

Review

Energy-Efficiency Actions in Food Cold Chains: A Systematic Review of Refrigeration, Logistics, Digital Monitoring and Collaborative Implementation

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Abstract

Food cold chains rely on refrigeration, cold storage, refrigerated transport, packaging and monitoring systems that consume electricity and fuel while preserving food safety, quality and shelf life. Although many studies propose energy-saving technologies or optimization models for individual cold-chain operations, less is known about how energy-efficiency actions are distributed across refrigeration, logistics and digital monitoring domains, which actors must collaborate to implement them, and which benefits and barriers shape adoption. This paper presents a systematic literature review supported by bibliometric and structured content analysis. Searches in Scopus and Web of Science identified 3930 records before deduplication. After removing out-of-year records and duplicates, 2368 unique records were screened; 896 reports were sought for full-text assessment; 751 reports were retrieved and assessed; 466 studies were included in the final review corpus; and 408 were coded as an applied/action corpus. The synthesis identifies ten energy-efficiency action families, seven cold-chain stage classes, multi-actor configurations, evidence types, collaboration-intensity levels, energy benefits, non-energy benefits and implementation barriers. Transport, routing and distribution is the largest action family (134 records), followed by cold storage and refrigeration technology (66), digital monitoring and information sharing (58), life-cycle assessment, energy assessment and decision support (36), energy systems and renewable cooling (34), packaging and thermal insulation (33), and inventory, and planning and coordination (27). The findings show that food cold-chain energy efficiency is not only a technical refrigeration problem but also a collaborative implementation challenge: many actions require information sharing, coordinated operating decisions, joint investment, data governance or cost/benefit-sharing mechanisms. The review contributes an action-oriented framework that links energy-saving actions to stages, actors, collaboration requirements, benefits and barriers, and it identifies future research priorities on comparable energy metrics, measured savings, renewable cooling, digital twins, demand-side flexibility and governance of collaborative energy-efficiency investments.

Keywords: food cold chain; energy efficiency; cold storage; digital monitoring; renewable cooling; collaboration intensity



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1. Introduction

Food cold chains are a critical part of modern food systems because they connect production, postharvest handling, processing, storage, transport, distribution and retail under controlled temperature conditions. Their contribution to food safety, shelf-life extension and market access is substantial, but it comes with a significant environmental and resource burden. Refrigeration, freezing, chilled storage, refrigerated vehicle operation, thermal packaging and monitoring systems consume electricity and fuel, while poor coordination can increase temperature abuse, food losses, redundant handling and avoidable emissions. From an energy-efficiency perspective, the cold chain is therefore not only a logistics infrastructure but also a distributed production–consumption system in which energy, materials, information and product quality are jointly transformed across organizational boundaries.

The energy relevance of this sector is increasingly recognized. The food system has been estimated to account for a substantial share of global energy consumption [1]. Refrigeration and sustainable cold-chain infrastructure represent central energy-demanding functions in food supply chains [2]. As urbanization, dietary change and demand for perishable products expand, the energy demand of temperature-controlled logistics is expected to increase unless cold-chain infrastructure, refrigeration systems and logistics operations are redesigned around efficiency, monitoring and energy-aware coordination [2]. This makes the cold chain a particularly important setting for studying how energy efficiency can be achieved across organizational boundaries rather than only within individual facilities.

The existing literature has generated a rich set of solutions for improving cold-chain sustainability. Engineering studies examine refrigeration upgrades, phase-change materials, insulation, renewable cooling, thermal storage and the performance of cold rooms or refrigerated vehicles. Operations and logistics studies optimize routing, scheduling, inventory policies, network design, delivery time windows and vehicle use. Sustainability-assessment studies quantify carbon footprints, energy hotspots and life-cycle trade-offs. Digitalization studies focus on sensors, Internet-of-Things platforms, blockchain, real-time visibility, digital twins and decision-support systems. These streams all contribute to energy-efficient food cold chains, but they often remain separated by discipline, method and unit of analysis. Recent examples illustrate this fragmentation across research streams. Logistics cold-storage studies discuss technology development, policy status and carbon-neutral cold storage [3]. Industry 4.0 research examines digitally enabled waste efficiency in cold supply chains [4]. Packaging research focuses on phase-change materials and thermal protection for food distribution [5]. Scheduling studies develop carbon-efficient models for fresh-food supply chains [6]. Broader cold-chain logistics reviews map current developments and emerging trends [7], while renewable and hybrid cooling studies examine refrigeration systems, photovoltaic integration, biomass-driven cooling and geothermal cooling options [8–12]. Other contributions address radiative cooling materials for food preservation [13] and dynamic time–temperature management for fruit storage [14]. Commodity- and context-specific studies add further detail: meat cold-chain reviews address waste reduction [15], real-time visibility adoption is examined in meat cold chains [16], IoT is discussed in fishery cold chains [17], and postharvest cold-storage reviews address storage technologies for fresh produce [18].

This fragmentation matters because energy efficiency in cold chains is rarely delivered by a single firm or technology in isolation. A refrigeration upgrade may reduce electricity demand at a warehouse, but its value depends on product flows, storage policies and service requirements. Route optimization may reduce fuel consumption, but it requires demand information, delivery-window flexibility and coordination between shippers, carriers and retailers. Thermal packaging can protect quality and reduce waste, but it changes responsibilities across producers, logistics providers, packaging suppliers and

customers. Digital monitoring generates data, but energy-efficiency benefits emerge only when data are shared, trusted and converted into action.

Recent evidence from buyer–supplier energy management research further supports this view. Xavier et al. show that integrating energy management into supplier performance assessment is hindered by unclear energy-related expectations, limited reporting criteria, information asymmetry and misaligned incentives. They identify energy-related KPIs, shared data protocols and SME capability-building as key practices for improving transparency and upstream decarbonization [19].

The paper therefore adopts the concept of collaborative energy efficiency. In this review, collaborative energy efficiency refers to energy and energy-efficiency actions whose implementation depends on the alignment of technical measures, operating processes, data flows, incentives and governance across food cold-chain actors. This framing extends the conventional view of energy efficiency as equipment performance and places it within a broader system of resource productivity, food-loss prevention, emissions reduction and value-chain coordination.

The review addresses four connected research questions. First, which energy and energy-efficiency actions have been proposed for food cold chains at the inter-organizational or value-chain level? Second, what level of collaboration intensity is required to implement these actions across actors? Third, what barriers and enabling conditions affect implementation? Fourth, which energy benefits and non-energy benefits are associated with different action families? By answering these questions together, the paper moves beyond listing technologies and develops an implementation-oriented map of energy-efficient cold-chain actions.

The remainder of the paper is structured as follows. Section 2 describes the systematic review protocol, search strategy, screening process and coding framework. Section 3 presents the results on publication dynamics, action families, cold-chain stages, collaboration intensity, actor configurations, evidence types, benefits and barriers. Section 4 discusses the implications for energy-efficiency theory and implementation. Section 5 develops the action-oriented framework that translates the synthesis into guidance for managers and policy makers. Section 6 concludes, and Section 7 outlines limitations and future research priorities.

2. Methods

The review was designed as a systematic literature review supported by bibliometric and structured content analysis. It was reported following the PRISMA 2020 statement [20], with explicit documentation of information sources, search strings, duplicate removal, title-and-abstract screening, full-text retrieval, exclusion reasons and inclusion decisions. No formal review protocol was registered before the review was conducted; however, the review protocol, eligibility criteria, coding framework and collaboration-intensity rubric are provided as Supplementary File S1 to support transparency and reproducibility. A PRISMA 2020 reporting matrix is provided as Supplementary File S2.

2.1. Search Strategy and Database Coverage

Two complementary search strategies were used. Query A defined the main corpus around food cold chains, cold-chain logistics, refrigeration, energy use, energy efficiency, sustainability and emissions. Query B acted as a collaboration sensitivity check by adding terms related to collaboration, coordination, integration, information sharing and value-chain governance. Searches were run in Scopus and Web of Science, limited to English-language articles and reviews, and bounded to publications up to 2025. Query A returned 1882 Scopus records and 2048 Web of Science records. Query B returned 356 Scopus records

and 388 Web of Science records. After deduplication, all Query B records were already covered by Query A, so Query A served as the main corpus for screening. The database-specific search strings are reported in Appendix A to support transparency and reproducibility.

2.2. Screening and Eligibility

The combined search produced 3930 records before deduplication. Forty-six records outside the target publication-year boundary and 1516 duplicates were removed, leaving 2368 unique records for title-and-abstract screening. Screening excluded 1472 records and retained 896 records for full-text assessment. Full text was retrieved for 751 records, while 145 records could not be retrieved and were retained in a missing-PDF log for transparency. Full-text screening excluded 285 retrieved records because they did not satisfy the eligibility criteria. The final review corpus includes 466 records. Within this final corpus, 408 records were coded as the applied/action corpus because they propose, model, evaluate, review or operationalize a concrete energy-efficiency or sustainability-related action relevant to the food cold chain. The distinction between the final review corpus and the applied/action corpus was made using an operational coding rule. A full-text eligible study was retained in the 466-record review corpus when it was relevant to food cold chains and energy, emissions or sustainability. It was coded in the 408-record applied/action corpus only when it contained a clearly identifiable action, technology, model, assessment framework or implementation practice that could be assigned to an action family, a cold-chain stage, actor categories and a collaboration-intensity level. The remaining 58 studies were retained in the broader review corpus but were not used for action-level cross-tabulations because they provided background, contextual, conceptual or otherwise non-codable evidence. Their exclusion from the applied/action corpus therefore does not remove them from the review; it prevents non-action records from biasing the action-family matrices. The entire process is illustrated in Figure 1 and summarized in Table 1.

2.3. Coding Framework

The coding framework was developed iteratively during full-text assessment. Each applied/action record was coded by action category, cold-chain stage, actors involved, collaboration intensity, evidence type, energy benefit, non-energy benefits and barriers/enabling conditions. Detailed categories were then normalized for synthesis. Action categories were consolidated into ten action families: transport, routing and distribution; cold storage and refrigeration technology; digital monitoring and information sharing; LCA, assessment and decision support; energy systems and renewable cooling; packaging and thermal insulation; inventory, planning and coordination; other/mixed action; value-chain collaboration and governance; and review/framework/conceptual study. Cold-chain stages were consolidated into seven stage classes. Actor categories and benefit/barrier themes were coded as multi-label fields, because a record can involve several actors and report several benefits or barriers. Table 2 operationalizes collaboration intensity as an implementation-complexity construct. Level 1 captures actions that can be mainly implemented within one firm or asset. Level 2 requires information exchange or joint assessment. Level 3 requires coordinated operating changes across firms. Level 4 captures actions that require formal governance, joint investment, contractual arrangements or cost/benefit-sharing mechanisms. This rubric was used consistently during coding to distinguish technical feasibility from collaborative implementability.

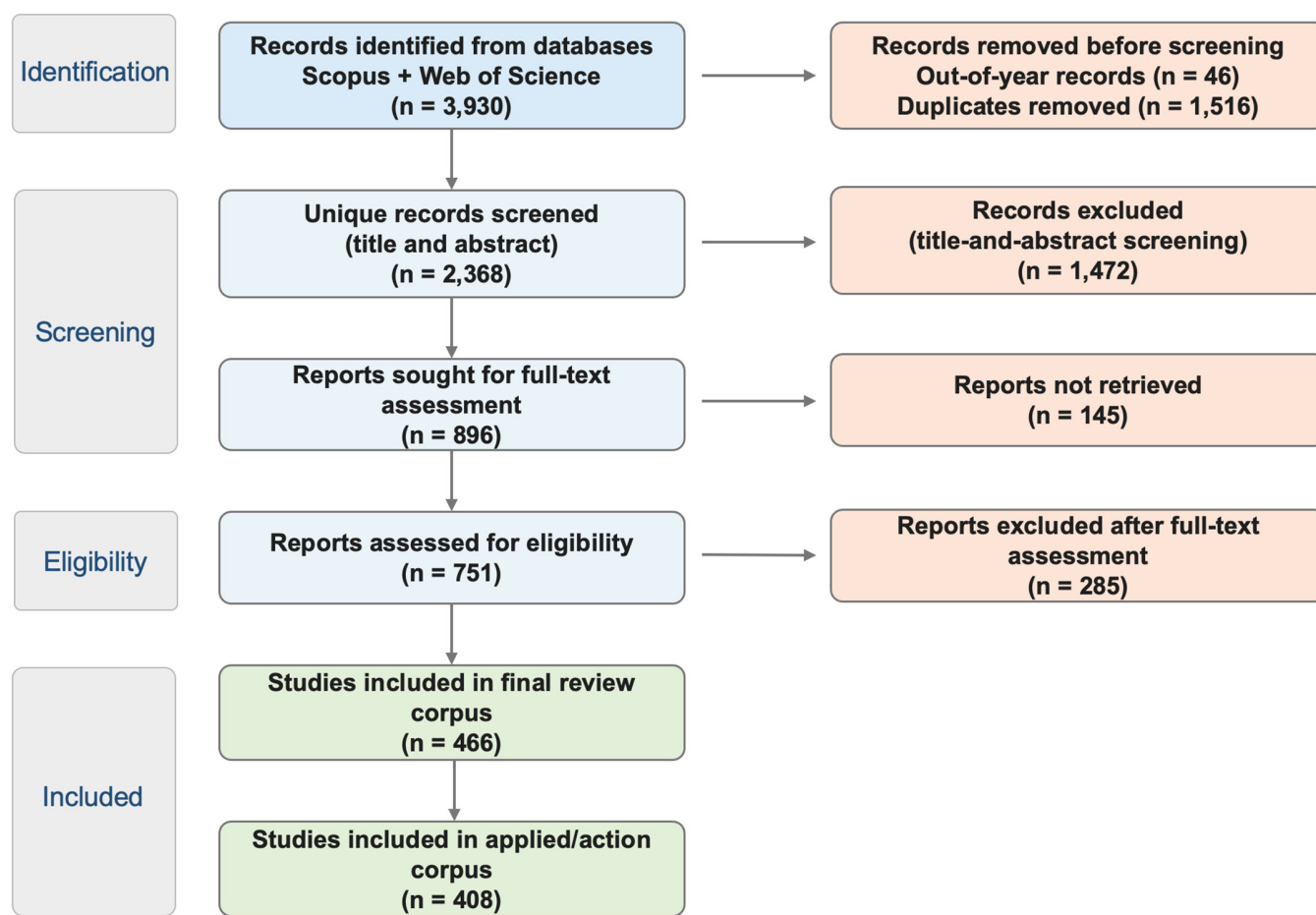


Figure 1. PRISMA-style flow diagram for corpus construction.

Table 1. Review flow and corpus construction numbers.

Step	Records
Records identified before deduplication	3930
Out-of-year records removed	46
Duplicates removed	1516
Unique records screened by title/abstract	2368
Records excluded at title/abstract stage	1472
Reports sought for full-text assessment	896
Reports not retrieved	145
Reports assessed for eligibility	751
Reports excluded after full-text assessment	285
Studies included in final review corpus	466
Studies included in applied/action corpus	408

Table 2. Collaboration-intensity rubric used in the content analysis.

Intensity	Label	Interpretation
1	Low	The action can mostly be implemented within a single organization, asset, technology or local operating process.
2	Moderate	The action requires information sharing, monitoring, joint assessment, operational alignment or limited coordination across actors.
3	High	The action requires coordinated changes in processes, routing, packaging, service commitments or cross-firm decision making.
4	Advanced	The action requires network redesign, joint investment, contracts, cost/benefit sharing, governance mechanisms or multi-actor strategic coordination.

2.4. Synthesis Methods, Robustness Checks and Methodological Quality

The synthesis combined descriptive bibliometric summaries, structured content analysis and configurational cross-tabulation. Record counts were calculated for publication trends, action families, cold-chain stages, actor classes, evidence types, collaboration-intensity levels, benefit themes and barrier themes. These counts are used to identify concentrations, gaps and implementation patterns in the literature, not to estimate pooled effects.

Several robustness checks were used to strengthen methodological transparency. First, Query B tested whether collaboration-specific terminology identified a distinct body of literature; after deduplication, all Query B records were covered by Query A. Second, borderline title-and-abstract decisions were manually reviewed before full-text assessment. Third, unretrieved reports were recorded separately rather than silently excluded. Fourth, the synthesis distinguishes the full review corpus from the applied/action corpus to avoid mixing general background studies with action-level evidence.

A formal risk-of-bias assessment and certainty-of-evidence rating were not conducted because the objective was to map, classify and synthesize heterogeneous research streams rather than estimate the effectiveness of specific interventions. The included studies differ substantially in research design, unit of analysis, outcome metrics and evidence type; therefore, a conventional effect-size synthesis was not appropriate.

3. Results

This section reports the descriptive synthesis of the final review corpus and the applied/action corpus. The results are presented as an implementation map for energy-efficient food cold chains: first, the temporal development of the field is described; second, action families and cold-chain stages are mapped; third, the collaboration intensity, actors, evidence types, benefits and barriers associated with each family are examined. Figure 2 provides the temporal overview of the final review corpus, while Figures 3–5 and Tables 3–8 progressively map the evidence by action family, cold-chain stage, collaboration intensity, actor configuration, evidence type, benefits and barriers.

Table 3. Action families by collaboration intensity.

Action Family	1 Low	2 Moderate	3 High	4 Advanced	Total
Transport, routing and distribution	9	16	80	29	134
Cold storage and refrigeration technology	25	36	5	0	66
Digital monitoring and information sharing	2	46	10	0	58
LCA, assessment and decision support	4	32	0	0	36
Energy systems and renewable cooling	2	27	5	0	34
Packaging and thermal insulation	0	1	32	0	33
Inventory, planning and coordination	0	1	6	20	27
Other/mixed action	0	5	1	4	10
Value-chain collaboration and governance	0	1	3	3	7
Review, framework or conceptual study	0	3	0	0	3

Table 4. Stage class by collaboration intensity.

Stage Class	1 Low	2 Moderate	3 High	4 Advanced	Total
Transport and distribution	30	32	97	32	191
Cold storage and warehousing	10	70	15	5	100
Multi-stage/whole cold chain	1	53	6	6	66
Packaging/product-logistics interface	0	0	4	0	4
Planning, inventory or network level	0	0	1	6	7
Production, postharvest or processing	0	3	0	0	3
Other/unspecified stage	1	10	19	7	37

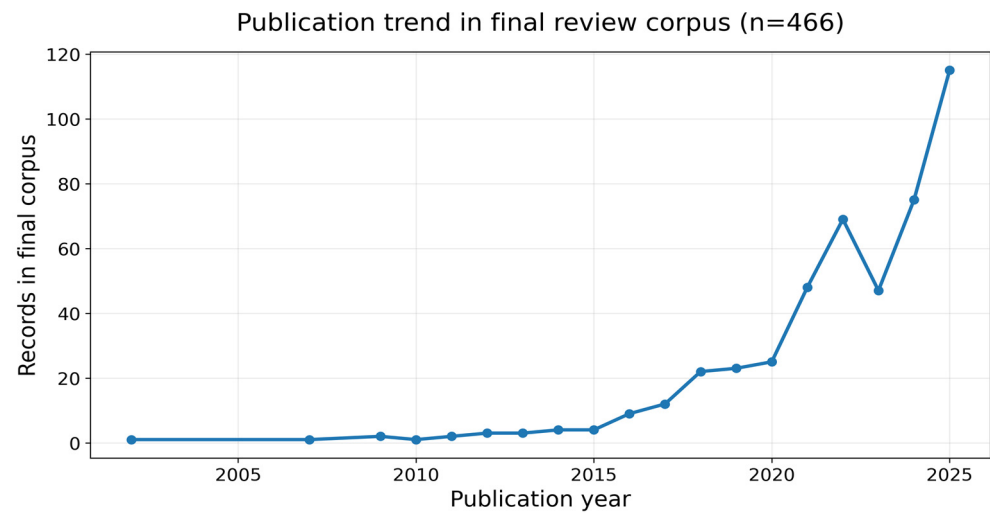


Figure 2. Publication trend in the final review corpus.

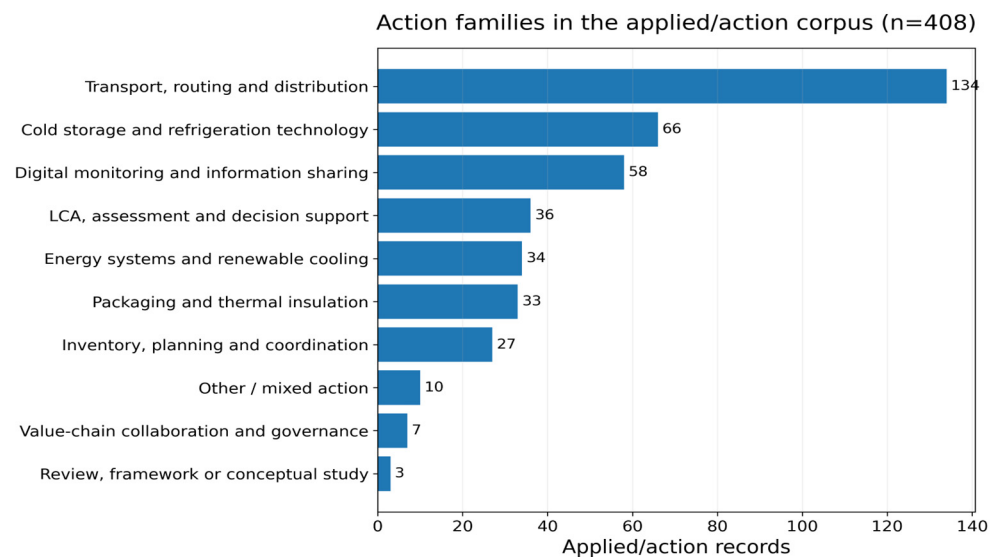


Figure 3. Distribution of applied/action records by action family.

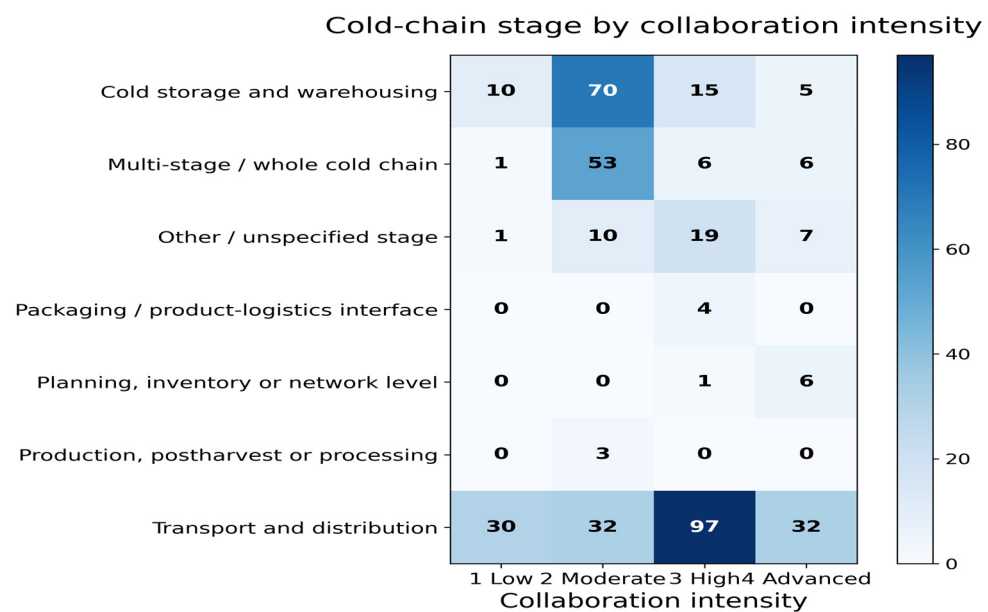


Figure 4. Heatmap of cold-chain stage by collaboration intensity.

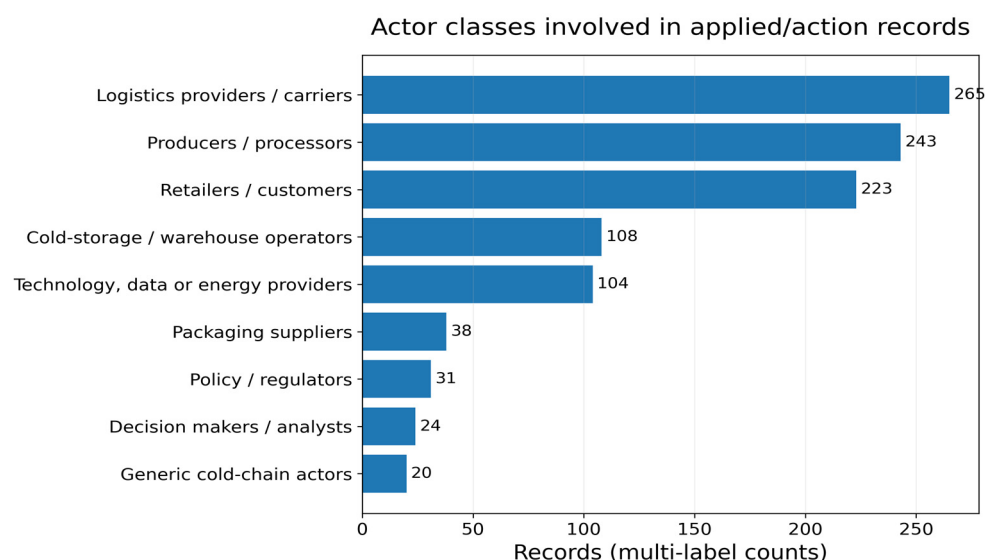


Figure 5. Actor classes involved in applied/action records.

Table 5. Actor classes in the applied/action corpus. Counts are multi-label.

Actor Class	Records
Logistics providers/carriers	265
Producers/processors	243
Retailers/customers	223
Cold-storage/warehouse operators	108
Technology, data or energy providers	104
Packaging suppliers	38
Policy/regulators	31
Decision makers/analysts	24
Generic cold-chain actors	20

Table 6. Evidence types in the applied/action corpus.

Evidence Class	Records
Modelling/optimization/simulation	198
Review	74
LCA/assessment	41
Case study/empirical	40
Technical/experimental	27
Other/mixed evidence	23
Conceptual/framework	5

Table 7. Source-characterization profile for records with available Web of Science affiliation metadata.

Dimension	Summary
Leading publication outlets in the final review corpus (n = 466)	Sustainability (Switzerland) (30); Journal of Cleaner Production (24); Journal of Energy Storage (20); Applied Energy (12); Energies (12); Applied Thermal Engineering (10); Energy (9); MATHEMATICS (8); Journal of Food Engineering (8); International Journal of Refrigeration (8)
Evidence types in the applied/action corpus (n = 408)	Modelling/optimization/simulation (198); Review (74); LCA/assessment (41); Case study/empirical (40); Technical/experimental (27); Other/mixed evidence (23); Conceptual/framework (5)
Country/region patterns in the WoS-matched subset (n = 413)	China (153); Italy (40); India (38); UK (38); South Africa (16); France (15); Canada (15); Spain (15); Iran (13); Netherlands (12)
Top institutional affiliations in the WoS-matched subset	Stellenbosch University (14); University of Padua (12); Shanghai Maritime University (11); National Institute of Technology (NIT System) (10); Swiss Federal Institutes of Technology Domain (9); Swiss Federal Laboratories for Materials Science & Technology (EMPA) (9); China Agricultural University (9); Wageningen University & Research (9); INRAE (8); University of Brescia (7)

Table 8. Main detailed subtopics within each normalized action family.

Action Family	Records	Detailed Topics Included in the Family
Transport, routing and distribution	134	Route planning, refrigerated transport, network design, delivery scheduling, low-carbon routing, hub/location decisions and disruption-aware distribution.
Cold storage and refrigeration technology	66	Cold-storage and warehouse energy management, refrigeration-system optimization, thermal/PCM storage, air-infiltration control, cold-room monitoring and equipment-level improvements.
Digital monitoring and information sharing	58	IoT monitoring, traceability, real-time visibility, data platforms, shelf-life prediction, FEFO logic, blockchain and smart cold-chain standardization.
LCA, assessment and decision support	36	Life-cycle assessment, GHG and carbon-footprint assessment, energy-efficiency assessment, scenario comparison, benchmarking and decision-support tools.
Energy systems and renewable cooling	34	Renewable refrigeration, solar/photovoltaic cold storage, hybrid refrigeration systems, polygeneration, ice storage and energy-system integration.
Packaging and thermal insulation	33	Packaging redesign, insulation materials, phase-change-material packaging, container airflow/ventilation design, Peltier integration and reusable/eco-designed cold-chain boxes.
Inventory, planning and coordination	27	Inventory policies, replenishment coordination, cost-sharing, pricing, time-temperature control, preservation investment, network optimization and smart energy coordination.
Other/mixed action	10	Industrial symbiosis, cold-energy recovery, loss-reduction initiatives, sustainable practices, food-loss mitigation and superchilling-related actions.
Value-chain collaboration and governance	7	Governance mechanisms, supplier selection, incentives, value-chain integration, environmental performance frameworks and low-carbon supply-chain management.
Review, framework or conceptual study	3	Barrier reviews, risk-management reviews and conceptual cold-chain management frameworks.

3.1. Action Families

The applied/action corpus is concentrated in a set of recurring action families, but these families represent different implementation logics. Some actions are mainly technical, such as refrigeration upgrades, renewable cooling or thermal insulation. Others are operational, such as vehicle routing, scheduling, load consolidation and inventory coordination. A third group is informational, because it depends on monitoring, traceability, LCA, decision support or shared platforms. A fourth group is governance-oriented, because it concerns contracts, cost-sharing, value-chain coordination and rules for allocating benefits and responsibilities. Reading the corpus through these families helps avoid treating energy efficiency as a single homogeneous intervention. The cited studies are embedded in the discussion of each family because they exemplify recurring subtopics observed during the coding of the 408 applied/action records; the complete record-level allocation is reported in Supplementary File S3.

Transport, routing and distribution is the largest family, with 134 records. This dominance reflects the visibility of refrigerated transport in cold-chain energy use and emissions, but also the analytical tractability of routing and scheduling problems. Studies in this family commonly examine vehicle routing, time-window constraints, delivery frequency, multi-compartment trucks, modal choices, disruption scenarios and distribution-network design. For this reason, network-design and multi-compartment reefer-truck studies were cited as anchors for the network-configuration subtopic [21,22], while urban cold-chain decarbonization and transport-mode choice studies were cited to represent system-level transport planning [23,24]. Time-window scheduling, route-level fuel and carbon estimation, multi-timescale coordination between renewable-energy systems and agri-product supply chains, and fresh e-commerce collaboration were cited because they illustrate the

operational and collaborative mechanisms through which transport energy savings are pursued [6,25–27]. Studies on quality-emissions trade-offs, local versus non-local perishable supply, and sustainable on-field perishable supply-chain design were retained because they show that transport energy efficiency is often evaluated together with service reliability, product quality and food-loss implications [28–30]. The typical managerial problem is therefore not only how to reduce fuel use, but also how to do so while respecting product temperature, delivery reliability, customer service and loading constraints.

As shown in Figure 3 and Table 3, this family is also the main concentration of high- and advanced-intensity actions, confirming that transport energy efficiency usually depends on inter-firm coordination rather than isolated vehicle-level decisions.

Cold storage and refrigeration technology, with 66 records, represents a more equipment- and facility-centred family. It includes refrigeration systems, storage design, insulation, air infiltration control, phase-change materials in warehouses, digital twins and technical assessments of low-carbon cooling options. Within this family, logistics cold-storage development was cited to anchor the system and policy dimension of cold-storage infrastructure [3], while flexible refrigerated warehouses and inorganic cold-storage charging systems represent the phase-change-material and thermal-storage subtopics [31,32]. Warm-air infiltration and field measurement studies were cited because they represent operational facility-performance assessment [33,34]. Renewable-driven hybrid refrigeration, techno-economic optimization, biomass-driven refrigeration and geothermal cooling systems were selected because they exemplify low-carbon cooling technologies and energy-system integration in cold storage [8,10–12]. Cooling access in low- and middle-income contexts and solar-powered cold-storage adoption broaden the family from equipment efficiency to infrastructure access and implementation feasibility [35,36]. These actions can sometimes be implemented within one facility, yet they still influence downstream product quality and upstream supply reliability, which explains why many are coded as moderate rather than purely low collaboration.

Digital monitoring and information sharing includes 58 records and acts as a bridge between technical and organizational change. Sensors, IoT platforms, real-time visibility, blockchain, traceability systems and analytics do not save energy by themselves; they create the information conditions for better decisions about routing, temperature management, stock rotation, exception handling and waste prevention. Industry 4.0-enabled digitalization was cited because it represents waste-efficiency and process-visibility applications [4], IoT fishery cold-chain studies anchor sensor-enabled monitoring and traceability [17], blockchain-enabled fresh-food supply chains represent shared ledgers and information governance [37], smart cold-chain standardization illustrates the institutional layer of digital transformation [38], and artificial-intelligence reviews represent analytics and decision-support applications [39]. For this reason, this family is strongly connected to data governance, interoperability and trust between actors.

The remaining families complete the picture. LCA, assessment and decision-support studies provide the measurement infrastructure for comparing alternatives and identifying hotspots; the cited records were selected because they anchor carbon-footprint, food-system assessment and environmental-efficiency subtopics across fruit processing and storage, frozen desserts, fish value chains, and fresh fruit and vegetable markets [40–43]. Energy systems and renewable-cooling studies focus on decarbonizing the energy supply for refrigeration and storage, including hybrid refrigeration, photovoltaic and thermal-storage integration, and alternative cooling systems [8,10–12]. Packaging and thermal insulation studies address the interface between product protection and logistics performance, so phase-change-material packaging, electrospun thermal-management packaging, insulated box comparisons and passive preservation gels were cited as representative

product-logistics interface actions [5,44–46]. Inventory, planning and coordination studies examine joint decisions over stock levels, replenishment, preservation investment and carbon constraints; the cited records explicitly connect energy use with preservation effort, carbon regulation, pricing, inventory decisions, uncertainty and cost-sharing across actors [47–51]. Finally, value-chain collaboration, governance, review and framework papers make explicit the institutional conditions needed to transform isolated efficiency options into coordinated value-chain practices and synthesize broader cold-chain logistics trends, sustainability challenges, risk-management issues and conceptual frameworks for perishable cold-supply-chain management [7,52–54].

3.2. Cold-Chain Stages and Action Placement

Stage-level analysis shows that collaborative energy-efficiency actions are unevenly distributed across the cold chain. The strongest concentration is in transport and distribution, with 191 applied/action records. This is the stage where energy use, service commitments and inter-firm coordination are most visibly intertwined: routes, loads, delivery windows, temperature set-points and vehicle availability are rarely decided by one actor alone. Transport and distribution therefore becomes the natural locus for high collaboration intensity.

Cold storage and warehousing is the second major stage, with 100 records. It includes refrigerated warehouses, logistics cold stores, packhouses, distribution centres and storage rooms. Actions at this stage often focus on electricity use, equipment performance and temperature stability, but they also affect product quality, shelf life and the timing of downstream distribution. Multi-stage or whole-cold-chain studies, with 66 records, are especially important because they show that energy-efficiency decisions can shift impacts across stages: a packaging improvement may reduce transport losses, while a storage strategy may change inventory levels and delivery frequency.

Smaller stage classes are also informative. Packaging and product-logistics interface studies are fewer in number, but they are highly collaborative because packaging decisions influence producers, logistics providers, retailers and waste-management arrangements. Planning, inventory and network-level studies are also relatively few, yet they are among the most strategic because they determine how demand, service levels, replenishment and cold assets are coordinated across the value chain. This distribution suggests that the literature is strongest on operationally measurable stages and weaker on the upstream governance and planning decisions that often determine whether technical solutions can be implemented.

3.3. Collaboration Intensity

Collaboration intensity is concentrated in the middle and upper levels: 42 records are coded as low intensity, 168 as moderate, 142 as high and 56 as advanced. This distribution is important because it indicates that most cold-chain energy-efficiency actions cannot be understood as isolated technical fixes. They require at least some degree of information exchange, operational alignment or coordinated implementation across organizational boundaries.

Low-intensity actions are mainly local technical measures. They include some equipment upgrades, storage-room improvements or narrowly defined thermal-control interventions that can be implemented by a single warehouse operator, carrier or technology user. Moderate-intensity actions require actors to share information or align assessments: examples include monitoring systems, LCA-based decision support, renewable-cooling feasibility studies and coordinated temperature-management practices. High-intensity actions require changes in how the cold chain operates, such as routing redesign, packaging-service

alignment, synchronized delivery practices or cross-firm temperature-control routines. Advanced actions go further because they require joint investment, network redesign, contractual arrangements, preservation-cost sharing, carbon-related incentives or formal governance mechanisms.

This four-level distinction is not only descriptive. It helps interpret why some apparently promising measures are difficult to adopt. A low-intensity intervention may fail because the payback period is too long, but a high- or advanced-intensity intervention may fail even when the technical case is strong, because the actors who bear the cost are not the actors who capture the benefit. Collaboration intensity therefore works as a design variable: it tells managers and policy makers what kind of coordination infrastructure must accompany each action family.

3.4. *Actors and Evidence Types*

The actor matrix confirms that collaborative energy efficiency is a multi-actor problem. Logistics providers and carriers appear in 265 records, producers and processors in 243, retailers and customers in 223, and cold-storage or warehouse operators in 108. Technology, data or energy providers are also prominent, appearing in 104 records. Packaging suppliers, policy actors, decision makers and generic cold-chain actors appear less frequently but are important in specific action families. The evidence base is dominated by modelling, optimization and simulation (198 records), followed by reviews (74), LCA/assessment (41), case study/empirical work (40), technical/experimental work (27), mixed evidence (23) and conceptual/framework papers (5). This shows that the field is analytically strong but still needs more implementation studies, longitudinal cases and evaluations of cross-firm governance mechanisms.

3.5. *Source Characteristics and Detailed Action-Family Structure*

Table 7 is based on the subset of included records for which Web of Science affiliation metadata were available, because country and institutional-affiliation fields were not consistently available across all deduplicated Scopus and Web of Science records. Accordingly, the table is used to characterize publication outlets, evidence-type patterns and geographical/institutional signals in the available metadata subset; it is not intended to provide exhaustive country or institutional counts for the whole 466-record review corpus or the 408-record applied/action corpus. This limitation is reported explicitly to avoid over-interpreting the source-characterization results. Table 8 provides a more detailed view of the topics within each normalized action family. Similar source-characterization logic is common in bibliometric reviews of energy-related research fields [55].

The detailed action-family structure in Table 8 clarifies which subtopics are grouped inside each normalized family. This avoids treating broad families as homogeneous categories and makes visible the internal differences between, for example, cold-storage energy management, refrigeration-system optimization, thermal-storage solutions and renewable-cooling technologies.

3.6. *Benefits and Non-Energy Benefits*

Energy, fuel and electricity reduction is the expected benefit, but the review shows that it is rarely the only reason for action. In food cold chains, energy efficiency is closely linked to the ability to preserve value: maintaining temperature stability protects product quality, avoiding temperature abuse reduces waste, and improving logistics reliability prevents emergency shipments, rework and stockouts. For this reason, non-energy benefits are not peripheral outcomes; they often provide the business case that makes energy-efficiency investments acceptable to several actors at the same time.

The benefit profile differs across action families (Table 9). Transport-distribution actions combine fuel and emissions reductions with cost and service-level benefits. Refrigeration and cold-storage actions connect electricity reduction with temperature control, quality preservation and storage reliability. Digital monitoring actions are especially associated with traceability, decision support and food-loss prevention, because they improve visibility over deviations and allow faster corrective action. Packaging and insulation actions emphasize shelf-life extension and product protection, while inventory and planning actions link energy, emissions and cost performance through better coordination of demand, stock and delivery decisions.

Table 9. Selected benefit themes by action family. Counts are multi-label.

Action Family	Energy/Fuel/ Electricity	Emissions/ Environment	Cost/Economic	Quality/Shelf Life	Food Loss/Waste	Traceability
Transport, routing and distribution	93	112	94	67	22	3
Cold storage and refrigeration technology	57	19	39	32	25	1
Digital monitoring and information sharing	44	20	4	31	53	51
LCA, assessment and decision support	30	35	11	22	21	0
Energy systems and renewable cooling	34	23	18	7	9	0
Packaging and thermal insulation	24	22	0	31	29	0
Inventory, planning and coordination	18	23	24	17	13	0
Other/mixed action	8	5	4	2	6	0
Value-chain collaboration and governance	4	3	2	3	1	0
Review, framework or conceptual study	3	2	0	0	2	0

3.7. Barriers and Enabling Conditions

Implementation barriers vary by action family (Table 10), and this variation reinforces the need for differentiated managerial responses. Transport-distribution actions face coordination barriers because route changes, delivery consolidation and time-window adjustments influence several firms simultaneously. They also face operational uncertainty: traffic, demand variability, vehicle availability and temperature constraints make optimized plans difficult to execute exactly as modelled. Refrigeration and cold-storage technologies are more constrained by capital cost, payback uncertainty, technical validation and integration into existing facilities.

Digital monitoring depends on a different set of enablers. Sensors and platforms require common data definitions, interoperability, rules for data ownership, cybersecurity arrangements and shared routines for responding to alarms. Packaging and thermal-insulation actions require coordination between product design, logistics performance, return systems, recyclability and end-of-life management. Inventory, planning and governance actions depend most strongly on trust, data quality and mechanisms for sharing costs and benefits. These barriers suggest that implementation policy should not be generic: subsidies may be appropriate for capital-intensive cooling technologies, while standards,

data-sharing protocols and contractual templates may be more effective for digital and coordination-heavy actions.

Table 10. Selected barrier themes by action family. Counts are multi-label.

Action Family	Data/Interoperability	Coordination/ Governance	Investment/ Capital	Technical Validation	Operational Uncertainty	Not Reported
Transport, routing and distribution	38	56	62	30	54	13
Cold storage and refrigeration technology	2	4	48	41	30	12
Digital monitoring and information sharing	46	31	15	14	2	3
LCA, assessment and decision support	20	11	11	0	1	4
Energy systems and renewable cooling	0	0	29	22	16	4
Packaging and thermal insulation	0	18	18	18	1	3
Inventory, planning and coordination	9	24	3	0	16	2
Other/mixed action	0	6	4	0	0	2
Value-chain collaboration and governance	2	5	1	0	1	2
Review, framework or conceptual study	0	2	1	0	0	1

4. Discussion

4.1. From Isolated Energy-Saving Measures to Collaborative Energy Efficiency

The review shows that energy efficiency in food cold chains cannot be reduced to equipment-level energy savings. Refrigeration upgrades, insulation, phase-change materials and renewable cooling remain important, but many high-potential actions are embedded in logistics choices, product-flow decisions, service promises and cross-firm information exchange. In this sense, the food cold chain should be viewed as a distributed energy-efficiency system: energy is consumed at specific assets, but the drivers of that consumption are often created by decisions distributed across producers, processors, warehouse operators, carriers, retailers, technology providers and customers.

Collaborative energy efficiency therefore refers to the combination of technical measures, operating practices and governance arrangements that allow energy, emissions, food losses and quality risks to be reduced together. It also shifts attention from whether an isolated measure can save energy under controlled assumptions to whether a value chain can organize the data, incentives and responsibilities needed to realize cleaner outcomes in practice.

4.2. Collaboration Intensity as an Implementation Capability

The collaboration-intensity rubric is one of the main conceptual outputs of the review because it makes implementation requirements visible. Low-intensity actions can often be adopted within a facility, asset or firm. Moderate actions depend on information sharing and joint assessment. High-intensity actions require coordinated operating changes such as route redesign, packaging-service alignment, synchronized temperature-control practices or shared monitoring protocols. Advanced actions require contractual arrangements, joint

investment, cost/benefit sharing, network redesign or multi-actor governance. For energy-efficiency research, this distinction matters because technical potential and implementation feasibility are not equivalent. A technology with high theoretical savings may fail if the chain lacks the collaboration capability required to deploy it.

4.3. From Single-Benefit Savings to Multi-Benefit Energy Efficiency

The benefit matrix suggests that non-energy benefits are not secondary outcomes but central mechanisms through which energy efficiency becomes attractive in food cold chains. Quality preservation, shelf-life extension, food-loss prevention, traceability, reliability and decision support often provide the operational or commercial justification for energy-efficiency measures. This is particularly relevant in perishable supply chains, where the environmental benefit of lower electricity or fuel use can be offset if a measure increases spoilage, service failure or product rejection.

This changes how payback and performance should be evaluated. A narrow calculation based only on direct electricity or fuel savings may underestimate the value of digital monitoring, thermal packaging, preservation investment or coordinated logistics planning. Conversely, a measure that reduces emissions but increases food loss may not be cleaner at system level. Future energy-efficiency assessments should therefore integrate energy intensity, emissions intensity, food-loss prevention, quality outcomes and service reliability into a common multi-benefit logic.

4.4. Evidence Gaps and Contribution to Food Cold-Chain Energy-Efficiency Research

The corpus is dominated by modelling, optimization and simulation. These studies are valuable for identifying feasible improvements and exploring trade-offs, but they often assume data availability, actor compliance and implementability. The smaller number of empirical, longitudinal and governance-focused studies limits knowledge about realized savings, behavioral responses, adoption barriers, data-sharing arrangements and the allocation of costs and benefits. The main contribution of this paper is therefore to connect the technical and operational evidence base with an implementation framework for collaborative energy efficiency. The review shows where energy-efficient cold-chain actions are concentrated, what types of collaboration they require, which benefits they promise and which barriers must be addressed before they can move from modelled potential to realized performance.

4.5. Managerial and Policy Implications

Managerially, the findings suggest that firms should not select cold-chain interventions only by comparing technical energy-saving potential. They should first identify the action family, dominant stage, required collaboration intensity and likely distribution of benefits. Policy makers can use the same logic to design differentiated support instruments: financial incentives and risk-sharing instruments are most relevant for capital-intensive refrigeration, renewable-cooling and packaging actions; standards and interoperability rules are more relevant for digital monitoring; and collaborative platforms, contracts and governance mechanisms are essential for transport, inventory and network-level actions.

5. Action-Oriented Framework

Table 11 is the central integrative output of the review and the main action-oriented contribution of the paper. It translates the coded evidence into an energy-efficiency framework that links each action family to the cold-chain stages where it is most often applied, the collaboration intensity typically required, the benefits most frequently reported and the barriers most likely to constrain implementation. The table should be read as a decision-support structure rather than as a simple summary table.

Table 11. Action-oriented framework for energy-efficiency actions in the food cold chain derived from the coded applied/action corpus.

Action Family	Dominant Stage(s)	Dominant Intensity	Dominant Benefit Themes	Dominant Barrier Themes
Transport, routing and distribution	Transport and distribution (110); Other/unspecified stage (11)	High (80); Advanced (29)	Emissions (112); Cost (94); Energy (93)	Investment (62); Multi-actor coordination (56); Operational constraints (54)
Cold storage and refrigeration technology	Cold storage and warehousing (42); Transport and distribution (21)	Moderate (36); Low (25)	Energy (57); Temperature control (41); Cost (39)	Investment (48); Technical integration (41); Operational constraints (30)
Digital monitoring and information sharing	Transport and distribution (18); Multi-stage/whole cold chain (17)	Moderate (46); High (10)	Food loss (53); Traceability (51); Energy (44)	Data sharing (46); Multi-actor coordination (31); Investment (15)
LCA, assessment and decision support	Multi-stage/whole cold chain (27); Transport and distribution (4)	Moderate (32); Low (4)	Emissions (35); Energy (30); Quality (22)	Data sharing (20); Regulation (12); Multi-actor coordination (11)
Energy systems and renewable cooling	Cold storage and warehousing (29); Multi-stage/whole cold chain (2)	Moderate (27); High (5)	Energy (34); Emissions (23); Cost (18)	Investment (29); Technical integration (22); Operational constraints (16)
Packaging and thermal insulation	Transport and distribution (20); Cold storage and warehousing (6)	High (32); Moderate (1)	Quality (31); Food loss (29); Energy (24)	Multi-actor coordination (18); Investment (18); Technical integration (18)
Inventory, planning and coordination	Transport and distribution (12); Other/unspecified stage (7)	Advanced (20); High (6)	Cost (24); Emissions (23); Energy (18)	Multi-actor coordination (24); Operational constraints (16); Data sharing (9)
Other/mixed action	Multi-stage/whole cold chain (3); Other/unspecified stage (3)	Moderate (5); Advanced (4)	Energy (8); Food loss (6); Emissions (5)	Multi-actor coordination (6); Investment (4); User adoption (2)
Value-chain collaboration and governance	Multi-stage/whole cold chain (4); Transport and distribution (2)	High (3); Advanced (3)	Energy (4); Emissions (3); Quality (3)	Multi-actor coordination (5); Data sharing (2); Investment (1)

The framework distinguishes three implementation logics. The first is an asset-efficiency logic, typical of refrigeration, cold storage and renewable cooling, where technical performance, capital investment and integration into existing operations are central. The second is an operational-coordination logic, typical of routing, packaging and inventory planning, where cleaner outcomes depend on aligning decisions across firms. The third is an information-governance logic, typical of digital monitoring, LCA and decision-support actions, where data quality, interoperability and trust determine whether information becomes useful for energy efficiency.

For practitioners, the framework can be used before project selection. A firm considering a refrigeration upgrade can use it to anticipate investment and technical-integration barriers. A logistics provider considering route optimization can use it to assess whether customers can provide demand information and flexible delivery windows. A retailer considering traceability or IoT monitoring can use it to identify data-sharing and interoperability needs. A policy maker can use the same table to identify where subsidies, standards, pilots or collaborative governance mechanisms are most appropriate.

The practical implication is that energy-efficient cold-chain actions should not be selected on technical grounds alone. Transport, packaging and inventory actions may offer strong system-level benefits, but they also require higher collaboration capability. Digital monitoring can reduce waste and improve decision support, but only when data are shared and acted upon. Refrigeration and renewable-cooling technologies can reduce electricity demand, but adoption may be limited by capital cost and integration risk. The framework therefore helps match energy-efficiency ambition with the organizational capacity needed to implement it.

Overall, the framework indicates that collaborative energy efficiency is a staged capability-building process. Firms with limited inter-organizational integration may start with local asset-efficiency actions and measurement systems. As collaboration capacity increases, they can move toward shared monitoring, coordinated logistics planning, packaging redesign, joint investments and network-level optimization. This progression is central for turning energy-efficiency principles into implementable cold-chain strategies.

6. Conclusions

This systematic and bibliometric review consolidates the literature on energy-efficiency actions in food cold chains, with particular attention to refrigeration, refrigerated transport, cold storage, packaging, digital monitoring, renewable cooling and collaborative implementation. From 3930 records identified in Scopus and Web of Science, the review retained 466 full-text eligible studies and 408 applied/action records. The action-level synthesis shows that the literature is concentrated in transport distribution, refrigeration technology, digital monitoring, energy assessment and decision support, renewable cooling, packaging and inventory/planning.

The main contribution of the paper is an action-oriented framework that links energy-efficient cold-chain action families to stages, actors, collaboration intensity, benefits and barriers. The framework shows that energy efficiency, emissions reduction and food-loss prevention should be treated as connected energy-efficiency outcomes rather than isolated objectives. It also shows that implementation depends on the collaboration capability of the value chain. For researchers, the review identifies where empirical validation, metrics and governance research are most needed. For managers and policy makers, it provides a structured basis for selecting, sequencing and supporting energy-efficient cold-chain interventions.

7. Limitations and Future Research

The review has limitations that should be considered when interpreting the findings. First, the corpus is limited to English-language articles and reviews indexed in Scopus and Web of Science; relevant grey literature, technical standards, industry reports and non-English studies may therefore be underrepresented. Second, 145 potentially relevant reports could not be retrieved in full text. Third, the synthesis is based on record counts and coded themes rather than pooled effect sizes, because energy, emissions, cost, waste and quality outcomes are reported with heterogeneous methods and units. Fourth, collaboration intensity is an interpretive classification based on the implementation requirements reported or implied by each study; it should therefore be viewed as a structured analytical judgement rather than a direct measurement.

Future research should move from modelled potential to measured implementation (Table 12). The field has developed a strong base of models, simulations and technical assessments, but fewer studies measure realized energy savings, emissions reductions, food-loss prevention and operational performance after implementation. Longitudinal field studies, intervention studies and comparative case studies would help determine when modelled energy-efficiency potential is actually achieved.

Table 12. Future research agenda for food cold-chain energy-efficiency research.

Research Priority	Why it Matters	Illustrative Questions
Implementation and longitudinal evidence	The field is dominated by models and simulations, while realized savings and adoption processes are less visible.	Which actions deliver measurable savings in practice? Which organizational routines sustain them over time?
Cost, benefit and risk sharing	Collaborative actions often create chain-level value but uneven actor-level incentives.	Who pays, who benefits and which contractual mechanisms make adoption viable?
Integrated energy-quality-waste metrics	Energy savings may interact with shelf life, food loss, safety and service reliability.	How can studies measure energy, emissions, waste, quality and reliability in one consistent framework?
Digital and data governance	Monitoring and traceability require trust, interoperability and rules for acting on data.	Which data-sharing architectures and governance rules convert visibility into operational efficiency?
Context-specific cold-chain development	Low-resource settings face infrastructure, finance and access constraints that differ from mature cold chains.	Which collaborative business models support affordable cooling, renewable energy and food-loss prevention?

A second research priority concerns the allocation of costs, risks and benefits. Many energy-efficient cold-chain actions create value for the chain as a whole but distribute costs and benefits unevenly. Renewable cooling may require warehouse investment while benefits accrue to retailers or consumers; monitoring systems may require data disclosure by one actor and quality benefits for another; routing changes may reduce emissions but alter service commitments. Future studies should examine contracts, cost-sharing mechanisms, incentives and governance arrangements that make collaborative energy efficiency economically viable.

A third priority is the integration of energy, emissions, food-loss and quality metrics. Future work should develop comparable indicators such as kWh per kilogram handled, fuel use per delivered unit, CO₂-equivalent emissions per kilogram delivered, temperature-deviation indicators, shelf-life preservation and avoided food loss. Without shared metrics,

it remains difficult to compare action families or determine whether a measure is genuinely cleaner at system level.

A fourth priority is digital and data governance. IoT, blockchain, artificial intelligence and digital twins are increasingly visible in the literature, but their energy-efficiency value depends on interoperability, data ownership, cybersecurity, trust and decision rights. Future research should study how digital infrastructures can support real-time energy optimization, temperature-risk management, demand response, renewable integration and coordinated waste prevention across multiple actors.

Finally, more attention is needed to low- and middle-income contexts, smallholder supply chains and infrastructure-constrained settings. In these contexts, energy-efficient cold-chain development may require different action sequences, such as solar-powered cold storage, shared cooling infrastructure, simple monitoring systems, cooperative business models and public support for access to reliable cooling. Studying these contexts would broaden the energy-efficiency relevance of the field beyond advanced, data-rich supply chains.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en19174214/s1>, Supplementary File S1—Review protocol and coding framework; Supplementary File S2—PRISMA 2020 reporting matrix; Supplementary File S3—The complete record-level allocation.

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Appendix A. Database Search Strings

The review used two search strategies. Query A defined the main corpus; Query B was used as a collaboration sensitivity check. The same conceptual query was adapted to Scopus and Web of Science syntax.

Appendix A.1. Scopus Query A—Main Corpus

TITLE-ABS-KEY(("food cold chain" OR "food cold supply chain" OR "cold chain" OR "cold supply chain" OR "cold-chain logistics" OR "refrigerated transport" OR "refrigerated storage" OR "cold storage" OR refrigeration) AND (food OR agri-food OR fruit OR vegetable OR meat OR fish OR seafood OR dairy OR perishable*) AND (energy OR "energy efficiency" OR "energy consumption" OR "energy saving" OR "fuel consumption" OR electric* OR emission* OR carbon OR decarbon* OR sustainab*))

AND (LIMIT-TO(LANGUAGE,"English")) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re")) AND PUBYEAR < 2026.

Appendix A.2. Web of Science Query A—Main Corpus

TS=((("food cold chain" OR "food cold supply chain" OR "cold chain" OR "cold supply chain" OR "cold-chain logistics" OR "refrigerated transport" OR "refrigerated storage" OR "cold storage" OR refrigeration) AND (food OR agri-food OR fruit OR vegetable OR meat OR fish OR seafood OR dairy OR perishable*) AND (energy OR "energy efficiency" OR "energy consumption" OR "energy saving" OR "fuel consumption" OR electric* OR emission* OR carbon OR decarbon* OR sustainab*)); refined by English language, Article or Review, and publication years up to 2025.

Appendix A.3. Scopus Query B—Collaboration Sensitivity Check

TITLE-ABS-KEY(("food cold chain" OR "food cold supply chain" OR "cold chain" OR "cold supply chain" OR "cold-chain logistics" OR "refrigerated transport" OR "refrigerated storage" OR "cold storage" OR refrigeration) AND (food OR agri-food OR fruit OR vegetable OR meat OR fish OR seafood OR dairy OR perishable*) AND (energy OR "energy efficiency" OR "energy consumption" OR "energy saving" OR "fuel consumption" OR electric* OR emission* OR carbon OR decarbon* OR sustainab*) AND (collaborat* OR coordinat* OR integrat* OR "information sharing" OR "data sharing" OR "supply chain coordination" OR "value chain" OR inter-organizational OR interfirm OR partnership OR governance)) AND (LIMIT-TO(LANGUAGE,"English")) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re")) AND PUBYEAR < 2026.

Appendix A.4. Web of Science Query B—Collaboration Sensitivity Check

TS=((("food cold chain" OR "food cold supply chain" OR "cold chain" OR "cold supply chain" OR "cold-chain logistics" OR "refrigerated transport" OR "refrigerated storage" OR "cold storage" OR refrigeration) AND (food OR agri-food OR fruit OR vegetable OR meat OR fish OR seafood OR dairy OR perishable*) AND (energy OR "energy efficiency" OR "energy consumption" OR "energy saving" OR "fuel consumption" OR electric* OR emission* OR carbon OR decarbon* OR sustainab*) AND (collaborat* OR coordinat* OR integrat* OR "information sharing" OR "data sharing" OR "supply chain coordination" OR "value chain" OR inter-organizational OR interfirm OR partnership OR governance)); refined by English language, Article or Review, and publication years up to 2025.

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