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Human-centered barriers to green supply chain management in fossil fuel-dependent logistics systems: an ISM-based analysis

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Introduction: Green supply chain management (GSCM) barriers are widely documented, yet prior studies often treat them as isolated constraints rather than interdependent drivers within transition systems. This limitation is particularly relevant in fossil-fuel-dependent logistics systems.

Methods: This study employs a mixed-method design combining survey data from logistics professionals in Saudi Arabia with interpretive structural modeling (ISM) and MICMAC analysis to identify hierarchical relationships among GSCM barriers.

Results: The results reveal that human capability, training, and managerial support function as primary driver barriers influencing technological, financial, and policy-related constraints. Technological and financial barriers act as linkage factors, while policy-related barriers emerge as dependent outcomes.

Discussion: These findings demonstrate that sustainability challenges in fossil-fuel-dependent logistics systems are structurally interdependent rather than independent obstacles. The study highlights the importance of addressing human and organizational capabilities as upstream drivers to enable effective sustainability transitions.

KEYWORDS

green supply chain management, human-centered sustainability, interpretive structural modeling, logistics, sustainability transition, MICMAC analysis, Saudi logistics sector

1 Introduction

Prior research on green supply chain management (GSCM) has identified a wide range of barriers that limit adoption across industries (Awa and Ojiabo, 2016; Burki et al., 2020; Das et al., 2023; Wiredu, 2024). These include financial constraints, limited access to appropriate technologies, weak managerial support, low employee awareness, and regulatory uncertainty (Seuring and Müller, 2008; Govindan et al., 2014; Mathiyazhagan et al., 2013). Several studies have also applied multi-criteria decision-making (MCDM) approaches, such as interpretive structural modeling (ISM) and DEMATEL, to rank or classify these barriers and assess their relative importance (Rahman et al., 2020; Ahmed et al., 2020).

However, the literature still leaves two important gaps. First, most existing studies focus on manufacturing or general supply chain contexts, with limited attention to

fossil-fuel-dependent logistics systems where operational conditions, infrastructure, and energy reliance differ significantly. Second, many studies identify and rank barriers without clearly explaining which ones function as root causes and how they generate downstream constraints within the system. As a result, the causal structure linking barriers remains underdeveloped.

This issue is especially important in fossil-fuel-dependent logistics systems, where infrastructure, organizational capabilities, and institutional conditions co-evolve. In such contexts, sustainability barriers are likely to be structurally entangled rather than independent, meaning that addressing isolated constraints may not lead to effective system-wide change. Instead, some barriers may act as upstream drivers that shape the emergence and persistence of other constraints, creating path dependency in sustainability transitions.

Drawing on socio-technical transitions, institutional theory, human-centered sustainability, and systems thinking, this study examines the structural causality of GSCM barriers in the Saudi logistics sector. It focuses on identifying how barriers are hierarchically related, distinguishing between driver, linkage, and dependent barriers, and explaining how these relationships influence sustainability adoption in fossil-fuel-dependent logistics systems.

Recent sustainability analytics studies strengthen the case for this approach. Karuppiyah et al. (2020) show that green economy practices are shaped by interdependent causal factors rather than isolated variables, with implications for sustainable development outcomes. Similarly, Karuppiyah et al. (2023) demonstrate that life cycle assessment challenges form cause effect structures when analyzed using Best Worst Method and DEMATEL. These studies suggest that sustainability barriers should be examined as structured systems with directional influence. This paper extends that logic to GSCM barriers in fossil-fuel-dependent logistics systems through ISM–MICMAC analysis.

This study makes three contributions. First, it shifts GSCM barrier research from generic barrier identification to structural causality analysis in a fossil-fuel-dependent logistics context. Second, it integrates socio-technical, institutional, and systems perspectives to explain barrier hierarchy and interdependence. Third, it shows that human capability and managerial support act as upstream conditions that shape technological, financial, and policy outcomes, providing a more grounded explanation of sustainability transition challenges.

2 Theoretical background

This study treats GSCM barriers as structurally embedded constraints within fossil-fuel-dependent logistics systems. Socio-technical transitions explain why barriers emerge across interconnected technical and social elements. Institutional theory explains why external pressure does not automatically lead to adoption. Human-centered sustainability highlights the role of leadership, skills, and organizational learning. Systems thinking links these perspectives by showing how barriers reinforce one another through hierarchical dependence. Together, these perspectives provide a unified explanation of why GSCM barriers should

be analyzed as interdependent and hierarchical rather than as isolated constraints.

2.1 Green supply chain management as a socio-technical sustainability transition

GSCM adoption is not only a technical process. It requires coordinated change across technologies, operational routines, workforce skills, and infrastructure (Hsu et al., 2016). From a socio-technical perspective, logistics systems are composed of interconnected technical and social elements that evolve together (Handfield et al., 1997; Sarkis, 2001). In fossil-fuel-dependent logistics systems, this coordination is more complex due to legacy infrastructure, high capital intensity, and established operational practices. As a result, barriers emerge not as isolated technical problems but as part of a broader system of interdependent constraints that shape transition pathways (Anilkumar and Sridharan, 2019; Bag et al., 2022; Lerman et al., 2022).

Prior studies show that GSCM has evolved from a focus on regulatory compliance and operational efficiency to broader sustainability transitions involving coordinated changes across technologies, practices, and governance structures (Seuring and Müller, 2008; Govindan et al., 2014). This shift reinforces the need to analyze barriers as interdependent elements within a structured system rather than as isolated constraints. (Sarkis et al., 2004; Stellingwerf et al., 2022).

2.2 Human-centered sustainability and learning-oriented perspectives

Human-centered sustainability emphasizes the role of leadership, workforce capability, and organizational learning in enabling transition (Govindan et al., 2014). Prior studies show that insufficient awareness, lack of training, and weak managerial support are critical barriers to GSCM adoption. These factors do not only limit implementation directly but also reduce the effectiveness of technological and policy interventions (Luthra et al., 2011). In fossil-fuel-dependent logistics systems, where routines are deeply embedded, weak human capability can act as a root barrier that constrains system-wide change (Elzarka et al., 2026).

These barriers reflect limitations in organizational learning and change capability. Without sufficient leadership commitment and workforce readiness, technological and policy interventions may not translate into operational change (Govindan et al., 2014).

2.3 Organizational and institutional dimensions of GSCM adoption

Institutional theory explains how external pressures such as regulation, industry norms, and competitive dynamics influence GSCM adoption (El-Nakib and Elzarka, 2026; European Commission, 2021). However, compliance with external demands does not guarantee implementation (DiMaggio and Powell, 1983). The effect of institutional pressure depends on internal organizational readiness, including governance structures, managerial priorities, and available capabilities. In logistics systems, fragmented decision-making and short-term performance incentives can

weaken the translation of policy into practice. This shows that institutional drivers are mediated by organizational conditions rather than acting as direct triggers (Chaudhari et al., 2025).

In fossil fuel-dependent logistics systems, regulatory ambiguity, inconsistent enforcement, and conflicting policy signals can reinforce organizational inertia. These conditions interact with human-centered factors, such as leadership commitment and organizational culture, shaping whether sustainability objectives are prioritized or marginalized in strategic decision-making.

2.4 Systems thinking and structural interdependencies among barriers

Systems thinking highlights that GSCM barriers are not independent but form an interconnected structure. Some barriers act as drivers that influence multiple other constraints, while others function as linkage factors or emerge as dependent outcomes. These relationships create reinforcing effects that shape system behavior over time. As a result, addressing individual barriers in isolation may produce limited impact. Instead, effective intervention requires identifying hierarchical relationships and targeting upstream constraints (El-Nakib and Elzarka, 2015; Takeishi, 2001). Without addressing capability and governance conditions, investments in technology or financial incentives may produce limited impact (Kim and Chai, 2017; Ahmed et al., 2019).

Recent studies support the need for structural-causality approaches. Karuppiyah et al. (2020) show that green economy practices are shaped by interdependent causal factors rather than isolated variables. Similarly, Karuppiyah et al. (2023) use Best-Worst Method and DEMATEL to reveal cause effect relationships among life cycle assessment challenges. These studies demonstrate that sustainability barriers form interconnected systems with directional influence. This study extends this logic to GSCM in fossil-fuel-dependent logistics systems using ISM–MICMAC.

Taken together, these perspectives show that GSCM barriers are not isolated obstacles but structurally embedded constraints within fossil-fuel-dependent logistics systems. Socio-technical conditions define system complexity, institutional pressures shape external expectations, human capability determines implementation capacity, and systems thinking explains how these elements interact. This integrated view supports the use of structural modeling to identify causal hierarchy and intervention priorities. This integrated view justifies the use of structural modeling to identify causal hierarchy, distinguish between driver and dependent barriers, and prioritize effective intervention points.

Building on this integrated framework, the causal relationships among the study variables can be theoretically explained. From a socio-technical perspective, technological infrastructure barriers (ITI) do not operate independently but depend on the alignment of skills, routines, and organizational capabilities. Human-centered sustainability explains why knowledge and support barriers (IKS) act as foundational drivers, as leadership commitment, training, and awareness determine the organization's ability to adopt and utilize technological systems. Institutional theory further clarifies that external pressures to adopt sustainable technologies are filtered through internal capability, meaning that weak knowledge and support limit the effectiveness of technological investments. Systems thinking integrates these relationships by showing that IKS functions as an upstream driver influencing ITI and financial constraints, while

policy and organizational barriers emerge as dependent outcomes. This provides a theoretical basis for the hierarchical structure identified in the ISM analysis, where human capability constraints shape downstream technological and organizational conditions. In this structure, knowledge and support (IKS/KS) act as primary drivers that condition the effectiveness of technological infrastructure (ITI/T1), explaining why technology-related barriers emerge as dependent or linkage factors rather than independent constraints.

2.5 Structural modeling of GSCM barriers

Building on this theoretical framework, GSCM barriers can be understood as a structured system of interrelated constraints in which some barriers act as upstream drivers while others emerge as downstream outcomes. Some barriers act as upstream drivers, while others emerge as downstream outcomes (El-Nakib and Elzarka, 2026; Saudi Vision 2030, 2025a,b; Saudi Green Initiative, 2025a,b; Warfield, 1974).

In particular, human capability barriers such as lack of knowledge, training, and managerial support can shape technological, financial, and policy-related constraints (Kolk, 2016). Interpretive structural modeling (ISM) is applied to identify hierarchical relationships among barriers. This approach aligns with the theoretical premise that GSCM barriers are layered and path-dependent rather than independent. Unlike ranking methods, ISM reveals which barriers act as drivers and which function as dependent outcomes. MICMAC analysis complements this by classifying barriers based on their driving and dependence power. This approach is especially relevant in fossil-fuel-dependent logistics systems, where barriers are deeply interconnected and require coordinated intervention. By identifying hierarchical relationships, ISM–MICMAC provides a structured basis for prioritizing actions and targeting leverage points in sustainability transitions (Geels, 2020; Grin, 2010; Smith et al., 2005). This provides a theory-informed basis for moving beyond barrier identification toward causal analysis and intervention prioritization.

3 Methods

3.1 Research design

By viewing barriers to GSCM adoption as part of a socio-technical system, this study employs a multi-stage research design combining survey-based barrier identification with expert-driven structural modeling using ISM.

This study adopts a multi-stage research design combining survey-based barrier identification with expert-driven structural modeling using ISM. ISM is used because the objective of this study is to identify hierarchical dependency among barriers rather than only their relative importance. This choice follows the theoretical premise that GSCM barriers in fossil-fuel-dependent (Rahman et al., 2020; Pathak et al., 2024). Logistics systems are layered and path-dependent. While ranking methods show salience and DEMATEL highlights directional influence, ISM is especially suitable when the goal is to identify upstream drivers and downstream outcomes. MICMAC complements this by classifying barriers according to driving and dependence power (Dey et al., 2026).

This approach is consistent with recent sustainability analytics studies that examine causal structure among implementation

barriers rather than treating them as stand-alone constraints, including work on green economy practices and life cycle assessment challenges.

3.2 Data collection

Professionals in the logistics and transport sector who are currently adopting, or are going to adopt, GSCM practices and systems were approached to collect primary data using a structured questionnaire. The respondents were asked to rate the relative importance of the barriers to GSCM adoption using a five-point Likert scale. The study's target audience comprises respondents with operational and strategic responsibilities, including logistics managers, sustainability officers, and logistics consultants. A purposive sampling technique was used to elicit responses from logistics professionals with first-hand experience in supply chain management and sustainability initiatives. The research received 150 usable results for the statistical analysis. The study assessed GSCM adoption barriers among logistics and transport firms operating in Saudi Arabia, specifically in consumer electronics and appliance firms, focusing on supplier selection and relationship management processes. The survey participants represented important logistics sub-sectors, including freight forwarding ($n = 45$), warehousing and distribution ($n = 38$), multimodal transport and ports ($n = 38$), and consulting or policy advisory ($n = 29$). The country's main logistics hubs provided secondary data for logistics services. The cities Riyadh ($n = 60$); Jeddah ($n = 45$); Dammam ($n = 45$). These distributions ensured the data's sectoral and geographical representation. According to the earlier GSCM study conducted in Saudi Arabia, the respondents' profiles are similar. The representation of genders was almost equal. The majority of respondents (over 75%) were aged between.

A questionnaire was prepared and distributed using online survey tools (Google Forms and SurveyMonkey). It was also disseminated through professional networks such as LinkedIn and logistics consulting groups in Saudi Arabia. The first stage of the research process to select the barriers involved an initial pool of barriers identified from the literature review; however, only data with validated survey responses were retained for the final analysis to reduce bias. Based on an extensive literature review and experts' views, barriers were grouped into four major categories, and 10–12 aggregated sub-barriers were identified for subsequent rounds (Rahman et al., 2020). The SSIM structure modelling and ISM subsequent phases were developed through expert consultation rounds using the Delphi method, involving a core panel of 20 experts across 2–3 rounds. The chosen experts were experienced in logistics operations. The finalized main barriers and related sub-barriers are given in Table 1. Consistent with the scope of this research and the Delphi-based ISM analysis, the policy and sustainability backgrounds of the experts are suitable for the sampled panel. Expert responses were assessed for inter-rater agreement using Cohen's kappa ($\kappa = 0.82$), indicating strong agreement among experts. The expert panel reviewed and validated the SSIM and the resulting ISM hierarchy in accordance with interpretive structural modelling guidelines.

The expert panel used for ISM analysis was distinct from the survey respondents and consisted of professionals with direct experience in GSCM implementation and sustainability initiatives,

ensuring methodological separation between perception-based data and structural modeling.

3.3 Expert selection and panel composition

Given that each logistics operation, as with each sustainability issue in Saudi Arabia, pertains to a specific context, purposive expert sampling was applied to the interpretive structural modeling process. Twenty experts in GSCM gathered to provide their judgment on the interrelationships among the barriers. A strict set of criteria was laid out to select experts, ensuring relevance and in-depth expertise. A minimum of 10 years of professional experience in the sector of logistics and transport; a current senior (or senior role within the past 5 years) (e.g., director, manager, consultant); and documented involvement in a sustainability- or GSCM-related initiative. To ensure representativeness at the sub-sector level, the experts included the following sub-sectors: freight forwarding ($n = 6$), warehousing and distribution ($n = 5$), multimodal transport and ports ($n = 5$), and consulting or policy advisory ($n = 4$). The specialists were scattered across the prominent Logistics Hubs in Saudi Arabia, namely Riyadh, Jeddah, and Dammam. The initial expert set was identified using professional networks. This included industry associations such as Saudi Logistics Consulting and LinkedIn. Each expert completed an eligibility screening form and was then validated through a review of the curriculum vitae and a short telephone interview.

Several actions were taken to mitigate bias and enhance the validity of expert judgments. To minimize network-based sampling bias, recommendations were first obtained from two independent external industrial bodies. In addition, all expert opinions were collected anonymously and by secure online tools. Careful attention was paid to the wording of these questions to ensure they were neither effortful nor leading. To avoid the effects of groupthink and social desirability bias, all experts held two rounds of individual pairwise comparisons (prior to any group discussion). After two Delphi rounds, aggregated feedback was shared with experts, allowing them to revise their judgments. This iterative process improved convergence and reduced disagreement, and a final consensus meeting was conducted to resolve any remaining differences.

3.4 Measurement, data analysis, validity, and reliability

To measure hurdles in the adoption of GSCM, an instrument was developed in four areas. These were technology, knowledge, organization, and communication. To measure each construct, the research adopted multiple items identified as important dimensions in past GSCM literature. This includes availability and integration of technology [insufficient technology and infrastructure (ITI)], awareness, training, and managerial support [inadequate knowledge and support (IKS)], customized policy alignment and stakeholder commitment [unsupportive organizational and operational policy (UOOP)], investment cost and financial incentives [financial constraints (FC)]. Using a 5-point Likert scale, the respondent rated the item on its importance (5 = strongly agree, 1 = strongly disagree). Description statistics were conducted for all barrier variables using the full sample of 150 valid responses. The complete response data were used to rank these

TABLE 1 Barriers to green supply chain management.

Main barrier	Sub-barriers	References
Technology and infrastructure (TI)	<ol style="list-style-type: none"> 1. Absence of progressive technology solutions (ITI1) 2. Insufficient sharing of knowledge of best GSCM practices (ITI2) 3. Inadequate R&D for product recovery systems (ITI3) 4. Shortage of technical expertise (ITI4) 5. Operational complexities in recovery processes (ITI5) 6. Deficiency in modern Infrastructure (facilities, storage, transportation) (ITI6) 	Rahman et al. (2020), Pathak et al. (2024), Ara et al. (2024), and Mathiyazhagan et al. (2013)
Knowledge and support (KS)	<ol style="list-style-type: none"> 1. Limited understanding of sustainable practices (IKS1) 2. Limited environmental knowledge (IKS2) 3. Inadequate employee training on GSCM (IKS3) 4. Low consumer awareness of eco-friendly products (IKS4) 5. Lack of knowledge about tax policies for returned products (IKS5) 6. Weak senior management commitment/support (IKS6) 	Rahman et al. (2020), Hariyani and Mishra (2023), Wong et al. (2023), and Ara et al. (2024)
Organizational and operational policy (OOP)	<ol style="list-style-type: none"> 1. Inefficient organizational structure hindering GSCM (UOOP1) 2. Absence of supportive government policies (UOOP2) 3. Inefficient stakeholder backing (UOOP3) 4. Insufficient recycling/reusing facilities (UOOP4) 5. Lack of compliance with international standards (UOOP5) 6. Absence of standardized GSCM procedures (UOOP6) 7. Weak legislative frameworks (UOOP7) 	Rahman et al. (2020), Pathak et al. (2024), Ara et al. (2024), and Tumpa et al. (2019)
Financial constraints (FC)	<ol style="list-style-type: none"> 1. Financial burden of implementation (FC1) 2. Limited access to bank financing for green initiatives (FC2) 3. Economic instability creating investment uncertainty (FC3) 4. High costs for hazardous material disposal (FC4) 5. Inefficient awareness of GSCM financial benefits (FC5) 6. Perceived high upfront/ongoing costs (FC6) 	Rahman et al. (2020), Pathak et al. (2024), and Ara et al. (2024)

barriers to the adoption of GSCM in logistical and transport operations in Saudi Arabia by importance. The study analyzed the mean, standard deviation, and frequency distribution of various items, including the above barriers. The analysis culminated in a comprehensive examination of the data and served as evidence for model specification. They employed interpretive structural modeling (ISM) on the barrier constructs. Interpretive structural modeling (ISM) was applied to examine the structural relationships among barriers.

The ISM technique followed the established procedure. It developed a Structural Self-Interaction Matrix (SSIM), which was then converted into a binary reachability matrix. Transitivity was used to partition hierarchical levels and establish the final reachability matrix. Finally, it depicted and interpreted the directed structural model. To enhance the instrument's quality, a pilot study with 30 samples was conducted to revise wording and ensure item clarity. Moreover, the value of consistency was 0.85, as indicated by Cronbach's alpha, thereby denoting high reliability. The reliability coefficients of the subscales range from 0.83 to 0.87, indicating strong internal consistency within each barrier category. Exploratory factor analysis was conducted only during the pilot stage to assess item clarity and internal

consistency. It was not used for construct validation, as ISM relies on expert-based structural modeling rather than latent variable analysis. The measures are drawn from established scales of GSCM barriers (Rahman et al., 2020) and from expert feedback. The measurement items are presented in Table 2.

Mean values reflect perceived importance rather than causal influence. Frequency distributions are based on rounded item averages.

3.5 Integration of survey results with ISM

Survey results were used to identify and rank the importance of barriers, while ISM analysis was used to determine their structural relationships. The data on barrier importance using a five-point Likert scale, which supports subsequent ISM analysis. These two approaches are complementary, with survey data capturing perceived significance and ISM revealing causal hierarchy. All identified barriers recorded mean scores above the midpoint ($M > 3.0$), indicating that they are considered relevant by industry practitioners and should be retained in the structural analysis. The survey findings were therefore used to confirm the inclusion of all barrier categories in the ISM model.

TABLE 2 Descriptive statistics for the GSCM barriers.

Barrier	Mean (M)	Standard deviation (SD)	Frequency distribution (rounded scores: 1–5)
Insufficient technology and infrastructure (ITI)	3.81	0.71	1: 0; 2: 8; 3: 38; 4: 80; 5: 24
Inadequate knowledge and support (IKS)	4.08	0.63	1: 0; 2: 3; 3: 23; 4: 85; 5: 39
Unsupportive organizational and operational policy (UOOP)	3.78	0.79	1: 1; 2: 9; 3: 41; 4: 70; 5: 29
Financial constraints (FC)	3.85	0.77	1: 1; 2: 7; 3: 38; 4: 65; 5: 39

During the development of the Structural Self-Interaction Matrix (SSIM), initial contextual relationships among barriers were established based on literature and expert judgment. These relationships were then cross-checked against survey rankings to ensure consistency between perceived importance and structural positioning. In cases of disagreement among experts, decisions were guided by both logical reasoning and the relative importance indicated by survey results. To support interpretation, survey-based importance scores were normalized and used to provide additional insight into the relative salience of barriers. However, these weights were not incorporated into the ISM reachability matrix, as ISM relies on binary relationships. Instead, survey results were used to complement the interpretation of driving and dependence power derived from the ISM model.

The study design reflects the distinction between barrier salience and barrier causality. The survey identifies relevant barriers, while ISM reveals their structural relationships. This distinction is central to the study's theoretical framework, which views GSCM barriers as structurally interdependent rather than independent constraints.

4 Results and structural analysis

4.1 Descriptive statistics of responses

This section presents the empirical results and structural analysis of GSCM barriers based on survey data and ISM modeling. The sample covers a wide range of sectors and regions across important logistics sub-sectors and major industrial regions. Table 2 summarizes the descriptive statistics for the four key categories of GSCM barriers, including the mean (M), standard deviation (SD), and frequency distribution.

Perceptions of GSCM adoption barriers were above the midpoint of 3.0 on the five-point Likert scale, as indicated by the mean values across the main barrier dimensions. This implies the importance of the barriers to GSCM adoption for respondents in this study in the Saudi logistics and transport sector. The most significant category was inadequate knowledge and support (IKS), followed by financial constraints (FC), insufficient technology and infrastructure (ITI), and unsupportive organizational and operational policy (UOOP). As in other GSCM studies in emerging and energy-intensive economies, the results establish human- and capability-related challenges as particularly salient.

The results of item-level descriptive statistics, including mean and standard deviation of each measurement item for each barrier category, are given in Table 3. The high average scores across all categories further confirm the relevance of the identified barriers.

The descriptive outcomes are employed to substantiate the prominence of the barrier and to endorse the ensuing structural design; their significance is not construed as providing evidence of causation.

4.2 Expert consensus and development of the Structural Self-Interaction Matrix (SSIM)

The Structural Self-Interaction Matrix (SSIM) was developed to assess the context relationships among four significant GSCM barriers based on validated barrier importance ratings from a survey. The SSIM is the outcome of the consensus process, structured along Delphi lines, of the 20-expert panel detailed in the methodology section. Neither survey respondents nor operating personnel were involved in the ISM computations. Expert judgments were first gathered through anonymous individual pairwise comparisons and later fine-tuned through a virtual consensus workshop. Consensus was achieved when 80% or more of the panelists agreed on the direction of each relationship. This range of expertise ensured a robust depth of reasoning while minimising groupthink.

Table 4 presents the finalized SSIMs for the significant GSCM barriers using standard ISM symbols (V, A, X, O). The IKS influences all other barriers, while the UOOP is primarily driven by upstream constraints, as per SSIM. insufficient technology and infrastructure (ITI) and financial constraints (FC) occupy intermediate positions, reflecting both driving and dependent roles within the barrier system.

4.3 Reachability analysis and driving–dependence assessment of main barriers

Using the basic ISM transformation rules, the SSIM was converted into the initial reachability matrix as recorded in Table 5. Transitivity was applied to account for indirect relationships between the barriers. This led to the study of the final reachability matrix presented in Table 6. The driving power and dependence power were determined by summing the rows and columns of the final reachability matrix.

As the one with the highest driving power and lowest dependence, Inadequate Knowledge and Support (IKS) is the most influential barrier in the system.

The unsupportive organizational and operational policy is highly dependent. However, it has the least driving power, indicating that the policy and organizational barriers are mainly due to deficiencies in upstream barriers. Insufficient technology and infrastructure (ITI) and financial constraints (FC) occupy intermediate positions, showing both strong driving power and dependence.

These results indicate that GSCM barriers operate as a hierarchical system, where human capability constraints act as upstream drivers shaping technological, financial, and organizational outcomes.

TABLE 3 Item-level descriptive statistics for GSCM barrier indicators (n = 150).

#	Mean	Std. deviation
Insufficient technology and infrastructure (ITI)		
ITI 1	4.6700	0.47080
ITI 2	4.6425	0.47986
ITI 3	4.5950	0.49151
ITI 4	4.6725	0.46989
ITI 5	4.6275	0.48408
ITI 6	4.6100	0.48836
Inadequate knowledge and support (IKS)		
IKS 1	4.1150	0.31942
IKS 2	4.1125	0.31638
IKS 3	3.8325	0.52453
IKS 4	3.8125	0.51770
IKS 5	3.8075	0.51098
IKS 6	3.8125	0.51770
Unsupportive organizational and operational policy (UOOP)		
UOOP 1	4.2575	0.47619
UOOP 2	4.2400	0.47746
UOOP 3	4.2575	0.47619
UOOP 4	4.2400	0.47746
UOOP 5	4.2025	0.53122
UOOP 6	4.1825	0.53844
UOOP 7	4.1625	0.53555
Financial constraints (FC)		
FC 1	4.3725	0.56083
FC 2	4.1475	0.72559
FC 3	4.2000	0.49051
FC 4	4.5750	0.71810
FC 5	4.5800	0.71054
FC 6	4.0575	0.86084

TABLE 4 SSIM for assessment of main GSCM barriers.

Item	ITI	IKS	UOOP	FC
ITI	X	A	V	X
IKS	V	X	V	V
UOOP	A	A	X	A
FC	X	A	V	X

TABLE 5 Initial reachability matrix for assessment of main GSCM barriers.

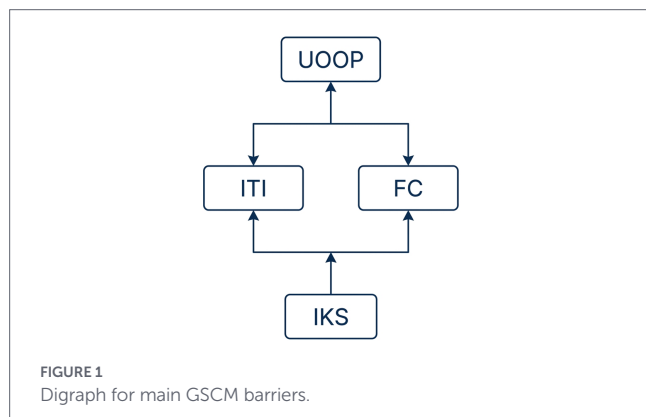
Item	ITI	IKS	UOOP	FC
ITI	1	0	1	1
IKS	1	1	1	1
UOOP	0	0	1	0
FC	1	0	1	1

TABLE 6 Final reachability matrix for assessment of main GSCM barriers.

Item	ITI	IKS	UOOP	FC	Driving power
ITI	1	0	1	1	3
IKS	1	1	1	1	4
UOOP	0	0	1	0	1
FC	1	0	1	1	3
Dependence power	3	1	4	3	1

TABLE 7 Level partition for assessment of main GSCM barriers.

Item	Reachability set	Antecedent set	Intersection set	Level
ITI	ITI, UOOP, FC	ITI, IKS, FC	ITI, FC	2nd
IKS	ITI, IKS, UOOP, FC	IKS	IKS	3rd
UOOP	UOOP	ITI, IKS, UOOP, FC	UOOP	1st
FC	ITI, UOOP, FC	ITI, IKS, FC	ITI, FC	2nd



From a structural perspective, inadequate knowledge and support (IKS) functions as a driver barrier because it shapes the organization’s ability to respond to technical and regulatory demands. Insufficient technology and infrastructure (ITI) and financial constraints (FC) act as linkage barriers, reflecting system-level interactions where changes in one condition influence others. Unsupportive organizational and operational policy (UOOP) appears as a dependent barrier, emerging as an outcome of upstream capability and governance constraints.

4.4 Level partitioning and ISM hierarchy of main GSCM barriers

The final reachability matrix was obtained by performing level partitioning to assign each barrier to a level based on its reachability and antecedent sets. Table 7 shows the output after level partitioning. The analysis places inadequate knowledge and support (IKS) at the bottom (most influential) level of the hierarchy, indicating that it serves as the foundation for the other constructs. Insufficient technology and infrastructure (ITI) and financial constraints (FC) are at intermediate levels, while unsupportive organizational and operational policy (UOOP) is at the top level, as it is dependent on them.

As depicted in Figure 1, the ISM digraph visually illustrates the influence structure of the main GSCM barriers.

Table 8 summarizes the structural ranking of the primary barriers based on driving-dependence relationships rather than perceived importance.

The ranks presented reflect structural influence based on ISM driving dependence relationships rather than perceived importance derived from survey means. To improve readability, detailed SSIM and reachability matrices for sub-barriers are provided in Appendix A. The main text focuses on key structural insights and hierarchical interpretations rather than procedural repetition.

4.5 Structural analysis of GSCM sub-barriers

4.5.1 Insufficient technology and infrastructure (ITI)

This category comprises six sub-barriers (ITI1–ITI6), whose structural relationships are summarized in Tables 9–13. The ISM analysis reveals clear hierarchical linkages among these technological constraints. The results indicate that core technological capability limitations, particularly those related to system integration and infrastructure readiness, act as primary driving sub-barriers within this category. These foundational constraints influence downstream operational challenges and hinder the effective implementation of GSCM practices. In contrast, sub-barriers such as ITI5 and ITI6 exhibit higher dependence, indicating that they are largely outcomes of upstream technological deficiencies. This structural pattern suggests that improvements in fundamental technological capacity and digital infrastructure are essential for mitigating broader operational and implementation-related barriers.

The hierarchical structure and influence relationships are illustrated in Figure 2, while the relative driving and dependence power of each sub-barrier is presented in Table 13.

This pattern reflects a hierarchical structure in which upstream constraints shape downstream operational outcomes.

4.5.2 Inadequate knowledge and support (IKS)

This category includes six sub-barriers (IKS1–IKS6), with their structural relationships presented in Tables 14–18. The ISM results highlight

TABLE 8 Ranks of main GSCM barriers.

Sub-barriers	Rank
ITI	2
IKS	1
UOOP	3
FC	2

TABLE 9 SSIM for sub-barriers of insufficient technology and infrastructure barriers of GSCM.

Item	ITI1	ITI2	ITI3	ITI4	ITI5	ITI6
ITI1	X	X	V	V	V	V
ITI2	X	X	V	V	V	V
ITI3	A	A	X	X	V	V
ITI4	A	A	X	X	V	V
ITI5	A	A	A	A	X	X
ITI6	A	A	A	A	X	X

TABLE 10 Initial reachability matrix for sub-barriers of insufficient technology and infrastructure barriers of GSCM.

Item	ITI1	ITI2	ITI3	ITI4	ITI5	ITI6
ITI1	1	1	1	1	1	1
ITI2	1	1	1	1	1	1
ITI3	0	0	1	1	1	1
ITI4	0	0	1	1	1	1
ITI5	0	0	0	0	1	1
ITI6	0	0	0	0	1	1

TABLE 11 Final reachability matrix for sub-barriers of insufficient technology and infrastructure barriers of GSCM.

Item	ITI1	ITI2	ITI3	ITI4	ITI5	ITI6	Driving power
ITI1	1	1	1	1	1	1	6
ITI2	1	1	1	1	1	1	6
ITI3	0	0	1	1	1	1	4
ITI4	0	0	1	1	1	1	4
ITI5	0	0	0	0	1	1	2
ITI6	0	0	0	0	1	1	2
Dependence power	2	2	4	4	6	6	

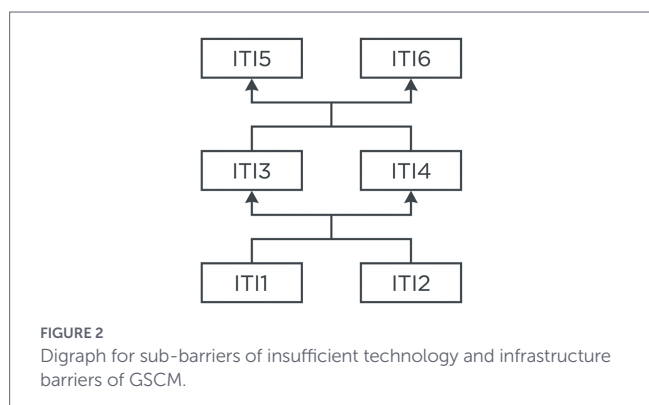
TABLE 12 Level partition for sub-barriers of insufficient technology and infrastructure barriers of GSCM.

Item	Reachability set	Antecedent set	Intersection set	Level
ITI1	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6	ITI1, ITI2	ITI1, ITI2	3rd
ITI2	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6	ITI1, ITI2	ITI1, ITI2	3rd
ITI3	ITI3, ITI4, ITI5, ITI6	ITI1, ITI2, ITI3, ITI4	ITI3, ITI4	2nd
ITI4	ITI3, ITI4, ITI5, ITI6	ITI1, ITI2, ITI3, ITI4	ITI3, ITI4	2nd
ITI5	ITI5, ITI6	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6	ITI5, ITI6	1st
ITI6	ITI5, ITI6	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6	ITI5, ITI6	1st

the dominant role of human-centered constraints within the barrier system. The analysis shows that sub-barriers related to knowledge, training, and managerial support particularly IKS1 and IKS6 act as primary driving factors. These elements exert strong influence over other sub-barriers by shaping organizational readiness, awareness, and the capacity to implement sustainable practices. In contrast, sub-barriers such as IKS4 and IKS5 exhibit higher dependence, indicating that they are largely outcomes of upstream deficiencies in knowledge, capability, and leadership

TABLE 13 Ranks of sub-barriers of insufficient technology and infrastructure barriers of GSCM.

Sub-barriers	Rank
IT11	1
IT12	1
IT13	2
IT14	2
IT15	3
IT16	3



commitment. This pattern reinforces the structural importance of human-centered capabilities as foundational drivers in GSCM adoption.

The hierarchical relationships are illustrated in Figure 3, while the relative driving and dependence power of each sub-barrier is summarized in Table 18.

This pattern reflects a hierarchical structure in which upstream constraints shape downstream operational outcomes.

4.5.3 Unsupportive organizational and operational policy (UOOP)

This category comprises seven sub-barriers (UOOP1–UOOP7), with their structural relationships summarized in Tables 19–23. The ISM analysis reveals that organizational and policy-related barriers are largely influenced by upstream human and capability constraints. The results show that sub-barriers such as UOOP1 and UOOP2 act as key influencing factors within this category, shaping governance structures, regulatory alignment, and operational practices. These elements play an important role in determining how sustainability initiatives are supported or constrained within organizations. In contrast, sub-barriers including UOOP5, UOOP6, and UOOP7 demonstrate higher dependence, indicating that they are outcomes of broader structural limitations related to knowledge, leadership, and resource availability. This suggests that policy and organizational barriers are less likely to be resolved in isolation and require prior improvements in foundational capabilities.

The hierarchical structure of these relationships is illustrated in Figure 4, while the relative driving and dependence power of each sub-barrier is presented in Table 23.

This pattern reflects a hierarchical structure in which upstream constraints shape downstream operational outcomes.

4.5.4 Financial constraints (FC)

This category includes six sub-barriers (FC1–FC6), with their structural relationships summarized in Tables 24–28. The ISM results indicate that financial constraints occupy an intermediate position within

TABLE 14 SSIM for sub-barriers of inadequate knowledge and support.

Item	IKS1	IKS2	IKS3	IKS4	IKS5	IKS6
IKS1	X	V	V	V	V	X
IKS2	A	X	X	V	V	A
IKS3	A	X	X	V	V	A
IKS4	A	A	A	X	X	A
IKS5	A	A	A	X	X	A
IKS6	X	V	V	V	V	X

TABLE 15 Initial reachability matrix for sub-barriers of inadequate knowledge and support.

Item	IKS1	IKS2	IKS3	IKS4	IKS5	IKS6
IKS1	1	1	1	1	1	1
IKS2	0	1	1	1	1	0
IKS3	0	1	1	1	1	0
IKS4	0	0	0	1	1	0
IKS5	0	0	0	1	1	0
IKS6	1	1	1	1	1	1

TABLE 16 Final reachability matrix for sub-barriers of inadequate knowledge and support.

Item	IKS1	IKS2	IKS3	IKS4	IKS5	IKS6	Driving power
IKS1	1	1	1	1	1	1	6
IKS2	0	1	1	1	1	0	4
IKS3	0	1	1	1	1	0	4
IKS4	0	0	0	1	1	0	2
IKS5	0	0	0	1	1	0	2
IKS6	1	1	1	1	1	1	6
Dependence power	2	4	4	6	6	2	

TABLE 17 Level partition for sub-barriers of inadequate knowledge and support.

Item	Reachability set	Antecedent set	Intersection set	Level
IKS1	IKS1, IKS2, IKS3, IKS4, IKS5, IKS6	IKS1, IKS6	IKS1, IKS6	3rd
IKS2	IKS2, IKS3, IKS4, IKS5	IKS1, IKS2, IKS3, IKS6	IKS2, IKS3	2nd
IKS3	IKS2, IKS3, IKS4, IKS5	IKS1, IKS2, IKS3, IKS6	IKS2, IKS3	2nd
IKS4	IKS4, IKS5	IKS1, IKS2, IKS3, IKS4, IKS5, IKS6	IKS4, IKS5	1st
IKS5	IKS4, IKS5	IKS1, IKS2, IKS3, IKS4, IKS5, IKS6	IKS4, IKS5	1st
IKS6	IKS1, IKS2, IKS3, IKS4, IKS5, IKS6	IKS1, IKS6	IKS1, IKS6	3rd

TABLE 18 Ranks of sub-barriers of inadequate knowledge and support.

Sub-barriers	Rank
IKS1	1
IKS2	2
IKS3	2
IKS4	3
IKS5	3
IKS6	1

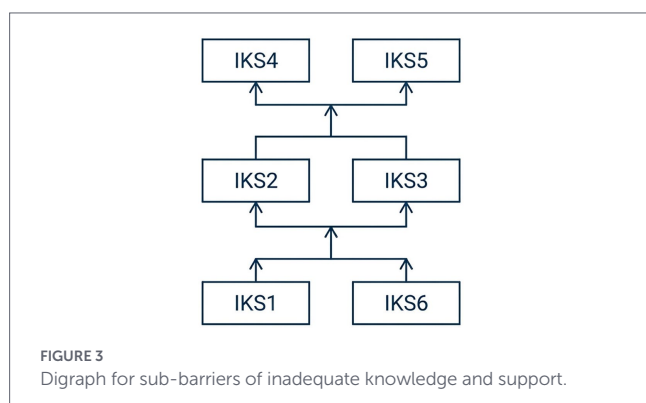


FIGURE 3 Digraph for sub-barriers of inadequate knowledge and support.

the overall barrier hierarchy. The analysis shows that sub-barriers such as FC1, FC2, and FC3 act as key influencing factors, reflecting the importance of investment capacity, cost considerations, and financial risk in shaping GSCM adoption. These factors influence the ability of organizations to invest in technology, training, and sustainability initiatives. In contrast, sub-barriers including FC4 and FC6 exhibit higher dependence, suggesting that they are outcomes of broader structural

conditions related to technological readiness and organizational capabilities. This indicates that financial barriers are not entirely independent but are closely linked to upstream human and technological constraints.

The hierarchical relationships are illustrated in Figure 5, while the relative driving and dependence power of each sub-barrier is presented in Table 28.

This pattern reflects a hierarchical structure in which upstream constraints shape downstream operational outcomes.

4.6 Integrated ISM analysis of all sub-barriers

The integrated analysis of all sub-barriers reveals a comprehensive hierarchical structure across the GSCM system. The results confirm that human-centered sub-barriers, particularly those related to knowledge, training, and managerial support, occupy the most influential positions in the hierarchy. These factors act as foundational drivers that shape technological readiness, financial feasibility, and organizational-policy outcomes. Technological and financial sub-barriers appear at intermediate levels, reflecting their dual role as both influenced and influencing factors. In contrast, several policy and operational sub-barriers emerge as highly dependent, indicating that they are largely outcomes of upstream structural constraints (see Tables 29–32).

The integrated digraph Figure 6 and ranking results Table 33 provide a consolidated view of these relationships, highlighting key leverage points for effective intervention.

4.7 MICMAC analysis of main GSCM barriers

MICMAC analysis complements the ISM hierarchy and provides deeper strategic classification. MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) analysis was performed

TABLE 19 SSIM for sub-barriers of unsupportive organizational and operational policy of GSCM.

Item	UOOP1	UOOP2	UOOP3	UOOP4	UOOP5	UOOP6	UOOP7
UOOP1	X	X	V	V	V	V	V
UOOP2	X	X	V	V	V	V	V
UOOP3	A	A	X	X	V	V	V
UOOP4	A	A	X	X	V	V	V
UOOP5	A	A	A	A	X	X	X
UOOP6	A	A	A	A	X	X	X
UOOP7	A	A	A	A	X	X	X

TABLE 20 Initial reachability matrix for sub-barriers of unsupportive organizational and operational policy of GSCM.

Item	UOOP1	UOOP2	UOOP3	UOOP4	UOOP5	UOOP6	UOOP7
UOOP1	1	1	1	1	1	1	1
UOOP2	1	1	1	1	1	1	1
UOOP3	0	0	1	1	1	1	1
UOOP4	0	0	1	1	1	1	1
UOOP5	0	0	0	0	1	1	1
UOOP6	0	0	0	0	1	1	1
UOOP7	0	0	0	0	1	1	1

TABLE 21 Final reachability matrix for sub-barriers of unsupportive organizational and operational policy of GSCM.

Item	UOOP1	UOOP2	UOOP3	UOOP4	UOOP5	UOOP6	UOOP7	Driving power
UOOP1	1	1	1	1	1	1	1	7
UOOP2	1	1	1	1	1	1	1	7
UOOP3	0	0	1	1	1	1	1	5
UOOP4	0	0	1	1	1	1	1	5
UOOP5	0	0	0	0	1	1	1	3
UOOP6	0	0	0	0	1	1	1	3
UOOP7	0	0	0	0	1	1	1	3
Dependence Power	2	2	4	4	7	7	7	

TABLE 22 Level partition for sub-barriers of unsupportive organizational and operational policy of GSCM.

Item	Reachability set	Antecedent set	Intersection set	Level
UOOP1	UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP1, UOOP2	UOOP1, UOOP2	1st
UOOP2	UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP1, UOOP2	UOOP1, UOOP2	1st
UOOP3	UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP1, UOOP2, UOOP3, UOOP4	UOOP3, UOOP4	2nd
UOOP4	UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP1, UOOP2, UOOP3, UOOP4	UOOP3, UOOP4	2nd
UOOP5	UOOP5, UOOP6, UOOP7	UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP5, UOOP6, UOOP7	3rd
UOOP6	UOOP5, UOOP6, UOOP7	UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP5, UOOP6, UOOP7	3rd
UOOP7	UOOP5, UOOP6, UOOP7	UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7	UOOP5, UOOP6, UOOP7	3rd

using the driving power (sum of rows) and dependence power (sum of columns) from the final reachability matrix (Table 6 for main barriers; aggregated for sub-barriers where relevant). Barriers are classified into four quadrants based on their driving and dependence powers: Independent/Driving (high driving power, low dependence): Strong influencers/root causes (e.g., inadequate knowledge and

support—IKS). Linkage (high driving and high dependence): Unstable, requiring careful management (e.g., particular technology sub-barriers). Dependent (low driving, high dependence): Outcomes affected by others (e.g., unsupportive organizational and operational policy—UOOP). Autonomous (low driving, low dependence): Relatively disconnected/weak barriers. The MICMAC quadrant diagram is presented in Figure 7.

TABLE 23 Ranks of sub-barriers of unsupportive organizational and operational policy of GSCM.

Sub-barriers	Rank
UOOP1	1
UOOP2	1
UOOP3	2
UOOP4	2
UOOP5	3
UOOP6	3
UOOP7	3

This classification highlights IKS as the most substantial driving/independent barrier, confirming its foundational role, while UOOP emerges as highly dependent, aligning with the ISM hierarchy. MICMAC thus offers actionable insights for prioritizing interventions on independent and linkage barriers to achieve cascading improvements.

4.8 Summary of key structural findings

Overall, the findings show that the GSCM adoption barriers of the Saudi Arabian logistics and transport sector are hierarchical and inter-dependent. The main barriers are a lack of knowledge, skills, and managerial support, which influence technological readiness, financial feasibility, and policy fit. Intermediate issues include technology and financial barriers. Meanwhile, organizational and policy constraints are largely downstream effects. The findings highlight the relevance of interventions that focus on people and capabilities as effective levers for accelerating the transformation of supply chains towards sustainability in logistics systems that rely on fossil fuels. Furthermore, they provide a clear structural foundation for the ensuing discussion.

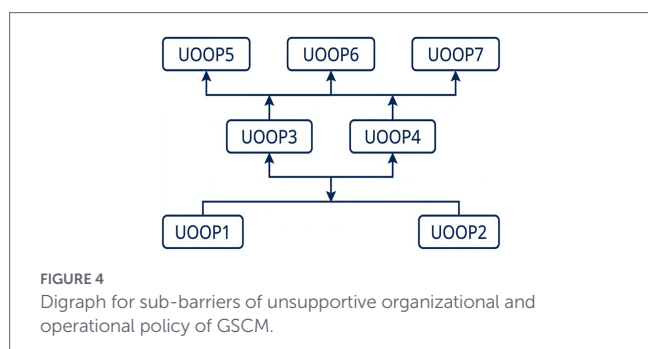


FIGURE 4 Digraph for sub-barriers of unsupportive organizational and operational policy of GSCM.

5 Discussion

This hierarchy is consistent with the theoretical expectation that human capability (IKS) conditions the effectiveness of technological infrastructure (ITI) and financial resources. The findings

TABLE 24 SSIM for sub-barriers of financial constraints barriers of GSCM.

Item	FC1	FC2	FC3	FC4	FC5	FC6
FC1	X	X	X	V	V	V
FC2	X	X	X	V	V	V
FC3	X	X	X	V	V	V
FC4	A	A	A	X	A	X
FC5	A	A	A	V	X	V
FC6	A	A	A	X	A	X

TABLE 25 Initial reachability matrix for sub-barriers of financial constraints barriers of GSCM.

Item	FC1	FC2	FC3	FC4	FC5	FC6
FC1	1	1	1	1	1	1
FC2	1	1	1	1	1	1
FC3	1	1	1	1	1	1
FC4	0	0	0	1	0	1
FC5	0	0	0	1	1	1
FC6	0	0	0	1	0	1

TABLE 26 Final reachability matrix for sub-barriers of financial constraints barriers of GSCM.

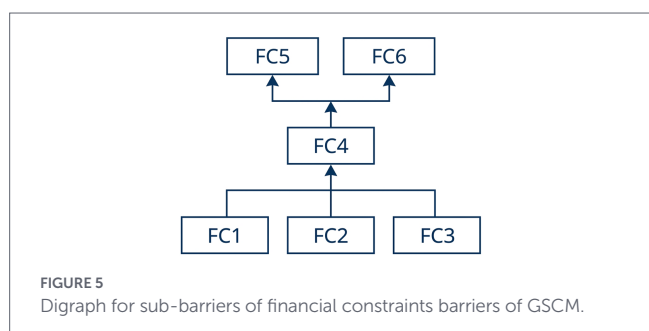
Item	FC1	FC2	FC3	FC4	FC5	FC6	Driving power
FC1	1	1	1	1	1	1	6
FC2	1	1	1	1	1	1	6
FC3	1	1	1	1	1	1	6
FC4	0	0	0	1	0	1	2
FC5	0	0	0	1	1	1	3
FC6	0	0	0	1	0	1	2
Dependence power	3	3	3	6	4	6	

TABLE 27 Level partition for sub-barriers of financial constraints barriers of GSCM.

Item	Reachability set	Antecedent set	Intersection set	Level
FC1	FC1, FC2, FC3, FC4, FC5, FC6	FC1, FC2, FC3	FC1, FC2, FC3	3rd
FC2	FC1, FC2, FC3, FC4, FC5, FC6	FC1, FC2, FC3	FC1, FC2, FC3	3rd
FC3	FC1, FC2, FC3, FC4, FC5, FC6	FC1, FC2, FC3	FC1, FC2, FC3	3rd
FC4	FC4, FC6	FC1, FC2, FC3, FC4, FC6	FC4, FC6	1st
FC5	FC4, FC5, FC6	FC1, FC2, FC3, FC5	FC5	2nd
FC6	FC4, FC6	FC1, FC2, FC3, FC4, FC6	FC4, FC6	1st

TABLE 28 Ranks of sub-barriers of financial constraints barriers of GSCM.

Sub-barriers	Rank
FC1	1
FC2	1
FC3	1
FC4	3
FC5	2
FC6	3



indicate that knowledge, training, and managerial support operate as upstream barriers, shaping the overall structure of GSCM adoption. These human-centered constraints influence the ability of firms to respond to technological and financial requirements (Jayant and Azhar, 2014; Movahedipour et al., 2017). In contrast, technological and financial barriers act as linkage factors,

reflecting their dual role as both influenced by upstream conditions and capable of affecting other elements within the system. Organizational and policy-related barriers appear primarily as dependent outcomes, emerging as a result of deeper capability and governance limitations (Ahmed et al., 2020; Nteta and Mushonga, 2021; Wong et al., 2023).

These results support the view that GSCM barriers are structurally interdependent rather than independent constraints. Sustainability transition challenges arise from the interaction of technical, organizational, and institutional conditions rather than from isolated obstacles (Pathak et al., 2024). The distinction between perceived importance and structural influence is critical, as it shows that barriers with the highest visibility are not always those with the greatest systemic impact. The findings align with recent sustainability analytics studies showing that implementation barriers form cause-effect structures rather than stand-alone constraints (Karuppiah et al., 2020, 2023).

In fossil-fuel-dependent logistics systems, infrastructure rigidity and carbon lock-in make capability deficits more consequential. Investments in technology and infrastructure alone are unlikely to produce meaningful change if organizations lack the skills, leadership commitment, and learning capacity required to adopt and sustain new practices. The results show that sustainability transition is constrained not only by resource availability but also by the ability of firms to adapt routines and align strategic priorities. This indicates that human and organizational factors function as foundational conditions that shape the effectiveness of all other interventions (Wang et al., 2023).

Prior studies have identified knowledge, technology, and financial barriers as key constraints in GSCM adoption. This study extends the literature by explaining how these barriers interact through a causal hierarchy. The findings show that human

TABLE 29 SSIM for sub-barriers of all the main barriers of GSCM.

Item	ITI1	ITI2	ITI3	ITI4	ITI5	ITI6	IKS1	IKS2	IKS3	IKS4	IKS5	IKS6	UOOP1	UOOP2	UOOP3	UOOP4	UOOP5	UOOP6	UOOP7	FC1	FC2	FC3	FC4	FC5	FC6	
ITI1	X	V	V	V	V	V	A	V	V	V	V	X	V	X	V	V	V	V	V	V	V	V	X	V	V	V
ITI2	A	X	V	V	V	V	A	X	V	V	V	A	X	A	X	V	V	X	V	V	V	V	A	V	V	V
ITI3	A	A	X	A	A	V	A	A	A	A	A	A	A	A	A	X	X	A	A	A	A	A	X	A	A	A
ITI4	A	A	V	X	X	V	A	A	A	X	V	A	A	A	A	V	V	A	A	A	A	A	V	A	A	A
ITI5	A	A	V	X	X	V	A	A	A	X	V	A	A	A	A	V	V	A	A	A	A	A	A	V	A	A
ITI6	A	A	A	A	A	X	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
IKS1	V	V	V	V	V	V	X	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
IKS2	A	X	V	V	V	V	A	X	V	V	V	A	X	A	X	V	V	X	V	V	V	V	A	V	V	V
IKS3	A	A	V	V	V	V	A	A	X	V	V	A	A	A	A	V	V	A	V	X	A	A	V	X	V	V
IKS4	A	A	V	X	X	V	A	A	A	X	V	A	A	A	A	V	V	A	A	A	A	A	V	A	A	A
IKS5	A	A	V	A	A	V	A	A	A	A	X	A	A	A	A	V	V	A	A	A	A	A	A	V	A	A
IKS6	X	V	V	V	V	V	A	V	V	V	V	X	V	X	V	V	V	V	V	V	V	V	X	V	V	V
UOOP1	A	X	V	V	V	V	A	X	V	V	V	A	X	A	X	V	V	X	V	V	V	V	A	V	V	V
UOOP2	X	V	V	V	V	V	A	V	V	V	V	X	V	X	V	V	V	V	V	V	V	V	X	V	V	V
UOOP3	A	X	V	V	V	V	A	X	V	V	V	A	X	A	X	V	V	X	V	V	V	V	A	V	V	V
UOOP4	A	A	X	A	A	V	A	A	A	A	A	A	A	A	A	X	X	A	A	A	A	A	A	X	A	A
UOOP5	A	A	X	A	A	V	A	A	A	A	A	A	A	A	A	X	X	A	A	A	A	A	A	X	A	A
UOOP6	A	X	V	V	V	V	A	X	V	V	V	A	X	A	X	V	V	X	V	V	V	V	A	V	V	V
UOOP7	A	A	V	V	V	V	A	A	A	V	V	A	A	A	A	V	V	A	X	A	A	A	V	A	X	X
FC1	A	A	V	V	V	V	A	A	X	V	V	A	A	A	A	V	V	A	V	X	A	A	V	X	V	V
FC2	A	A	V	V	V	V	A	A	V	V	V	A	A	A	A	V	V	A	V	V	X	A	V	V	V	V
FC3	X	V	V	V	V	V	A	V	V	V	V	X	V	X	V	V	V	V	V	V	V	V	X	V	V	V
FC4	A	A	X	A	A	V	A	A	A	A	A	A	A	A	A	X	X	A	A	A	A	A	A	X	A	A
FC5	A	A	V	V	V	V	A	A	X	V	V	A	A	A	A	V	V	A	V	X	A	A	V	X	V	V
FC6	A	A	V	V	V	V	A	A	A	V	V	A	A	A	A	V	V	A	X	A	A	A	V	A	X	X

TABLE 30 Initial reachability matrix for sub-barriers of all the main barriers of GSCM.

Item	ITI1	ITI2	ITI3	ITI4	ITI5	ITI6	IKS1	IKS2	IKS3	IKS4	IKS5	IKS6	UOOP1	UOOP2	UOOP3	UOOP4	UOOP5	UOOP6	UOOP7	FC1	FC2	FC3	FC4	FC5	FC6	
ITI1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ITI2	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1
ITI3	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
ITI4	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
ITI5	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
ITI6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IKS1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
IKS2	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	1	1	1
IKS3	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	1	0	1	1	1	1
IKS4	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
IKS5	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
IKS6	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
UOOP1	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	1	1	1
UOOP2	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
UOOP3	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	1	1	1
UOOP4	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
UOOP5	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
UOOP6	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	1	1	1
UOOP7	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	1	1	0	0	1	0	1	1
FC1	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	1	0	1	1	1	1
FC2	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	1	0	1	1	1	1
FC3	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FC4	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0
FC5	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	1	0	1	1	1	1
FC6	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	1	1	0	0	1	0	1	1

TABLE 31 Final reachability matrix for sub-barriers of all the main barriers of GSCM.

Item	ITI1	ITI2	ITI3	ITI4	ITI5	ITI6	IKS1	IKS2	IKS3	IKS4	IKS5	IKS6	UOOP1	UOOP2	UOOP3	UOOP4	UOOP5	UOOP6	UOOP7	FC1	FC2	FC3	FC4	FC5	FC6	Driving power	
ITI1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24
ITI2	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	20
ITI3	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	5
ITI4	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	9
ITI5	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	9
ITI6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
IKS1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	25
IKS2	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	20
IKS3	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	0	0	1	1	1	1	14
IKS4	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	9
IKS5	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	6
IKS6	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24
UOOP1	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	20
UOOP2	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24
UOOP3	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	20
UOOP4	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	5
UOOP5	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	5
UOOP6	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	20
UOOP7	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	1	0	0	0	1	0	1	1	11
FC1	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	0	0	1	1	1	1	14
FC2	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	1	0	1	1	1	1	15
FC3	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24
FC4	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	5
FC5	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	0	1	1	0	0	1	1	1	1	14
FC6	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	0	1	0	0	0	1	0	1	1	11
Dependence power	5	10	24	19	19	25	1	10	14	19	20	5	10	5	10	24	24	10	15	14	13	5	24	14	15		

TABLE 32 Level partition for sub-barriers of financial constraints barriers of GSCM.

Item	Reachability set	Antecedent set	Intersection set	Level
ITI1	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI1, IKS1, IKS6, UOOP2, FC3	ITI1, IKS6, UOOP2, FC3	9th
ITI2	ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, UOOP1, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC3	ITI2, IKS2, UOOP1, UOOP3, UOOP6	8th
ITI3	ITI3, ITI6, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI3, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI3, UOOP4, UOOP5, FC4	2nd
ITI4	ITI3, ITI4, ITI5, ITI6, IKS4, IKS5, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, UOOP7, FC1, FC2, FC3, FC5, FC6	ITI4, ITI5, IKS4	4th
ITI5	ITI3, ITI4, ITI5, ITI6, IKS4, IKS5, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, UOOP7, FC1, FC2, FC3, FC5, FC6	ITI4, ITI5, IKS4	4th
ITI6	ITI6	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI6	1st
IKS1	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	IKS1	IKS1	10th
IKS2	ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, UOOP1, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC3	ITI2, IKS2, UOOP1, UOOP3, UOOP6	8th
IKS3	ITI3, ITI4, ITI5, ITI6, IKS3, IKS4, IKS5, UOOP4, UOOP5, UOOP7, FC1, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS3, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC1, FC2, FC3, FC5	IKS3, FC1, FC5	6th
IKS4	ITI3, ITI4, ITI5, ITI6, IKS4, IKS5, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, UOOP7, FC1, FC2, FC3, FC5, FC6	ITI4, ITI5, IKS4	4th
IKS5	ITI3, ITI6, IKS5, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, UOOP7, FC1, FC2, FC3, FC5, FC6	IKS5	3rd

(Continued)

TABLE 32 (Continued)

Item	Reachability set	Antecedent set	Intersection set	Level
IKS6	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI1, IKS1, IKS6, UOOP2, FC3	ITI1, IKS6, UOOP2, FC3	9th
UOOP1	ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, UOOP1, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC3	ITI2, IKS2, UOOP1, UOOP3, UOOP6	8th
UOOP2	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI1, IKS1, IKS6, UOOP2, FC3	ITI1, IKS6, UOOP2, FC3	9th
UOOP3	ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, UOOP1, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC3	ITI2, IKS2, UOOP1, UOOP3, UOOP6	8th
UOOP4	ITI3, ITI6, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI3, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI3, UOOP4, UOOP5, FC4	2nd
UOOP5	ITI3, ITI6, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI3, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI3, UOOP4, UOOP5, FC4	2nd
UOOP6	ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, UOOP1, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC3	ITI2, IKS2, UOOP1, UOOP3, UOOP6	8th
UOOP7	ITI3, ITI4, ITI5, ITI6, IKS4, IKS5, UOOP4, UOOP5, UOOP7, FC4, FC6	ITI1, ITI2, IKS1, IKS2, IKS3, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, UOOP7, FC1, FC2, FC3, FC5, FC6	UOOP7, FC6	5th
FC1	ITI3, ITI4, ITI5, ITI6, IKS3, IKS4, IKS5, UOOP4, UOOP5, UOOP7, FC1, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS3, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC1, FC2, FC3, FC5	IKS3, FC1, FC5	6th
FC2	ITI3, ITI4, ITI5, ITI6, IKS3, IKS4, IKS5, UOOP4, UOOP5, UOOP7, FC1, FC2, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC2, FC3	FC2	7th
FC3	ITI1, ITI2, ITI3, ITI4, ITI5, ITI6, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI1, IKS1, IKS6, UOOP2, FC3	ITI1, IKS6, UOOP2, FC3	9th
FC4	ITI3, ITI6, UOOP4, UOOP5, FC4	ITI1, ITI2, ITI3, ITI4, ITI5, IKS1, IKS2, IKS3, IKS4, IKS5, IKS6, UOOP1, UOOP2, UOOP3, UOOP4, UOOP5, UOOP6, UOOP7, FC1, FC2, FC3, FC4, FC5, FC6	ITI3, UOOP4, UOOP5, FC4	2nd

(Continued)

TABLE 32 (Continued)

Item	Reachability set	Antecedent set	Intersection set	Level
FC5	ITI3, ITI4, ITI5, ITI6, IKS3, IKS4, IKS5, UOOP4, UOOP5, UOOP7, FC1, FC4, FC5, FC6	ITI1, ITI2, IKS1, IKS2, IKS3, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, FC1, FC2, FC3, FC5	IKS3, FC1, FC5	6th
FC6	ITI3, ITI4, ITI5, ITI6, IKS4, IKS5, UOOP4, UOOP5, UOOP7, FC4, FC6	ITI1, ITI2, IKS1, IKS2, IKS3, IKS6, UOOP1, UOOP2, UOOP3, UOOP6, UOOP7, FC1, FC2, FC3, FC5, FC6	UOOP7, FC6	5th

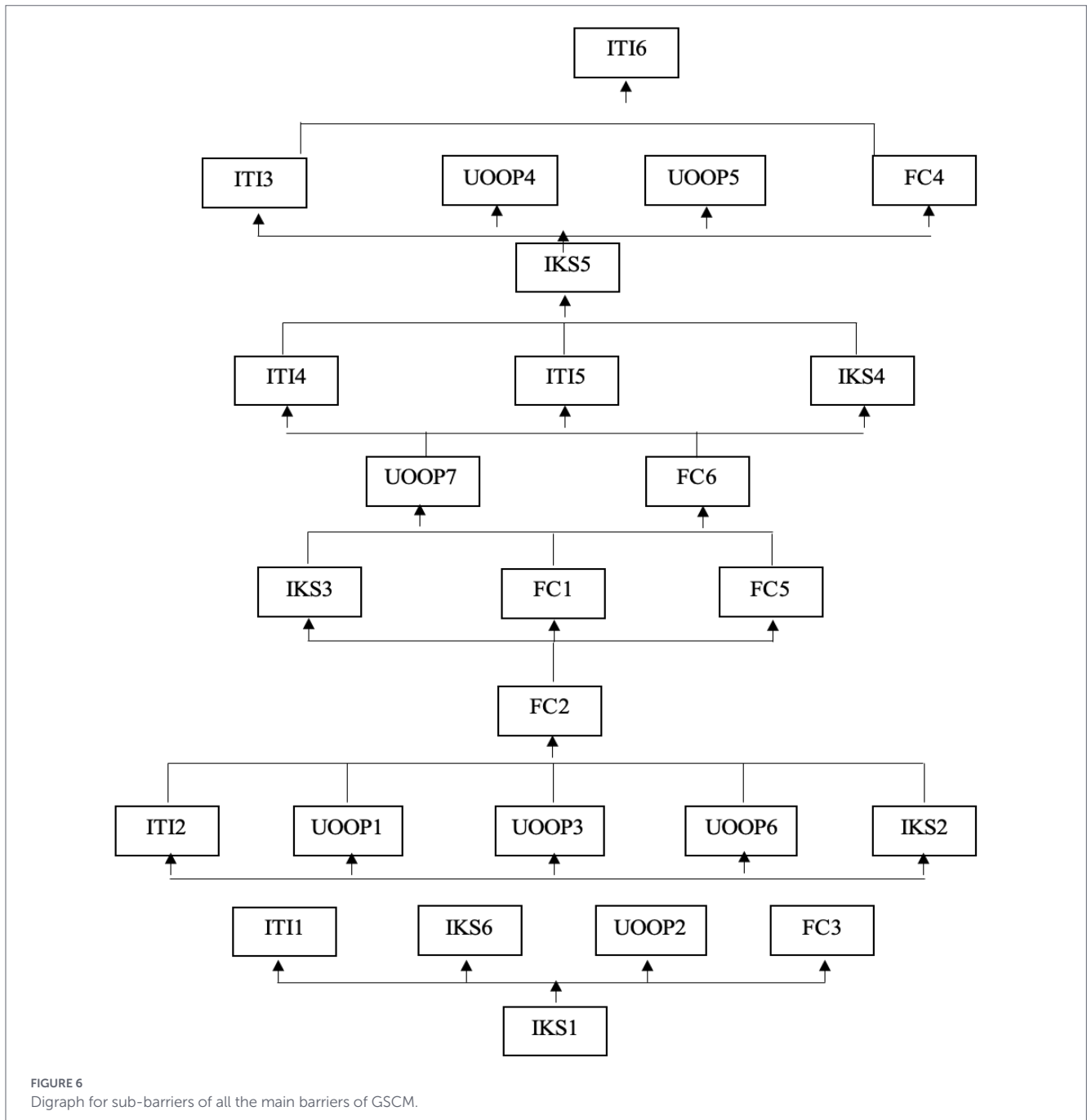


FIGURE 6 Digraph for sub-barriers of all the main barriers of GSCM.

TABLE 33 Ranks of sub-barriers of all the main barriers of GSCM.

Sub-barriers	Rank
ITI1	2
ITI2	3
ITI3	9
ITI4	7
ITI5	7
ITI6	10
IKS1	1
IKS2	3
IKS3	5
IKS4	7
IKS5	8
IKS6	2
UOOP1	3
UOOP2	2
UOOP3	3
UOOP4	9
UOOP5	9
UOOP6	3
UOOP7	6
FC1	5
FC2	4
FC3	2
FC4	9
FC5	5
FC6	6

capability barriers act as root drivers, while technological and financial constraints often reflect deeper systemic conditions. This shifts the focus from identifying barriers to understanding their causal structure and prioritizing intervention points (Seuring and Müller, 2008; Agrawal and Narain, 2023). It also highlights the importance of targeting upstream capability constraints to enable system-wide sustainability transitions.

6 Implications

This study shows that GSCM barriers should be analyzed as structured causal systems rather than independent constraints. It moves beyond linear barrier identification by explaining how barriers interact through hierarchical relationships. The findings highlight the role of human capability as a root driver, providing a clearer theoretical basis for understanding sustainability transition failure in fossil-fuel-dependent logistics systems.

Managers should prioritize leadership commitment, workforce capability development, and organizational learning before investing in technological solutions. The results indicate that technological and

financial interventions are unlikely to deliver impact without strong human and organizational readiness. A sequential approach that starts with capability development can improve the effectiveness of downstream investments.

Policymakers should complement regulatory frameworks with capability-building initiatives, including training programs, knowledge diffusion, and institutional support. The findings suggest that many policy-related barriers are downstream outcomes of deeper structural constraints. Therefore, policy effectiveness depends on strengthening organizational readiness alongside regulatory enforcement.

7 Conclusion

This study explains the causal hierarchy of GSCM barriers in fossil-fuel-dependent logistics systems. The findings show that human capability and managerial support act as upstream drivers that shape technological, financial, and policy outcomes. This reveals that sustainability challenges are not driven by isolated constraints but by structured interdependencies among barriers. The results demonstrate that effective GSCM adoption requires a systems-based and human-centered approach, where investments in knowledge, skills, and leadership precede technological and policy interventions. This sequencing improves the effectiveness and scalability of sustainability transitions. The main contribution of this study is not the identification of GSCM barriers, which is already well established in the literature, but the explanation of their causal structure. By identifying upstream drivers and downstream outcomes, the study provides a clearer basis for prioritizing intervention points and guiding sustainability strategies.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

IE-N: Conceptualization, Methodology, Writing – original draft, Supervision. SE: Data curation, Formal analysis, Writing – review & editing. NG: Investigation, Validation, Writing – review & editing.

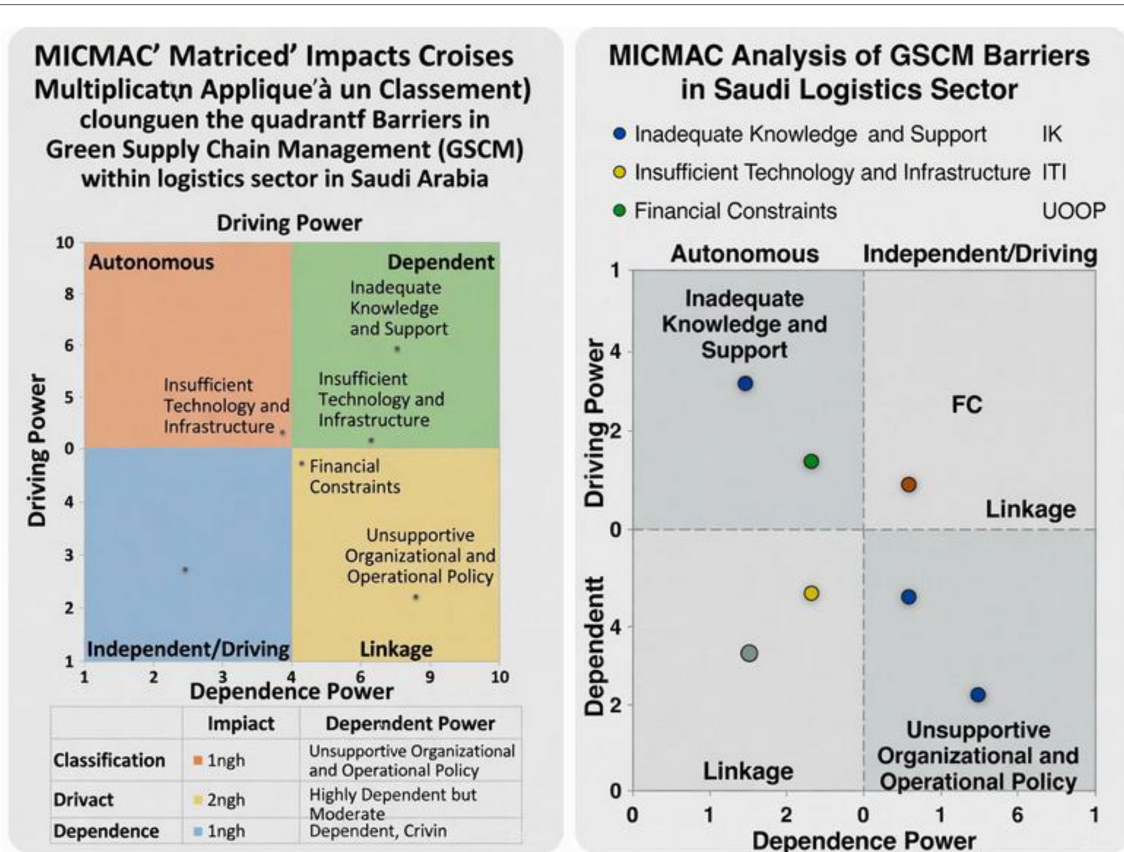


FIGURE 7 MICMAC quadrant classification of main GSCM barriers.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsus.2026.1806432/full#supplementary-material>

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