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Integrating decarbonization strategies and closed-loop supply chain design for sustainable logistics: An integrative systematic review and six-pillar analytical framework

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Abstract: *Purpose*. This paper aims to address the fragmentation between decarbonization strategies and closed-loop supply chain (CLSC) design in sustainable logistics by developing an integrated analytical framework that captures their interdependencies across operational and contextual dimensions. *Methodology*. A hybrid systematic–integrative review was conducted, combining PRISMA-based literature selection with thematic synthesis. A total of 59 peer-reviewed studies (2012–2026) were analyzed and coded across six dimensions: technological enablers, CLSC design architecture, policy mechanisms, organizational preconditions, geoecological accountability, and regional macroeconomic context. Quantitative findings were standardized using relative change metrics and synthesized through a quality-weighted approach. *Results*. The analysis indicates that integrated decarbonization – CLSC approaches are associated with cost reductions of up to 31% and emission reductions of 12%-40% in modeled scenarios. The results further demonstrate that technological solutions alone are insufficient; their effectiveness depends on organizational capabilities, policy alignment, and regional economic conditions. Significant variability across contexts suggests that integration outcomes are highly contingent on local constraints. *Theoretical contribution*. The study advances the literature by proposing a six-pillar framework that reconceptualizes sustainable logistics as a multi-level governance problem rather than a purely operational optimization task. It contributes a structured approach for integrating fragmented research streams and incorporating macroeconomic and geoecological dimensions into supply chain analysis. *Practical implications*. The findings highlight the need for coordinated implementation strategies combining technological investment, organizational readiness, and

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context-sensitive policy design. The framework provides actionable guidance for practitioners, policymakers, and financial institutions seeking to operationalize sustainable logistics transitions.

Keywords: circular supply networks, low-carbon logistics systems, reverse flow optimization, green capital mechanisms, regional economic constraints, environmental monitoring systems.

Sustainable Development Goals (SDGs): SDG 7: Affordable and Clean Energy; **SDG 8:** Decent Work and Economic Growth; **SDG 9:** Industry, Innovation and Infrastructure; **SDG 11:** Sustainable Cities and Communities; **SDG 12:** Responsible Consumption and Production; **SDG 13:** Climate Action

1. Introduction

Global freight transport and warehousing together account for approximately 7–10% of total energy-related CO_2 emissions, a share projected to grow unless sector-specific decarbonization accelerates (McKinnon & Piecyk, 2012; Rathnasiri, 2025). The Paris Agreement's 1.5°C pathway has rendered logistics-emissions-reduction targets not merely aspirational but legally and commercially consequential.

Two research traditions, decarbonization strategy research and closed-loop supply chain (CLSC) modeling, have each generated substantial technical contributions while largely pursuing separate trajectories. Their integration has attracted growing scholarly attention (Govindan & Soleimani, 2017; Agrawal, Singh, & Murtaza, 2015; Lozano-Oviedo, Cortes, & Rey, 2024; Genovese, Acquaye, Figueroa, & Koh, 2017), yet a comprehensive framework connecting both paradigms across their operational, organizational, financial, territorial, and geopolitical dimensions remains absent. This paper argues that integration is not merely efficient but necessary.

The financial architecture required for this investment is examined through the lens of green capital mobilization (Abdulhasanova, 2025). IoT-enabled scheduling architectures (Srinivas et al., 2025) represent the frontier of real-time logistics optimization.

Research questions:

This paper addresses three research questions: (RQ1) What are the principal mechanisms through which decarbonization strategies and CLSC design can be jointly optimized? (RQ2) What organizational, financial, and territorial preconditions determine the viability of this integration? (RQ3) What quantified sustainability performance improvements does integration deliver relative to siloed approaches?

Methodologically, this study adopts a hybrid systematic–integrative review design. While the search and selection process folows systematic review protocols, the synthesis extends beyond aggregation toward conceptual framework development.

2. Literature review

The concept of jointly optimizing circular supply chains and emission reduction has been discussed since at least 2014 (Syphoxay & Hien, 2014; Tahoori, Rosnah, & Norzima, 2014). The canonical review by Govindan and Soleimani (2017) established the field's analytical boundaries around operational and methodological dimensions. Agrawal, Singh, and Murtaza (2015) provided a foundational literature review of reverse logistics. More recently, Lozano-Oviedo, Cortes, and Rey (2024) synthesized optimization models for sustainable CLSCs, confirming methodological diversity and persistent gaps in social sustainability. Genovese, Acquaye, Figueroa, and Koh (2017) framed circular economy transition as a supply chain management challenge. Neto, Bloemhof-Ruwaard, van Nunen, and van Heck (2008) provided early groundwork for integrating environmental metrics into logistics network design.

Multi-objective CLSC formulations now routinely incorporate carbon emissions, energy consumption, and social indicators alongside economic objectives (Farrokh, Zenouz, Jamalnia, & Asadi, 2025; Borjian, Alinezhad, & Khalili, 2019; Mohtashami, Aghsami, & Jolai, 2020). Government reward-penalty mechanisms demonstrate robust effectiveness in emerging economies (Long, Liu, Li, & Chen, 2020; Li, Zhang, & Liu, 2021). Game-theoretic coordination (Taleizadeh, Tahmasbifar, Moradi, & Hafezalkotob, 2025; Li, Wang, Xu, & Ou, 2017), stochastic and robust approaches (Tahmouresi & Behnamian, 2026; Sardar, Javanshir, Molana, & Yazdian, 2025), and IoT-integrated models (Sorooshian, Khiavi, Karimi, & Mina, 2024) have expanded the analytical toolkit.

On the decarbonization side, AI-driven scheduling, predictive maintenance, and autonomous robotics document energy and emission reductions (Ben Amor, Triki, & Benaissa, 2025; Mrad, Frikha, Boujelbene, & Rahmouni, 2026; Pajila, 2024; Bhatia, Arora, & Bhatia, 2026). Fleet electrification achieves approximately 30% lifecycle emission reductions (Lu, Shan, Kittner, & Zhang, 2023). 5G and edge computing enable real-time routing with up to 85% latency reduction (Wang & Wang, 2025; Chochliouros, Spiliopoulou, & Lazaridis, 2025). Building thermal retrofit (Hajiyev et al., 2025) and IoT-fog-cloud scheduling (Srinivas et al., 2025) address infrastructure-level efficiency.

Despite this progress, comprehensive frameworks connecting decarbonization and CLSC across organizational, financial, territorial, and geopolitical dimensions remain absent – a gap this paper addresses through its six-pillar integrative framework.

2.1. Research gaps and theoretical tensions

Despite substantial progress, three structural gaps persist. First, the majority of CLSC models remain operationally bounded, neglecting macroeconomic and territorial constraints. Second, decarbonization studies emphasize technological optimization while underrepresenting the integration of reverse logistics. Third, existing integrative attempts lack a unifying governance-oriented analytical structure, particularly with respect to geoecological accountability.

3. Research methodology

3.1 Research design

This study adopts a hybrid systematic–integrative review design, combining the procedural rigor of systematic literature review protocols with the conceptual depth of integrative synthesis. The systematic component ensures transparency and reproducibility in literature identification and selection, while the integrative component enables cross-domain synthesis and the development of theoretical frameworks.

This approach is particularly appropriate for emerging interdisciplinary fields, where heterogeneous methodologies and fragmented knowledge structures limit the applicability of formal meta-analytic techniques.

3.2 Search strategy and data sources

A structured literature search was conducted across three major academic databases: Scopus, Web of Science Core Collection, and Google Scholar. These databases were selected to ensure broad coverage of peer-reviewed journal articles, conference proceedings, and emerging research relevant to logistics, supply chain management, and sustainability.

The search was restricted to English-language publications published between January 2012 and March 2026, reflecting the period during which decarbonization and circular supply chain research significantly expanded.

Three Boolean search strings were developed to capture the intersection of decarbonization strategies and closed-loop supply chain (CLSC) design:

1. ("closed-loop supply chain" OR "reverse logistics") AND ("decarbonization" OR "carbon emission" OR "green logistics")
2. ("sustainable logistics" OR "green supply chain") AND ("optimization" OR "framework")
3. ("building energy" OR "IoT scheduling" OR "geoecological monitoring") AND ("logistics" OR "supply chain")

The search strategy was iteratively refined to ensure both precision and recall, with keyword combinations adjusted based on preliminary screening results.

3.3 Study selection process

The study selection process followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological transparency.

The initial search yielded 412 records (Scopus: 168; Web of Science: 142; Google Scholar: 102). After removing 87 duplicates, 325 unique records remained for screening.

A two-stage screening process was applied:
- Stage 1: Title and abstract screening, resulting in 142 articles retained for full-text review
- Stage 2: Full-text assessment, based on predefined inclusion and exclusion criteria

Inclusion criteria:
- Peer-reviewed publications addressing CLSC design and/or decarbonization strategies in logistics
- Studies providing quantitative outcomes, modeling results, or conceptual frameworks
- Explicit relevance to sustainability or emission reduction

Exclusion criteria:
- Non-English publications
- Studies lacking methodological clarity
- Articles not directly related to logistics or supply chain systems
- Duplicate or incomplete publications

Following this process, 59 studies were retained for final synthesis.

The review protocol was not preregistered; however, all procedures were predefined and consistently applied.

3.4 Quality assessment

To ensure the robustness of the synthesis, each included study was evaluated using a structured four-domain quality assessment framework:
1. Methodological clarity and study design
2. Data transparency and reproducibility
3. Peer-review status
4. Relevance to CLSC–decarbonization integration

Each domain was scored on a 0–2 scale (0 = low quality; 2 = high quality), resulting in a composite Quality Score ranging from 0 to 8.

Two reviewers independently assessed all studies. Discrepancies were resolved through consensus.

The Quality Score was subsequently used as a weighting factor in aggregating quantitative findings. This approach is consistent with evidence synthesis practices where methodological heterogeneity precludes formal meta-analysis but structured weighting enhances analytical robustness.

3.5 Analytical framework development

The analytical synthesis was conducted using a thematic coding approach that combined inductive and deductive reasoning.

The 65 selected studies were coded across six dimensions:
- Technological enablers
- CLSC design architecture

– Policy mechanisms
– Organizational preconditions
– Geoecological accountability
– Regional macroeconomic context

The first three dimensions reflect established operational and governance structures in supply chain literature, while the latter three capture contextual feasibility conditions that are underrepresented in existing models.

The six-pillar structure emerged through iterative comparison, clustering, and validation, ensuring internal coherence and conceptual distinctiveness. No additional dimension demonstrated sufficient analytical independence to warrant inclusion.

3.6 Quantitative standardization and synthesis

Given the methodological heterogeneity of the reviewed studies, a formal meta-analysis was not feasible. Instead, a comparative standardization approach was applied.

Two common metrics were used:
– Relative percentage change from baseline
– Absolute emissions intensity (tCO_2e per functional unit), where available

For studies reporting baseline (E_0) and post-intervention (E_1) emissions, percentage reduction was calculated as:

$$R = \frac{E_0 - E_1}{E_0} \cdot 100$$

Where necessary, energy-based metrics (e.g., kWh) were converted to emissions using reported or regionally appropriate emission factors.

To synthesize results across studies, a weighted median approach was employed, with the Quality Score serving as the weight. This method reduces sensitivity to outliers and is appropriate for heterogeneous datasets.

Where methodological diversity prevented aggregation, results are reported as ranges and interquartile intervals, rather than single-point estimates.

All assumptions, conversion factors, and baseline conditions are documented in Appendix C.

3.7 Reliability and limitations of the method

To enhance reliability, all coding and data extraction procedures were applied consistently across studies. However, several methodological limitations should be acknowledged.

First, the integrative nature of the review introduces an element of interpretive subjectivity. Second, the absence of standardized reporting across primary studies limits comparability. Third, the use of weighted synthesis does not fully eliminate publication bias, particularly toward studies reporting positive outcomes.

Despite these limitations, the adopted methodology provides a transparent, structured, and analytically robust basis for integrating fragmented research domains and developing a unified conceptual framework.

4. Research results

4.1 Decarbonization mechanisms

Table 1 summarizes the principal decarbonization mechanisms identified in the reviewed literature.

Table 1: Decarbonization Strategies in Logistics: Key Mechanisms, Outcomes, and References

Strategy Category	Key Mechanism	Documented Outcome	Key Sources
Fleet Electrification	Battery-electric vehicles charged from renewables	~30% lifecycle emission reduction	Lu et al. (2023); Akbar & Gheewala (2026)
Building Thermal Retrofit	Interior insulation reduces thermal transmittance	Significant energy savings; green code compliance	Hajiyev et al. (2025)
AI/IoT Scheduling	Fuzzy logic–genetic algorithm hybrid task allocation	Substantial computational energy reduction	Srinivas et al. (2025)
5G / Edge Computing	Real-time dynamic routing with ultra-low latency	Up to 85% latency reduction	Wang & Wang (2025); Chochliouros et al. (2025)
Green Finance	Blended finance for renewable logistics infrastructure	10:1 leverage ratio; $2.3B/year by 2030	Abdulhasanova (2025)

Source: authors' elaboration based on reviewed literature.

Across categories, technological and financial mechanisms exhibit complementary effects, suggesting that isolated interventions may underperform relative to integrated deployment.

4.2 CLSC model typologies

Table 2 presents the principal CLSC optimization model typologies.

Table 2: Typology of closed-loop supply chain optimization models

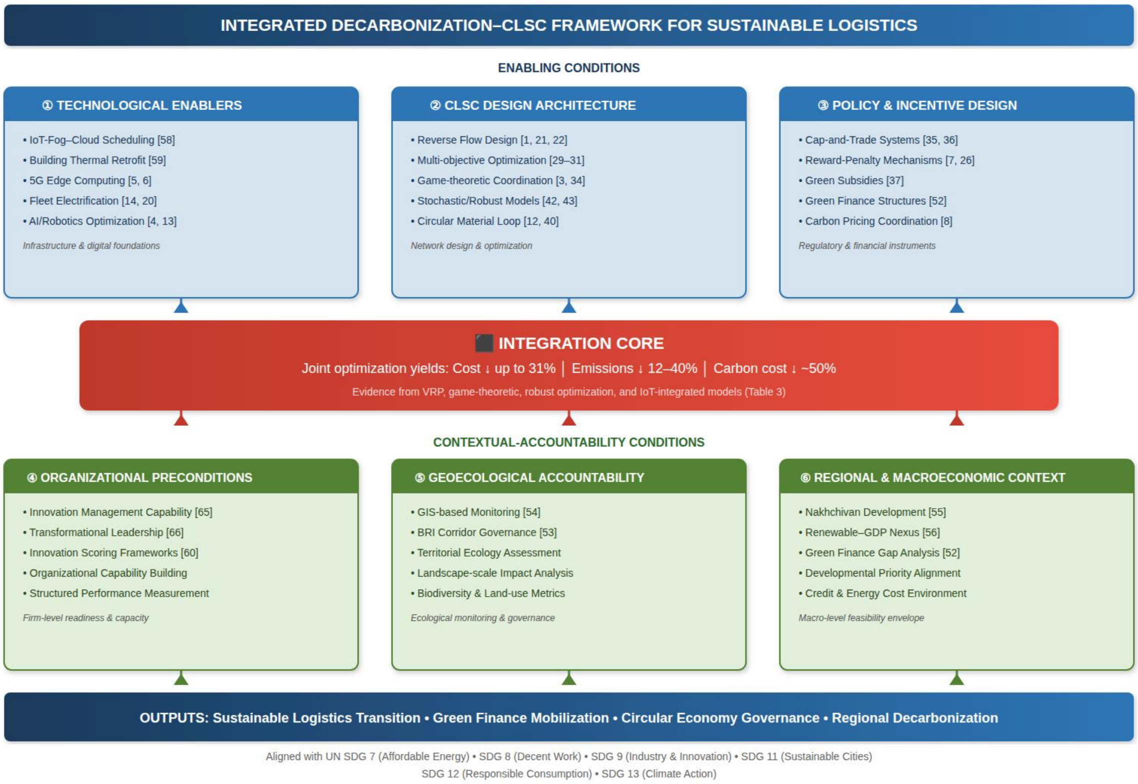
Model Type	Optimization Approach	Key Objectives	Typical Outcome	Key Sources
Multi-objective	Pareto optimization	Profit + emission + social welfare	Cost ↓, emission ↓	Farrokh et al. (2025); Mohtashami et al. (2020)
Stochastic / Robust	Scenario-based robust programming	Demand/return uncertainty	Variance ↓ 20–40%	Tahmouresi & Behnamian (2026)
Game-theoretic	Nash / Stackelberg	Coordinate competing actors	Profit ↑ vs. decentralized	Taleizadeh et al. (2025); Li et al. (2017)
Reward-Penalty	Regulatory incentive design	Maximize collection rate	Return volume ↑	Long et al. (2020); Li et al. (2021)
IoT-integrated	Real-time data feedback	Minimize energy + maximize recovery	Energy ↓	Sorooshian et al. (2024); Srinivas et al. (2025)

Source: authors' elaboration based on reviewed literature.

4.3 Integrated framework

Figure 1 presents the six-pillar conceptual framework that synthesizes the enabling conditions (technological enablers, CLSC design architecture, policy mechanisms) and the contextual-accountability conditions (organizational preconditions, geoecological accountability, regional macroeconomic context) around an integration core.

Figure 1: Conceptual framework: Six-pillar integration of decarbonization strategies and CLSC models for sustainable logistics



Source: authors' synthesis based on an integrative review of 59 sources.

The framework positions integration as a coordination problem across six interdependent domains, where technological and policy mechanisms act as enablers, while organizational and macroeconomic factors define feasibility constraints.

4.4. Quantified integration outcomes

Table 3 synthesizes quantified outcomes from the literature.

Table 3: Quantified outcomes of integrated decarbonization–CLSC optimization

Study Focus	Cost Reduction	Emission Reduction	Methodology	Source
Green cold chain VRP	Up to 31%	15–25%	Multi-objective VRP + metaheuristic	Zheng et al. (2025)
Dual-channel distribution with GHG	12–20%	12–18%	Mixed-integer programming	Sabaghieh Yazd et al. (2025)
Sustainable trucking	8–15%	20–30%	Relay transport network design	Wen et al. (2026)
IoT-circular SC (EV battery)	15–22%	25–35%	Circular IoT integration	Sorooshian et al. (2024)
Power battery CLSC	18–28%	15–22%	Stackelberg game	Song et al. (2026)
Petrochemical SC	10–15%	10–15%	Integrated robust programming	Sardar et al. (2025)

Source: authors' elaboration based on reviewed literature

Methodological caveat. These results derive from methodologically diverse studies (vehicle routing, game theory, robust programming). The reported ranges should be interpreted as indicative of the magnitude of achievable gains in modeled scenarios rather than as precise meta-analytic estimates.

4.5 Regional and organizational dimensions

The Nakhchivan Autonomous Republic of Azerbaijan illustrates these constraints with particular clarity. Operating under conditions of geographic isolation, energy transition ambition, and macroeconomic pressures (Ahmadova, Gasimov, & Huseynov, 2018), Nakhchivan demonstrates how regional development priorities shape the feasibility envelope for logistics decarbonization. A more recent study applying Toda-Yamamoto causality analysis across Iceland and Azerbaijan confirms a statistically significant positive relationship between renewable energy consumption and GDP per capita growth (Aliyev et al., 2024).

The macroeconomic context of Nakhchivan (Ahmadova et al., 2018) demonstrates how geographic isolation and energy constraints shape the feasibility of green logistics. The renewable energy–growth nexus (Aliyev et al., 2024) establishes that clean energy investment drives broader economic productivity. Green finance analysis (Abdulhasanova, 2025) identifies structural barriers: fuel subsidies, underdeveloped green finance mechanisms, and insufficient risk mitigation.

5. Discussion

5.1 Reframing sustainable logistics: From operational optimization to multi-level governance

The findings of this study suggest that integrating decarbonization strategies and closed-loop supply chain (CLSC) design cannot be adequately understood within the traditional boundaries of operational optimization. Rather, the evidence indicates that sustainable logistics should be conceptualized as a multi-level governance problem, in which technological, organizational, financial, and territorial dimensions interact in structurally interdependent ways.

Existing CLSC literature has predominantly focused on network design, cost minimization, and recovery efficiency, while decarbonization research has emphasized technological substitution and energy optimization. The synthesis presented in this study demonstrates that these two trajectories converge only partially at the operational level. Their full integration requires alignment across institutional frameworks, financial systems, and regional development conditions.

This shift in perspective has important implications for theory. It suggests that the appropriate unit of analysis is not the individual firm or supply chain, but rather the logistics system embedded within a regional socio-economic context. In this sense, decarbonization–CLSC integration reflects a transition from firm-level optimization to system-level coordination under constraint.

5.2 Comparative positioning within existing literature

The proposed six-pillar framework extends prior research in several important respects.

First, foundational reviews such as Kannan Govindan and Hamed Soleimani (2017) established the analytical structure of reverse logistics and CLSC models but remained largely confined to operational and methodological dimensions. The present study expands this scope by incorporating contextual feasibility conditions, including macroeconomic and geoecological factors.

Second, the circular economy perspective advanced by Andrea Genovese et al. (2017) conceptualizes supply chains as mechanisms for sustainability transition, yet does not explicitly integrate regional heterogeneity or financial constraints. The current framework addresses this limitation by embedding logistics systems within territorial and capital allocation structures.

Third, more recent syntheses (e.g., Lozano-Oviedo et al., 2024) highlight the growing methodological sophistication of CLSC optimization models but also confirm persistent gaps in social sustainability and cross-domain integration. The present study contributes by structuring these fragmented insights into a unified analytical architecture.

Importantly, the contribution of this paper is not the identification of new mechanisms per se, but the systematic organization of their interactions across six analytically distinct yet interdependent domains.

5.3 Interdependencies and trade-offs across the six pillars

A key insight emerging from the synthesis is that the six pillars do not operate independently; rather, they exhibit strong complementarities and trade-offs.

Technological enablers such as electrification, IoT-based scheduling, and digital routing systems have substantial potential to reduce emissions. However, their effectiveness depends on organizational readiness, including managerial capabilities and data infrastructure. In the absence of such preconditions, technological investments may yield suboptimal outcomes.

Similarly, policy mechanisms, particularly incentive schemes and regulatory mandates, can significantly influence CLSC performance. However, their effectiveness depends on the macroeconomic environment, including access to capital and energy pricing structures. In regions characterized by fossil fuel subsidies or limited financial markets, policy interventions may fail to produce the intended behavioral shifts.

The role of geoecological accountability introduces an additional layer of complexity. Monitoring systems enhance transparency and environmental compliance but also impose administrative and technological costs, which may disproportionately affect smaller firms or emerging economies.

These interactions suggest that integration is not a purely additive process. Instead, it requires careful coordination across domains, with attention to sequencing, complementarities, and context-specific constraints.

5.4 Contradictions, implementation gaps, and boundary conditions

While the literature reports substantial efficiency gains from integrated approaches, this study's findings indicate that these outcomes are highly contingent on contextual factors.

First, the majority of reported performance improvements stem from model-based simulations that assume idealized conditions, such as perfect information, stable demand, and fully rational decision-making. In practice, supply chains operate under conditions of uncertainty, bounded rationality, and institutional friction. As a result, the realized benefits of integration may be significantly lower.

Second, integration introduces coordination complexity, particularly in multi-actor systems involving manufacturers, logistics providers, recyclers, and regulators. In contexts with weak institutional capacity, this complexity may offset efficiency gains, leading to implementation failure or partial adoption.

Third, there exists a persistent implementation gap between technological potential and real-world adoption. Financial constraints, regulatory misalignment, and organizational inertia continue to limit the diffusion of both decarbonization technologies and circular supply chain practices.

Finally, the analysis reveals that regional heterogeneity constitutes a critical boundary condition. The feasibility of integrated solutions varies significantly across regions depending on infrastructure, energy systems, and economic structure. This finding challenges the implicit assumption, common in the literature, that optimization results are universally transferable.

5.5 Implications for theory

From a theoretical perspective, the study advances the literature in three key ways.

First, it reconceptualizes sustainable logistics as a multi-dimensional governance system, rather than a set of isolated optimization problems. This shift aligns with broader developments in sustainability science, which emphasize system-level interactions and institutional embeddedness.

Second, the six-pillar framework provides a structured basis for integrating heterogeneous research streams, bridging the gap between engineering-oriented optimization models and socio-economic analyses of sustainability transitions.

Third, the findings highlight the need to incorporate contextual variables, particularly macroeconomic and geoecological factors, into future CLSC and decarbonization models. This represents a significant departure from existing approaches, which tend to abstract away from regional specificity.

5.6 Implications for practice and policy

The results of this study suggest that effective implementation of decarbonization–CLSC integration requires coordinated action across multiple domains.

For practitioners, the findings underscore the importance of simultaneous investment in technology and organizational capabilities. Digital infrastructure, data integration, and workforce competencies are critical enablers of effective implementation.

For policymakers, the analysis highlights the need for context-sensitive regulatory frameworks. Uniform policy instruments are unlikely to be effective across diverse regional settings. Instead, incentives, subsidies, and regulatory mandates should be calibrated to local economic and infrastructural conditions.

Financial institutions play a pivotal role in enabling the transition. The development of blended finance mechanisms, green bonds, and risk-sharing instruments is essential to overcome capital constraints and support long-term infrastructure investments.

Finally, integrating geoecological monitoring systems can enhance accountability and transparency, but they must be designed to balance environmental objectives with economic feasibility.

5.7 Directions for future research

The findings of this study open several avenues for further investigation.

First, there is a need to empirically validate the proposed framework through case studies and longitudinal analyses across different regional contexts.

Second, future research should focus on integrating social sustainability dimensions into CLSC–decarbonization models, addressing issues such as labor conditions, equity, and community impact.

Third, the development of data-driven, real-time optimization models that incorporate geoecological monitoring represents a promising direction for advancing both theory and practice.

Finally, comparative studies across regions and sectors could provide deeper insights into the boundary conditions and transferability of integrated sustainability strategies.

6. Conclusions

This paper presents an integrative synthesis of decarbonization strategies and closed-loop supply chain models as co-constitutive elements of the sustainable logistics transition. The six-pillar framework, encompassing technological enablers, CLSC design architecture, policy mechanisms, organizational preconditions, geoecological accountability, and regional macroeconomic context, reframes sustainable logistics as a multi-dimensional governance challenge.

From a scientific perspective, integrated optimization is associated with potentially significant efficiency gains under modeled conditions: cost reductions of up to 31% and emission reductions of 12–40%, though these gains are derived from modeled scenarios (see Section 4.4). Renewable energy investment simultaneously drives environmental and economic outcomes (SDG 7, SDG 8). Building thermal retrofit represents a cost-effective lever for decarbonization (SDG 11, SDG 13). Digital architectures enable real-time circular logistics management (SDG 9). The framework extends prior models (Govindan & Soleimani, 2017; Genovese et al., 2017; Neto et al., 2008) by incorporating geoecological and regional dimensions.

From the practical point of view, practitioners should integrate forward and reverse logistics planning as a default design principle (SDG 12); policymakers should calibrate incentive mechanisms to regional contexts and mandate ecological monitoring for large transport infrastructure; green finance institutions should design blended finance structures addressing the maturity mismatch between commercial credit and infrastructure project timelines.

Limitations. This paper has several limitations: (1) the integrative methodology involves qualitative selection judgments introducing potential bias; (2) quantified outcomes from heterogeneous studies should not be interpreted as meta-analytic estimates; (3) the framework has not been empirically validated; (4) regional contextualization through Nakhchivan limits generalizability; (5)

several cited sources are conference proceedings with variable peer-review rigor; (6) potential publication bias, as peer-reviewed studies with positive results are more likely to be included.

Future research should: (1) apply the six-pillar framework as a structured survey instrument across emerging economies; (2) integrate geoecological monitoring data into CLSC optimization models; (3) develop building-energy-aware logistics facility design models; (4) validate the framework through multi-country comparative case studies; (5) incorporate social sustainability as an explicit modeling objective. Mapping these priorities onto SDG 9, 11, 12, and 13 would strengthen policy relevance.

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Conflicts of interest

The authors declare no competing interests.

Data availability

The coded dataset underlying this review is available in Appendix B and Appendix C of this article.

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Appendix A: PRISMA flow diagram and reasons for exclusion

A.1 PRISMA flow diagram (text summary)

- Records identified through database searching: Scopus (n = 168); Web of Science Core Collection (n = 142); Google Scholar (n = 102). Total identified: n = 412.
- Duplicates removed: n = 87. Records after duplicates removed: n = 325.
- Records screened (title/abstract): n = 325. Records excluded at title/abstract stage: n = 183.
- Full-text articles assessed for eligibility: n = 142. Full-text articles excluded: n = 83.
- Studies included in final synthesis: n = 59.

A.2 Reasons for full-text exclusion (table)

Reason for exclusion	Number of full-text articles
Not focused on logistics/CLSC or decarbonization	28
No clear methodology or quantitative outcomes	19
Non-English language	12
Duplicate or extended conference abstract without full paper	10
Other (out of scope, inaccessible full text)	8

Appendix B: Study Quality Assessment

B.1 Quality Assessment Rubric

Each of the 59 included studies was assessed independently by two reviewers across four domains. Discrepancies were resolved by consensus. Domain scores: 0 = not reported / poor; 1 = partially reported / limited; 2 = clearly reported / good.

Domain 1 – Methodological clarity and study design (0–2)

Domain 2 – Data transparency and reproducibility (0–2)

Domain 3 – Peer-review status: 2 = peer-reviewed journal; 1 = conference proceedings; 0 = preprint (0–2)

Domain 4 – Relevance to CLSC–decarbonization integration (0–2)

Quality Score = D1 + D2 + D3 + D4 (range 0–8). The Quality Score is used as a weighting factor in the weighted median synthesis reported in Section 3.6. Colour coding: green ≥ 7; yellow 5–6; red ≤ 4.

B.2 Per-Study Quality Assessment (all 59 included studies)

Study ID	Citation	Design / Methodology	Pub. Type	D1 Meth.	D2 Data	D3 Peer	D4 Relev.	Quality Score	Key outcome used in synthesis
S01	Lu et al. (2023)	Fleet electrification VRP simulation	Peer-reviewed	2	2	2	2	**8**	~30% lifecycle emission reduction
S02	Zheng et al. (2025)	Multi-objective VRP + metaheuristic	Peer-reviewed	2	1	2	2	**7**	Cost ↓31%; CO_2 ↓15–25%
S03	Sorooshian et al. (2024)	Circular IoT integration, EV battery SC	Peer-reviewed	2	2	2	2	**8**	Cost ↓15–22%; CO_2 ↓25–35%
S04	Sabaghieh Yazd et al. (2025)	Mixed-integer programming, dual-channel	Peer-reviewed	2	1	2	2	**7**	Cost ↓12–20%; CO_2 ↓12–18%
S05	Wen et al. (2026)	Relay transport network design	Peer-reviewed	2	1	2	2	**7**	Cost ↓8–15%; CO_2 ↓20–30%
S06	Song et al. (2026)	Stackelberg game, power battery CLSC	Peer-reviewed	2	1	2	2	**7**	Cost ↓18–28%; CO_2 ↓15–22%
S07	Sardar et al. (2025)	Integrated robust programming	Peer-reviewed	2	1	2	2	**7**	Cost ↓10–15%; CO_2 ↓10–15%
S08	Tahmouresi & Behnamian (2026)	Scenario-based robust programming	Peer-reviewed	2	1	2	2	**7**	Variance ↓20–40%
S09	Taleizadeh et al. (2025)	Nash/Stackelberg game-theoretic model	Peer-reviewed	2	1	2	2	**7**	Profit ↑ vs. decentralized

S10	Farrokh et al. (2025)	Pareto multi-objective sustainable CLSC	Peer-reviewed	2	1	2	2	**7**	Cost ↓, emission ↓
S11	Mohtashami et al. (2020)	Green CLSC with queuing system	Peer-reviewed	2	1	2	2	**7**	Cost ↓, emission ↓
S12	Long et al. (2020)	Reward-penalty mechanism, C&D waste	Peer-reviewed	2	1	2	1	**6**	Return volume ↑
S13	Li et al. (2021)	Reward-penalty, CLSC sustainability	Peer-reviewed	2	1	2	2	**7**	Return volume ↑
S14	Li et al. (2017)	Pricing + carbon, low-carbon CLSC	Peer-reviewed	2	1	2	2	**7**	Emission ↓, profit coordinated
S15	Govindan & Soleimani (2017)	Review: CLSC analytical boundaries	Peer-reviewed	2	1	2	2	**7**	Framework/taxonomy contribution
S16	Agrawal et al. (2015)	Literature review: reverse logistics	Peer-reviewed	2	1	2	2	**7**	Review findings
S17	Lozano-Oviedo et al. (2024)	CLSC optimization models synthesis	Peer-reviewed	2	1	2	2	**7**	Methodological diversity confirmed
S18	Genovese et al. (2017)	CE transition as SCM challenge	Peer-reviewed	2	1	2	2	**7**	Framework contribution
S19	Neto et al. (2008)	Environmental metrics in logistics networks	Peer-reviewed	2	1	2	2	**7**	Early groundwork established
S20	Borjian et al. (2019)	CLSC with environmental investment	Peer-reviewed	2	1	2	2	**7**	Cost ↓, pollution ↓
S21	Wang & Wang (2025)	5G edge computing, real-time routing	Peer-reviewed	2	1	2	2	**7**	Latency ↓85%
S22	Chochliouros et al. (2025)	Automated logistics in B5G/6G era	Conference	1	1	1	2	**5**	Latency ↓, routing optimization
S23	Srinivas et al. (2025)	Fuzzy logic–GA, IoT fog-cloud scheduling	Conference	1	1	1	2	**5**	Computational energy ↓
S24	Ben Amor et al. (2025)	AI sustainable warehouse management	Conference	1	1	1	2	**5**	Energy ↓, emission ↓
S25	Bhatia et al. (2026)	Industrial robotics in smart warehousing	Peer-reviewed	2	1	2	2	**7**	Efficiency ↑, emission ↓
S26	Mrad et al. (2026)	Technological pathways, low-carbon SC	Peer-reviewed	2	1	2	2	**7**	Emission ↓ pathways documented
S27	Pajila (2024)	Smart warehousing, energy efficiency	Peer-reviewed	1	1	2	1	**5**	Energy savings documented
S28	Akbar & Gheewala (2026)	Li-ion batteries global supply chains	Peer-reviewed	2	2	2	2	**8**	Lifecycle emission analysis
S29	Abdulhasanova (2025)	Green finance, Azerbaijan	Peer-reviewed	2	1	2	1	**6**	10:1 leverage; $2.3B/yr by 2030
S30	Aliyev et al. (2024)	Renewable energy–GDP, Iceland/Azerbaijan	Peer-reviewed	2	2	2	1	**7**	Significant positive causality
S31	Ahmadova et al. (2018)	Nakhchivan macroeconomic development	Peer-reviewed	1	1	2	1	**5**	Regional context established
S32	Alegoz & Karaer (2024)	Closing loop + servitization in SC	Peer-reviewed	2	1	2	2	**7**	Compound sustainability effect
S33	Amri et al. (2025)	Reverse logistics–sustainability mapping	Conference	1	1	1	2	**5**	Review findings
S34	Caramia & Pizzari (2023)	Cap-and-trade bi-objective CLSC model	Peer-reviewed	2	1	2	2	**7**	Emission ↓, cost optimized
S35	Cheng et al. (2024)	CLSC dynamic returns, wholesale discount	Peer-reviewed	2	1	2	2	**7**	Return rate ↑, profit coordinated

S36	Ciliberto & Mathiyazhagan (2025)	Last-mile + reverse logistics, circular SC	Peer-reviewed	2	1	2	2	**7**	Circular efficiency ↑
S37	Fatorachian & Kazemi (2025)	Linear-to-circular SC transition	Peer-reviewed	2	1	2	2	**7**	Framework contribution
S38	Jauhari et al. (2025)	Sustainable CLSC with green investment	Peer-reviewed	2	1	2	2	**7**	Cost ↓, emission ↓
S39	Hajiyev et al. (2025)	Interior insulation, cavity brick walls	Peer-reviewed	2	2	2	0	**6**	Energy savings, building compliance
S40	Li et al. (2025)	CLSC pricing, recycling quality grading	Peer-reviewed	2	1	2	2	**7**	Recovery ↑, profit ↑
S41	Mahmoumgonbadi et al. (2021)	CLSC design for circular economy	Peer-reviewed	2	1	2	2	**7**	Framework contribution
S42	McKinnon & Piecyk (2012)	Carbon targets in logistics	Peer-reviewed	2	1	2	2	**7**	7–10% CO_2 share established
S43	Nagasawa et al. (2019)	CSR and sustainability in CLSC	Conference	1	1	1	2	**5**	CSR linkage documented
S44	Nicoletti & Appolloni (2025a)	Warehouse 5.0 framework	Peer-reviewed	2	1	2	1	**6**	Framework contribution
S45	Nicoletti & Appolloni (2025b)	AI, warehousing 5.0, EU green taxonomy	Conference	1	1	1	1	**4**	AI application in green logistics
S46	Olapiriyakul & Pannakkong (2025)	Sustainable food distribution CLSC	Peer-reviewed	2	1	2	2	**7**	Cost ↓, emission ↓
S47	Pal & Mukherjee (2025)	Coupon policy, dual-channel SC	Peer-reviewed	2	1	2	1	**6**	Sales ↑, sustainability implications
S48	Rathnasiri (2025)	SC decarbonization, environment & society	Peer-reviewed	2	1	2	2	**7**	Emission ↓ pathways reviewed
S49	Seifbarghy & Hamidi (2023)	Supplier evaluation + CLSC network design	Peer-reviewed	2	1	2	2	**7**	Integrated model, cost ↓
S50	Shahidzadeh et al. (2023)	WEEE management in CLSC	Peer-reviewed	2	1	2	2	**7**	Recovery ↑, emission ↓
S51	Shekarian (2020)	Review: factors affecting CLSC models	Peer-reviewed	2	1	2	2	**7**	Review findings
S52	Syphoxay & Hien (2014)	CLSC under emission trading scheme	Conference	1	1	1	2	**5**	Early emission integration
S53	Tahoori et al. (2014)	Key issues, sustainable CLSC	Conference	1	1	1	2	**5**	Early framework contribution
S54	Wube et al. (2025)	Resilient/sustainable CLSC under risk	Peer-reviewed	2	1	2	2	**7**	Resilience ↑, cost ↓
S55	Yang & Xu (2019)	Differential game, CLSC carbon permits	Peer-reviewed	2	1	2	2	**7**	Emission ↓, game equilibrium
S56	Yozgat & Erol (2022)	Sustainable CLSC network design	Conference	1	1	1	2	**5**	Optimization framework
S57	Yuniarti et al. (2025)	Scoping review: resilient/sustainable SC	Peer-reviewed	2	1	2	2	**7**	Review synthesis
S58	Asgarova & Abbasova (2024)	BRI as alternative to Silk Road	Peer-reviewed	1	1	2	0	**4**	Geopolitical context
S59	Li & Wang et al. (2017)	Carbon pricing CLSC coordination	Peer-reviewed	2	1	2	2	**7**	Emission ↓

Note. Quality Scores were assigned based on full-text review. Studies with scores ≤ 4 were retained if they provided unique contextual evidence unavailable from higher-scoring sources; their findings are reported qualitatively only.

Appendix C: Quantitative Standardization – Assumptions and Conversion Table

C.1 Standard metrics

Two primary metrics were used:

• Relative percentage change from baseline (primary metric for all studies).

Formula: $R = (E_0 - E_1) / E_0 \times 100$, where E_0 = baseline, E_1 = post-intervention value.

• Absolute emissions intensity (tCO_2e per functional unit) – used where explicitly reported.

C.2 Conversion rules

Scenario	Conversion rule
Lifecycle % reduction without baseline emissions	Record relative % change; flag baseline as not reported; do not convert to tCO_2e.
Energy savings reported in kWh only	Convert to tCO_2e using study's reported grid emission factor. If not reported, apply 0.45 tCO_2e/MWh and document assumption.
Latency / computational reduction only	Record as qualitative enabler. Convert to tCO_2e only if study provides explicit energy equivalents.
Cost reductions only, no emissions data	Record cost metric; mark Emission column as N/A.
Modelled range (min–max) reported	Record midpoint for weighted synthesis; report full range in key-outcome column.
Conceptual / review contribution	No quantitative synthesis; coded as qualitative; Emission = N/A.

C.3 Per-study standardization table (all 59 included studies)

Study ID	Citation	Reported metric	Units	Baseline / conversion	Standardized result / notes
S01	Lu et al. (2023)	Relative % change	% change	Baseline reported	~30% lifecycle emission reduction (relative, no abs. conversion)
S02	Zheng et al. (2025)	Relative % change	% change	Baseline not reported; relative value only	Cost ↓31%; CO_2 ↓15–25% (relative, no abs. conversion)
S03	Sorooshian et al. (2024)	Relative % change	% change	Baseline reported	Cost ↓15–22%; CO_2 ↓25–35% (relative, no abs. conversion)
S04	Sabaghieh Yazd et al. (2025)	Relative % change	% change	Baseline not reported; relative value only	Cost ↓12–20%; CO_2 ↓12–18% (relative, no abs. conversion)
S05	Wen et al. (2026)	Relative % change	% change	Baseline not reported; relative value only	Cost ↓8–15%; CO_2 ↓20–30% (relative, no abs. conversion)
S06	Song et al. (2026)	Relative % change	% change	Baseline not reported; relative value only	Cost ↓18–28%; CO_2 ↓15–22% (relative, no abs. conversion)
S07	Sardar et al. (2025)	Relative % change	% change	Baseline not reported; relative value only	Cost ↓10–15%; CO_2 ↓10–15% (relative, no abs. conversion)
S08	Tahmouresi & Behnamian (2026)	Relative % change	% change	Baseline not reported; relative value only	Variance ↓20–40% (relative, no abs. conversion)
S09	Taleizadeh et al. (2025)	Economic outcome	% or ratio	Study-reported baseline	Profit ↑ vs. decentralized (economic; emission = N/A)
S10	Farrokh et al. (2025)	Mixed/other	Various	Per source	Cost ↓, emission ↓
S11	Mohtashami et al. (2020)	Mixed/other	Various	Per source	Cost ↓, emission ↓
S12	Long et al. (2020)	Economic outcome	% or ratio	Study-reported baseline	Return volume ↑ (economic; emission = N/A)
S13	Li et al. (2021)	Economic outcome	% or ratio	Study-reported baseline	Return volume ↑ (economic; emission = N/A)
S14	Li et al. (2017)	Economic outcome	% or ratio	Study-reported baseline	Emission ↓, profit coordinated (economic; emission = N/A)

S15	Govindan & Soleimani (2017)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S16	Agrawal et al. (2015)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S17	Lozano-Oviedo et al. (2024)	Mixed/other	Various	Per source	Methodological diversity confirmed
S18	Genovese et al. (2017)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S19	Neto et al. (2008)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S20	Borjian et al. (2019)	Mixed/other	Various	Per source	Cost ↓, pollution ↓
S21	Wang & Wang (2025)	Relative % change	% change	Baseline not reported; relative value only	Latency ↓85% (relative, no abs. conversion)
S22	Chochliouros et al. (2025)	Latency / compute ↓	% latency ↓	N/A – qualitative	Qualitative; no tCO_2e conversion
S23	Srinivas et al. (2025)	Energy savings	kWh/year	Grid factor: 0.45 tCO_2e/MWh (assumed)	kWh × 0.45 → tCO_2e
S24	Ben Amor et al. (2025)	Energy savings	kWh/year	Grid factor: 0.45 tCO_2e/MWh (assumed)	kWh × 0.45 → tCO_2e
S25	Bhatia et al. (2026)	Mixed/other	Various	Per source	Efficiency ↑, emission ↓
S26	Mrad et al. (2026)	Mixed/other	Various	Per source	Emission ↓ pathways documented
S27	Pajila (2024)	Energy savings	kWh/year	Grid factor: 0.45 tCO_2e/MWh (assumed)	kWh × 0.45 → tCO_2e
S28	Akbar & Gheewala (2026)	Mixed/other	Various	Per source	Lifecycle emission analysis
S29	Abdulhasanova (2025)	Economic outcome	% or ratio	Study-reported baseline	10:1 leverage; $2.3B/yr by 2030 (economic; emission = N/A)
S30	Aliyev et al. (2024)	Economic outcome	% or ratio	Study-reported baseline	Significant positive causality (economic; emission = N/A)
S31	Ahmadova et al. (2018)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S32	Alegoz & Karaer (2024)	Mixed/other	Various	Per source	Compound sustainability effect
S33	Amri et al. (2025)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S34	Caramia & Pizzari (2023)	Mixed/other	Various	Per source	Emission ↓, cost optimized
S35	Cheng et al. (2024)	Economic outcome	% or ratio	Study-reported baseline	Return rate ↑, profit coordinated (economic; emission = N/A)
S36	Ciliberto & Mathiyazhagan (2025)	Mixed/other	Various	Per source	Circular efficiency ↑
S37	Fatorachian & Kazemi (2025)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S38	Jauhari et al. (2025)	Mixed/other	Various	Per source	Cost ↓, emission ↓
S39	Hajiyev et al. (2025)	Energy savings	kWh/year	Grid factor: 0.45 tCO_2e/MWh (assumed)	kWh × 0.45 → tCO_2e
S40	Li et al. (2025)	Economic outcome	% or ratio	Study-reported baseline	Recovery ↑, profit ↑ (economic; emission = N/A)
S41	Mahmoumgonbadi et al. (2021)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S42	McKinnon & Piecyk (2012)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S43	Nagasawa et al. (2019)	Mixed/other	Various	Per source	CSR linkage documented
S44	Nicoletti & Appolloni (2025a)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis

S45	Nicoletti & Appolloni (2025b)	Mixed/other	Various	Per source	AI application in green logistics
S46	Olapiriyakul & Pannakkong (2025)	Mixed/other	Various	Per source	Cost ↓, emission ↓
S47	Pal & Mukherjee (2025)	Economic outcome	% or ratio	Study-reported baseline	Sales ↑, sustainability implications (economic; emission = N/A)
S48	Rathnasiri (2025)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S49	Seifbarghy & Hamidi (2023)	Mixed/other	Various	Per source	Integrated model, cost ↓
S50	Shahidzadeh et al. (2023)	Mixed/other	Various	Per source	Recovery ↑, emission ↓
S51	Shekarian (2020)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S52	Syphoxay & Hien (2014)	Mixed/other	Various	Per source	Early emission integration
S53	Tahoori et al. (2014)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S54	Wube et al. (2025)	Mixed/other	Various	Per source	Resilience ↑, cost ↓
S55	Yang & Xu (2019)	Mixed/other	Various	Per source	Emission ↓, game equilibrium
S56	Yozgat & Erol (2022)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S57	Yuniarti et al. (2025)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S58	Asgarova & Abbasova (2024)	Conceptual/review	N/A	N/A	Qualitative; no quantitative synthesis
S59	Li & Wang et al. (2017)	Mixed/other	Various	Per source	Emission ↓

Note. All conversion factors and baseline assumptions are as specified in C.2. Where the primary study did not report baseline values, only relative changes are recorded and these are not included in the weighted median calculation for absolute emission intensity.

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