets and innovation

The analysis of the Offsets and Innovation (OI) dimension via the NS-DEMATEL approach reveals a structural dichotomy: a handful of sub-dimensions act as strong initiators of system-wide influence, while others primarily absorb impact from elsewhere in the network. This contrast reflects the dynamic tension between policy-driven innovation momentum and structural or behavioral barriers within the system.

Leading the group of causal elements is OI1 (green technology adoption incentives), which records the highest net influence (Ri−Ci = 1.5668). Its significance lies in its capacity to create ripple effects across the entire innovation ecosystem, indicating that strategic incentives can energize sustainable transformation at scale. Following closely are OI4 (public-private collaboration) and OI10 (policy support for circular models), with Ri−Ci values of 1.0558 and 0.4590, respectively—both reinforcing the idea that institutional coherence and multisectoral partnerships are foundational to scalable innovation.

These findings are summarized in *Table 13* below.

Table 13. NS DEMATEL results of oi sub-dimensions.

	Ri	Ci	Ri+Ci	Ri-Ci	Check
OI1	7.6103	6.0435	13.6538	1.5668	Cause
OI2	7.2145	7.44	14.6545	-0.2255	Effect
OI3	6.5060	7.865	14.3710	-1.3590	Effect
OI4	7.8953	6.8395	14.7348	1.0558	Cause
OI5	7.4198	7.21425	14.6340	0.2055	Cause
OI6	6.4090	7.8805	14.2895	-1.4715	Effect
OI8	7.5810	7.812	15.3930	-0.2310	Effect
OI10	7.4450	6.986	14.4310	0.4590	Cause

OI5 (investment in R&D for eco-design) also appears as a driver, albeit with more moderate influence, suggesting its role as a technical enabler rather than a primary system trigger. Conversely, sub-dimensions like OI3 (high innovation costs) and OI6 (lack of risk appetite) represent significant bottlenecks, with strongly negative Ri−Ci scores (−1.3590 and −1.4715, respectively). These values reveal that such challenges are more symptomatic of deeper systemic issues—likely rooted in insufficient policy support or market readiness—than standalone factors that can be addressed in isolation. Of particular interest is OI8 (slow market adoption of innovation), which registers the highest total interaction score (Ri+Ci = 15.3930), yet remains an effect element (Ri−Ci = −0.2310). This suggests that even the most engaged components of the system can remain reactive without upstream intervention.

Taken together, the results point to a strategic imperative: efforts to accelerate innovation in reverse logistics must begin with enhancing enabling structures—such as green financing schemes, collaborative innovation platforms, and forward-looking policy mechanisms. By targeting these key drivers (OI1, OI4, OI10), stakeholders can address not only cost-related or behavioral resistance downstream but also nurture a system that sustains innovation organically.

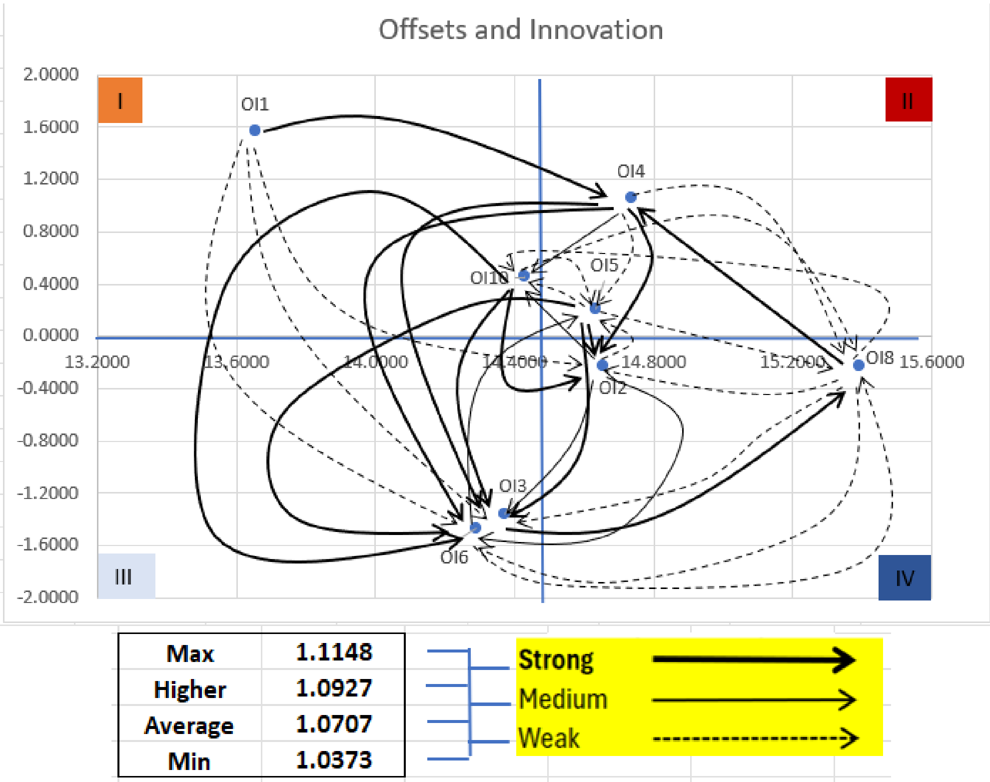

Fig. 7. Impact-relation offsets and innovation dimension.

5 | Discussion

Compared with Van Tam et al. [20] our findings similarly confirm that system-level enablers are foundational to decarbonization strategies. While their AHP–DEMATEL study in the construction sector positioned carbon pricing and financial mechanisms as causal strategies, our results extend this logic to smart reverse logistics, where sub-dimensions such as SDO2 (process automation) and SDO3 (digital system integration) play critical upstream roles. This distinction reflects a shift from national strategy to SDO capacity, especially under conditions of technological inertia in Vietnam. While Van Tam et al. [20] focused on high-level planning aligned with COP26 commitments, our work provides a micro-structural map of cause–effect relations among operational bottlenecks, enabling targeted interventions.

This divergence is important because Vietnam's carbon market development relies not only on legislative direction but also on bottom-up technical readiness. Nguyen et al. [23] emphasized that green bond issuance was hindered by weak regulation and capacity gaps. Our analysis adds nuance by showing how such gaps propagate within system architecture. For instance, SDO7 and SDO8—classified as effect dimensions—are shown to be responsive outcomes of the inefficiencies in SDO2 and SDO3. This confirms that operational constraints are not merely logistical issues but manifestations of deeper system design weaknesses.

TA, as emphasized in studies like Ahmed et al. [143] and Merger and Pistorius [144], are repeatedly cited as bottlenecks in carbon credit legitimacy. Our model not only supports this but further clarifies the role of TA2 (disclosure requirements) and TA3 (monitoring mechanisms) as primary causes. These dimensions form the backbone of system transparency, and their causal status reinforces the claim by Tanveer et al. [145] that digital platforms and verification standards are prerequisites to market credibility. Interestingly, we deviate from Parnphumeesup and Kerr [146], who viewed buyer perception as a market entry determinant, by showing that trust (TA7) is more an effect of institutional transparency than a direct input. In effect, trust must be built through systems, not assumed through market participation.

Moreover, our classification of TA8 (real-time data platforms) and TA6 (product lifecycle transparency) as reactive outcomes illustrates that technological transparency is not a given—it depends on systemic reinforcement through policy and institutional frameworks. This finding extends Nguyen et al. [24], who identified investor skepticism as a challenge for green finance, by showing how causal elements within TA can directly affect stakeholder confidence and market engagement.

In the domain of IE, our study reaffirms concerns raised by Warner et al. [16] and Steckel et al. [147], who criticized the limitations of project-based and fragmented mitigation initiatives. We move beyond that by detailing which elements are proactive (IE8, IE5, IE1) and which are response-driven (IE3, IE4, IE7). Our identification of IE8 (integration of circular economy goals) as a causal factor aligns with circularity-focused strategies emphasized Van Tam et al. [20] but adds that such integration is not only a desirable outcome—it must be a strategic input. IE1 (performance measurement) and IE5 (KPI orientation) are often overlooked in existing MRV-focused literature; we demonstrate that they are core enablers of a functional carbon credit ecosystem.

Furthermore, unlike previous analyses that group measurement and evaluation together, our study distinguishes between them structurally: while IE1 enables system-level assessment, IE4 reflects outcome evaluation and is dependent on upstream clarity. This differentiation is important for Vietnam, where MRV systems are underdeveloped, and our findings provide an evidence-based roadmap for improving MRV efficiency by restructuring its internal architecture.

GIR emerged in our study as among the most decisive causal forces. In line with Anjos et al. [148] and Kiss et al. [149] GIR8 (global partnership standards) is a top causal factor, emphasizing that policy harmonization and international alignment are essential to market credibility. While Lien et al. [21] focused on national readiness, our results suggest that foundational governance mechanisms—particularly GIR2 (role clarity) and GIR4 (policy alignment)—must be addressed before international credibility can be meaningfully pursued.

Enforcement and compliance, represented by GIR10, are shown to be effect variables, and thus should be treated as performance outcomes, not as structural solutions.

Moreover, the voluntary–compliance hybrid model currently adopted in Vietnam adds complexity to enforcement mechanisms. Our results support the observation made by the [6], [8] that MRV standardization is lacking. By mapping GIR3 and GIR10 as effect-driven, our model provides empirical justification for prioritizing early-stage governance and international policy alignment. This directly informs policy directions for the upcoming implementation phase (2025–2028) of Vietnam's carbon market roadmap.

The OI dimension contributes novel insights, especially when compared to Tanveer et al. [145]. Woo et al. [150] and Everhart [151] who emphasize the importance of digital tools, tokenization, and inclusive stakeholder collaboration. Our findings align with their direction but go further by identifying which innovation mechanisms are true levers of change. OI1 (green technology incentives), OI4 (public–private innovation), and OI10 (circular model policy support) are all classified as cause factors, illustrating that policy-level innovation scaffolding must be in place before market participation and technology diffusion can occur. On the other hand, OI3 (high cost) and OI6 (risk aversion) are categorized as effects, confirming that economic and psychological barriers in innovation adoption are outcomes of policy shortfalls.

We also contribute to the discussion on forestry-based carbon credits, as explored by Warner et al. [16] by showing that OI5 (R&D in eco-design) and OI10 can unlock forest-sector potentials—but only when upstream innovation policies are stable. Vietnam's potential in this area, substantiated by FCPF funding [8], remains underleveraged due to the lack of clarity and incentives. Our results recommend a clearer national innovation agenda that targets both technology and natural asset-based credit generation.

In synthesis, this study empirically maps interdependencies among the five dimensions—SDO, TA, IE, GIR, and OI—through stakeholder-informed NS-DEMATEL modeling. Unlike conventional fuzzy MCDM approaches [22], [23], our method accommodates indeterminacy and asymmetric influence, enabling a more realistic representation of Vietnam's carbon market development. As in Brown and Corbera [152], we recognize that institutional asymmetries create access gaps, but our findings provide a pathway for addressing them: by reinforcing transparency (TA2, TA3), measurement (IE1), governance clarity (GIR4), and innovation incentives (OI1), we can activate feedback loops that enhance systemic resilience.

6 | Conclusion

The core contribution of this study lies in its ability to translate stakeholder complexity into actionable system-wide reform priorities for Vietnam's carbon credit market. By integrating Neutrosophic Delphi and DEMATEL, this research establishes a multi-layered decision-support model that not only ranks stakeholder concerns but clarifies the influence pathways among them—something that previous studies often addressed only partially or qualitatively.

The results reveal high-impact entry points such as disclosure transparency, automation, circular economy alignment, and green innovation incentives—critical elements that, when improved, can shift the entire system toward greater effectiveness, accountability, and trust. These findings provide new value to both academic and policy communities by transforming abstract governance debates into prioritized, stakeholder-endorsed levers of change.

In practical terms, the analysis serves as a roadmap for Vietnam to strategically sequence its policy interventions. For example, before launching large-scale MRV systems or engaging in international carbon transactions, it becomes essential to establish foundational elements such as internal automation standards and transparent data disclosure protocols. These are prerequisites for credibility in both compliance and voluntary markets.

Recent modelling by International Economic Intergration affirms that flexible policy design—such as ETS offset caps of 20% (ETS20)—can reduce compliance costs and improve macroeconomic outcomes, particularly in sectors like thermal power and steel [153]. This supports our study's emphasis on prioritizing digital infrastructure and systemic innovation. It also aligns with the study's identification of causal levers (e.g., SDO2, IE8, OI1), reinforcing that policy flexibility must be grounded in robust internal capabilities.

Enterprises can draw on these findings to align their investment strategies with long-term climate commitments. For instance, thermal power firms projected as major credit buyers [8] should invest early in automation and emissions tracking to reduce costs and improve verification outcomes. Meanwhile, sectors with low-cost abatement potential, such as cement, can leverage credit sales as a financing tool for further innovation—if mechanisms for trust, transparency, and MRV are in place. For donors and development partners, this research offers evidence to justify reallocating resources toward structural market-building components. The findings underscore that investments in digital MRV, sector-specific benchmarks, and institutional coordination can unlock durable emissions reductions while enhancing Vietnam's integration into global carbon trading networks. By grounding its analysis in Vietnam's institutional context while offering a transferable framework, this research adds immediate utility for ongoing market development. This analysis demonstrates how stakeholder-centered systems modeling can drive more targeted, confident, and adaptive policymaking in carbon markets—and beyond.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All data are included in the text.

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