



Jiayue Zhang

**Potential of Quantum Computing for supply chain
management:
A systematic literature review**

School of Management
Procurement and Supply Chain Management

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Supervisor: Dr Abhijeet Ghadge
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This thesis is submitted in partial fulfilment of the requirements for
the degree of Master of Management
(NB. Remove if the degree award is based solely on examination of the thesis)

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Academic integrity declaration

I declare that:

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- the thesis submitted has not been previously submitted to this university or any other.
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Abstract

Purpose: This study explores the transformative potential of quantum computing (QC) in supply chain management (SCM), addressing the growing complexity of logistics, operations, and security where classical optimisation methods reach their limits.

Research method: A systematic literature review (SLR) was conducted, covering studies from 2015–2025 in Scopus and Web of Science. Following PRISMA screening, 61 articles were analysed using descriptive mapping and thematic synthesis.

Findings: The review identifies a three stage, adoption pathway awareness, pilot projects, and integration, which driven by computational efficiency, enhanced security, scalability, and potential cost-effectiveness. Current applications concentrate on logistics, scheduling, inventory management, and quantum-secure systems, though most remain at proof-of-concept level. Adoption is constrained by technological immaturity, integration complexity, high costs, and skills shortages.

Contribution: The study consolidates fragmented insights into QC and SCM, develops a conceptual adoption framework linking drivers, barriers, and implementation stages, and provides theoretical and practical guidance for researchers, managers, and policymakers. It highlights QC's potential to improve efficiency, resilience, and sustainability of supply chains.

Limitations: The review is limited by the small pool of relevant literature, the dominance of conceptual and pilot-level studies, and the exclusion of grey and non-English sources. Sector-specific variations and technical-economic evaluations remain underexplored, requiring further empirical research.

Keywords:

Quantum computing, systematic literature review, conceptual framework, digital supply chains, supply chain management, logistics

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List of Abbreviations

AI	Artificial Intelligence
API	Application programming interface
CQM	Constrained Quadratic Model
EOQ	Economic order quantity
EPQ model	Economic production quantity model
ERP	Enterprise resource planning
IoT	Internet of Things
LSTM	Long short-term memory
MES	Manufacturing Execution System
PCSC	Prefabricated construction supply chains
PQC	Post-quantum cryptography
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QAOA	Quantum Approximate Optimization Algorithm
QC	Quantum Computing
QHB-QA	Quantum hybrid blockchain-based framework
QPSO	Quantum-Inspire particle swarm optimisation
QUBO	Quadratic unconstrained binary optimization
SCM	Supply chain management
SLR	Systematic literature review
VRP	Vehicle routing problem
WMS	Warehousing management system

1 Introduction

1.1 Background of the research

In today's globalized business environment, the complexity of supply chain management (SCM) is constantly increasing, and enterprises are facing unprecedented challenges (Chand et al., 2018; Wiengarten et al., 2017). From demand forecasting to inventory management, from transportation optimization to risk control, every link has a profound impact on the efficiency and competitiveness of enterprises (Wieland, 2021).

Quantum computers have broken the limitations of traditional computers in processing information. It no longer relies on a single 1 or 0 to store and process information but introduces a brand-new concept - qubits or "qubits". These qubits can be both 1 and 0 simultaneously, or even any probability state between these two values. This characteristic gives quantum computers an advantage that traditional computers cannot match when dealing with complex problems (Chae et al., 2024). This advantage is particularly evident in the field of logistics. Traditional desktop computers or supercomputers, although they can also optimize the supply chain process to a certain extent, often seem inadequate when facing the increasingly complex and changeable logistics environment. Quantum computers, with their powerful computing capabilities and unique processing methods, can optimize supply chain processes in real time and dynamically, achieving more precise and efficient logistics management (Niu et al., 2025).

1.2 Research gap

In recent years, quantum information technology has become the focus of attention in the field of science and technology for major countries around the world, tech giants and other parties (Alberts et al., 2021; Van Deventer et al., 2022). The 2022 Nobel Prize in Physics was awarded to research achievements related to quantum information science (Fedorov et al., 2023). The planning layout and investment support for the field of quantum computing (QC) have been further strengthened (Liman & Weber, 2023).

Literature review reveals that existing studies of QC in supply chains to date have still tilted towards routing optimization as an end-of-pipe delivery approach. Phillipson's (2025) most updated review categorises existing research findings into six categories: 'route planning, network design, fleet optimisation, loading, forecasting and scheduling'. An econometric analysis carried out in supply chain assembly building also found that terms such as 'vehicle routing' emerged much higher than 'inventory', 'demand forecasting', reiterating that more emphasis was placed upon midstream. That, far, lesser prominence was given to upstream sections (Z.-S. Chen et al., 2025). Additionally, research studies mainly focus on a single link and fail to take an end-to-end approach to examine the interlinkage among procurement, production, warehousing, and delivery, resulting in a non-comprehensive assessment of the potential QC impact on the entire value chain of the supply chain.

1.3 Research aim and objectives

This research aims to explore the transformative potential of QC in enhancing supply chain operations through advanced cognitive analytics. Given the growing complexity and dynamism of modern supply chains, traditional optimization methods often struggle with limitations in scalability, speed, and adaptability (Chaudhry et al., 2025). Quantum computing, with its superior computational capacity, offers a promising alternative to address these persistent challenges.

To guide the thesis research, the primary research question is formulated as follows:

What potential does quantum computing have in the application of supply chain management?

To address this central question, the research is structured around the following three objectives:

Objective 1: To conduct a comprehensive systematic literature review (SLR) on the current developments and applications of QC in the context of SCM.

Objective 2: To analyse the outcomes of the SLR by identifying implementation level, drivers, key barriers and potential application areas in applying QC across core SC functions.

Objective 3: To synthesize insights from Objectives 1 and 2 and develop a conceptual framework that captures the broader transformative potential of QC in SCM.

The first two objectives are primarily addressed through the systematic review and thematic analysis presented in Chapters 3 and 4. The third objective is fulfilled in Chapter 5, where the conceptual framework is proposed and evaluated based on the synthesis of key insights.

1.4 Potential contributions

This study makes several contributions to the field of supply chain research and the emerging discipline of QC applications. First, it provides a timely and structured systematic literature review that consolidates current knowledge on QC in supply chains, covering its application to production scheduling, inventory management, and transportation logistics. This addresses a clear gap in existing academic literature. Second, the research identifies technological trends and implementation barriers, offering a nuanced understanding of the practical challenges and enablers for integrating QC into supply chain operations. This critical analysis aids both scholars and practitioners in assessing the current readiness of the technology.

Third, by developing a conceptual framework, the thesis contributes theoretically to the intersection of supply chain innovation and quantum technologies. This framework can serve as a foundation for future empirical studies and strategic planning in digital and quantum supply chain transformation. Finally, the findings support informed decision-making for industry stakeholders and policymakers, highlighting key factors such as organizational readiness, environmental enablers, and the need for interdisciplinary collaboration.

1.5 Structure of thesis

This thesis is structured to progressively develop a comprehensive understanding of quantum computing in supply chain management. It begins with an introduction that establishes the research background, objectives, and contributions, followed by a systematic literature review that outlines the methodological approach and identifies relevant studies in Chapter 2. The subsequent Chapters 3 and 4 move from descriptive mapping of research trends to a thematic analysis that synthesises key drivers, barriers, and applications of quantum computing across supply chain domains, respectively. Building on these insights, a conceptual framework is proposed to capture the adoption pathway and future potential of the technology in Chapter 5. The thesis concludes by summarising the main findings, discussing theoretical and practical contributions, acknowledging limitations, and pointing to avenues for further research.

2 Systematic Literature Review

2.1 SLR process

To investigate the emerging intersection between QC and SCM, this study adopts a SLR methodology. The SLR approach is recognised for its ability to provide a structured, transparent, and replicable framework for literature analysis (Tranfield et al., 2003). It mitigates the subjectivity often associated with narrative reviews by relying on predefined protocols and criteria for study inclusion (Denyer & Tranfield, 2009). In SCM research, where technological domains such as AI, Blockchain, and now QC rapidly evolve, SLR has proven effective in consolidating fragmented knowledge (Chen et al., 2025; Durach et al., 2017; Queiroz et al., 2020).

Following the widely accepted three-stage model proposed by Tranfield et al. (2003), the review process comprises: identification of data sources, data screening and synthesis, and data analysis and dissemination. In the planning phase, the scope of the review was clearly defined to examine the potential contributions of QC to various SCM functions, such as optimisation, risk modelling, and logistics. A structured review protocol was developed to specify research questions, databases, search strings, and inclusion/exclusion criteria, thereby ensuring methodological transparency and replicability (Denyer & Tranfield, 2009; Seuring & Mueller, 2008). The adopted systematic literature review process follows three main steps, as shown in Table 1.

During the conducting phase, a comprehensive search was performed across databases such as Scopus and Web of Science using carefully designed Boolean strings. The process aimed to capture both peer-reviewed and grey literature, aligning with best practices for inclusive evidence identification (Ghadge et al., 2012; Kakhki & Gargeya, 2019). The screening process involved multiple rounds—first at the title and abstract level, and then full-text screening—guided by eligibility criteria defined in the protocol.

Data extraction and synthesis followed a thematic coding approach, allowing the identification of key themes such as quantum-inspired algorithms, supply chain

resilience, and complexity handling. While quantitative synthesis (e.g., meta-analysis) is often less applicable in nascent fields with heterogeneous data, qualitative synthesis—such as concept-centric and thematic analysis—has been recommended and adopted here (Webster & Watson, 2002).

The final stage focused on analysing and dissemination. Both descriptive and thematic analyses were employed to map research developments and highlight gaps. Reporting was designed to be accessible to both scholars and practitioners, reflecting calls for evidence-informed yet context-sensitive research (Starkey & Madan, 2001).

Overall, the application of SLR in this study enables a coherent synthesis of existing work on QC in SCM, a domain still in its infancy. By integrating insights across diverse studies, this review supports the development of a cumulative knowledge base and offers direction for future research and practical innovation (Aken, 2004; Campbell et al., 2003).

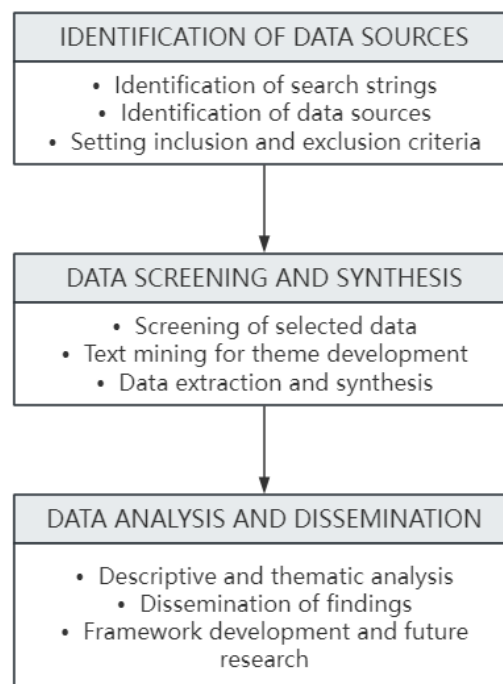


Figure 1. Systematic literature review process (Adopted from: Ghadge et al., 2012; Tranfield et al., 2003)

2.2 Identification of data sources

To capture the relevant literature on the potential applications of QC in SCM, a structured, two-tier keyword strategy was implemented. The search was conducted across two major academic databases: Scopus and Web of Science (WoS). Both of them are widely recognised for their comprehensive indexing of peer-reviewed literature in science, technology, and management (Carrera-Rivera et al., 2022; Mariani et al., 2023)

In the first stage, two primary keywords, “quantum computing” and “supply chain,” were selected to reflect the core focus of the study. These terms were combined using Boolean logic (e.g., “quantum computing” AND “supply chain”) to conduct the initial search. The results confirmed that research directly linking these two domains remains scarce, which is consistent with the early developmental stage of this interdisciplinary field (Ghadge et al., 2012).

To enhance the comprehensiveness of the review, a second set of extended keywords was derived through an analysis of the titles, abstracts, and keywords of the initially retrieved articles. These extensions reflect key areas within SCM where QC is likely to be applied or discussed. The complete list of search strings and logic used across Scopus and Web of Science is documented in Table 1, supporting transparency and future replicability. This structured process ensures that the review provides a robust foundation for analysing the intersection between QC and SCM across diverse research contexts.

Table 1. Choice of keywords

Key words	Secondary keywords
Quantum computing	“quantum”, “quantum computing”, “super computing”, “quantum annealing”.
Supply chain	“supply chain”, “logistics”, “value chain”.

2.3 Duration

The time frame for this systematic literature review was set from January 2015 to June 2025- decade long development in the field of computing.

This sharp increase reflects both the technological advancements in QC and its growing recognition as a tool for solving complex supply chain problems such as routing, scheduling, and optimisation. The chosen time frame aligns with common practice in technology-focused SLRs, where the review window is deliberately positioned to capture the period of rapid growth (Queiroz et al., 2020; Wang et al., 2019). Furthermore, including studies up to June 2025 ensures the inclusion of the most recent developments, including early-access publications. Accordingly, this timeframe offers a balanced view of the research landscape—broad enough to capture key developments, yet recent enough to reflect the current state and trajectory of the field.

2.4 Inclusion & exclusion

To ensure the methodological rigour and relevance of the dataset, this study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2015) to guide the literature screening process. The procedure comprised four main stages: identification, screening, eligibility assessment, and final inclusion. Each stage was conducted with predefined inclusion and exclusion criteria to systematically narrow down the literature to those studies most aligned with the research objectives—exploring the potential of QC in SCM.

The initial identification stage involved querying two major academic databases—Scopus and Web of Science (WoS)—using carefully constructed Boolean search strings combining primary keywords and secondary terms. This search yielded 1,332 articles from Scopus and 497 articles from WoS, resulting in a total of 1,829 records. After the removal of duplicate entries, 842 unique records were retained for further analysis.

In the screening stage, the titles, abstracts, and keywords of the 842 articles were manually reviewed. The purpose of this step was to assess each paper's preliminary relevance to the research domain. Articles were excluded if they (1) were not written in English, (2) lacked accessible full texts, (3) fell outside the publication window of January 2015 to June 2025, or (4) did not show a meaningful intersection between QC and SCM. Additionally, grey literature—

such as conference papers, book chapters, theses, white papers, and non-peer-reviewed sources—was excluded to maintain academic quality and replicability (Ghadge et al., 2012; Seuring & Mueller, 2008). This phase resulted in 408 articles that were retained for eligibility assessment.

At this stage, the full texts of the remaining 408 studies were examined in detail. Each article was evaluated for methodological robustness, conceptual alignment with the review topic, and contribution to either theory development or practical SCM problem-solving through QC. A total of 196 articles passed this in-depth review. Studies were excluded if they lacked clear methodological structure, were purely technical without SCM context, or mentioned SCM only peripherally without substantive treatment.

In the final inclusion stage, a comprehensive quality assessment was conducted. Studies were appraised based on research design, data analysis, theoretical grounding, and relevance to practical or strategic SCM applications. Emphasis was placed on studies that engaged with real-world supply chain issues—such as inventory optimisation, production scheduling, or routing—through QC techniques (e.g., QAOA, quantum annealing, quantum-inspired heuristics). Following this process, 61 articles were selected for inclusion in the final synthesis.

This multi-tiered filtering and quality assurance process ensured that only the most relevant, credible, and high-quality literature was retained. The overall selection flow is illustrated in the PRISMA diagram (Figure 2), offering a transparent overview of the inclusion logic and final article count.

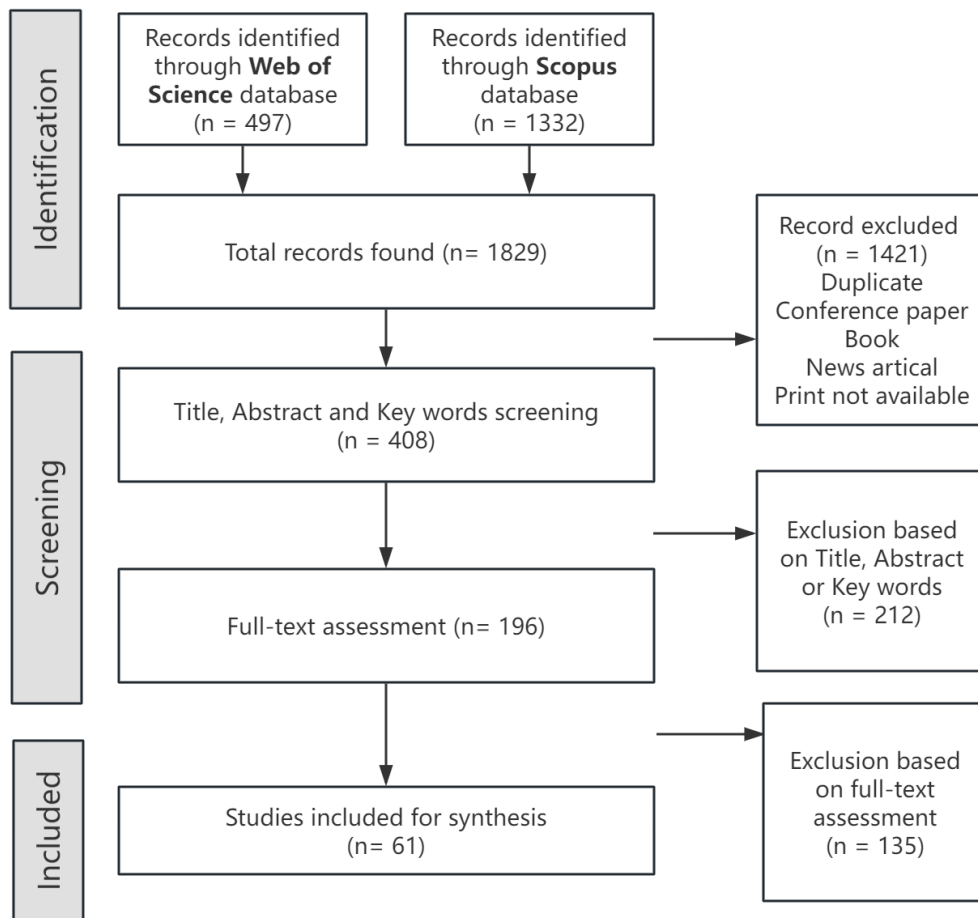


Figure 2. PRISMA flow diagram

The 61 final articles included in this review can be categorised into three major thematic clusters based on their focus and content.

3 Descriptive Analysis

3.1 Year-wise distribution

Figure 3 shows the distribution of the 61 selected articles by publication year. Between 2015 and 2019, research output in the field remained minimal, with only 2 articles published each year. From 2020 onwards, there was a noticeable surge, culminating in a sharp rise in 2023 and 2024. This shift corresponds with technological advancements in QC (MacQuarrie et al., 2020; Mansoor et al., 2025) . It also reflects the growing interest in applying quantum methods to solve complex supply chain problems(Gill et al., 2022). Meanwhile, over 90% of the articles were published after 2015, indicating a clear acceleration of research interest in this interdisciplinary field during the past decade(Z.-S. Chen et al., 2025).

The publication peak in recent years also aligns with the availability of quantum simulators and early-access quantum hardware platforms, which enabled researchers to test and validate quantum algorithms beyond theoretical models(Ajagekar et al., 2020). This trend confirms that QC in SCM is no longer a purely conceptual topic—it has evolved into a rapidly expanding research frontier with increasing technical feasibility.

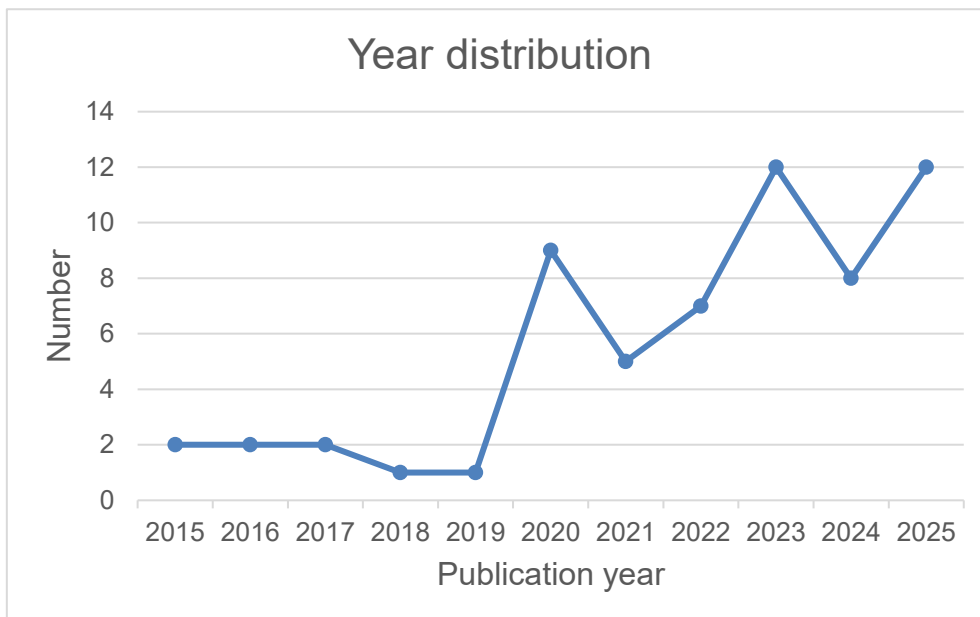


Figure 3. Year distribution

3.2 Regional distribution

As shown in Figure 4, China leads with 15 publications (24.6%), reflecting strong national investment in quantum research and digital supply chain transformation. The United States follows with 8 studies (13.1%), supported by robust research infrastructure and industry-academic partnerships. India ranks third with 7 articles (11.5%), suggesting rising engagement in applying advanced computing to SCM.

The UK (5 articles), Australia (4), and Spain (4) also show moderate research activity. Countries such as Germany, Saudi Arabia, and South Korea contributed two publications each. The remaining 15 countries—including Brazil, Canada, Singapore, and France—each contributed one article, indicating broader but more dispersed international interest.

The concentration of research in a handful of countries suggests that QC-SCM integration is driven by national strategies, funding priorities, and technical capabilities(Orús et al., 2019). While global representation exists, the field remains regionally imbalanced, with innovation efforts primarily led by a few technologically advanced economies(Núñez-Merino et al., 2024).

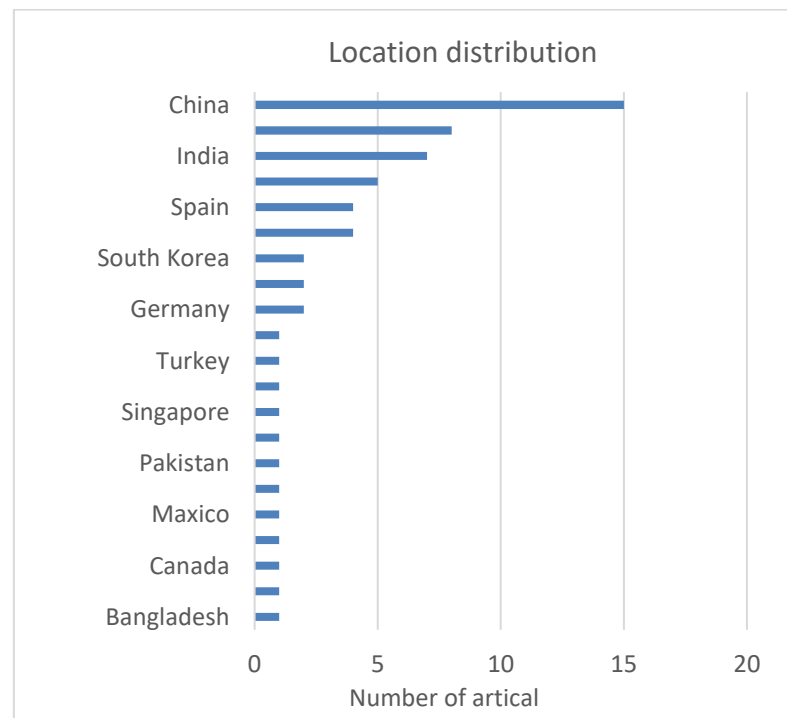


Figure 4. Location distribution

3.3 Research methods

The methodological composition of the reviewed studies reveals a balanced use of diverse research approaches. As shown in Figure 5, 41% of the studies (n=25) employed mixed-method designs, reflecting an integrative tendency to combine conceptual insights with structured evidence. This suggests that researchers increasingly recognise the value of drawing on multiple methodological traditions to explore the complex intersection of QC and SCM.

Quantitative studies accounted for 31% (n=19), often characterised by structured hypothesis testing, numerical analysis, and the use of predefined datasets or formalised indicators. These studies tend to adopt a positivist stance, aiming to generalise findings through measurable outcomes and replicable procedures, often using simulated or benchmark scenarios.

By contrast, qualitative studies (28%, n=17) typically engaged with exploratory questions and interpretive reasoning. These works often drew upon conceptual frameworks, expert opinions, or literature-based thematic synthesis to assess readiness, strategic alignment, or implementation barriers in QC adoption. Rather than generalisation, the emphasis was placed on depth of understanding, contextual interpretation, and theory development.

This methodological distribution enhances the inherent complexity and interdisciplinary nature of research at the intersection of QC and SCM. The presence of distinct yet complementary methodological approaches—quantitative, qualitative, and mixed—reflects the field's evolving demands to address both abstract theoretical constructs and context-specific operational challenges.

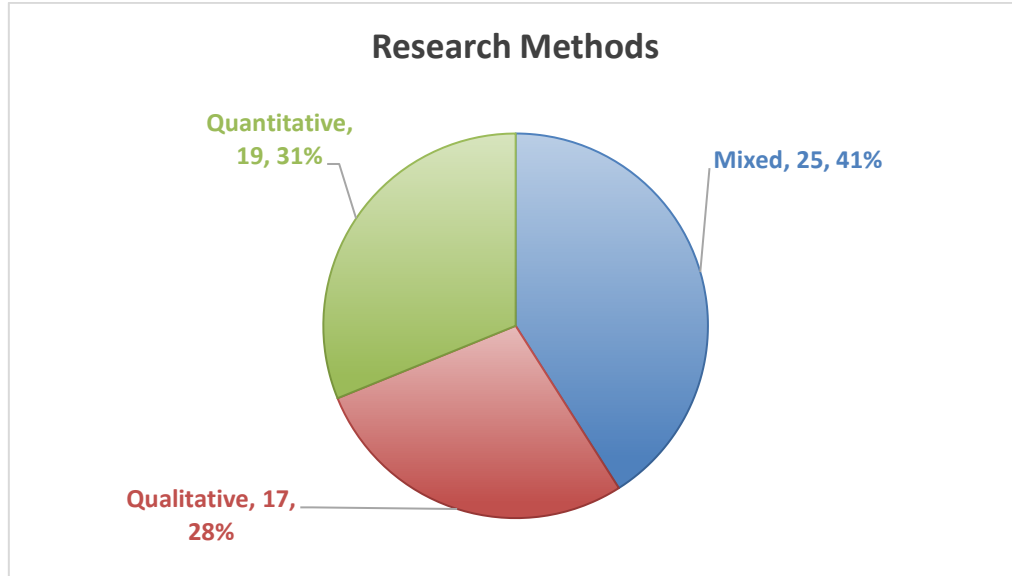


Figure 5. Research methods

3.4 Keyword frequency

To further uncover thematic trends in the reviewed literature, keyword frequency analysis was conducted using both visual and quantitative methods. As illustrated in Figure 6, the word cloud highlights the prominence of terms that frequently appeared across the 61 selected studies. The term “quantum computing” overwhelmingly dominates the landscape, reflecting the core technological foundation shared across all studies. This is followed by “optimization” and “quantum annealing”, which suggest a strong research focus on computational problem-solving techniques and specific quantum algorithms used for supply chain applications.

The presence of “logistics” as the fourth most frequent keyword indicates that logistical operations remain a central area of exploration within quantum supply chain research. Additionally, terms such as “combinatorial optimization”, “Ising model”, and “vehicle routing problem” point to recurring interest in addressing complex decision problems using quantum-inspired methods.

“Quantum cryptography” also appears among the top eight, reflecting emerging concerns about security, especially in the context of digitally connected and data-sensitive supply networks. This hints at a growing awareness of the need to

traditionally considered computation-intensive and thus well-suited for quantum-enhanced algorithms (Ajagekar et al., 2020; Niu et al., 2025). The emphasis on digitalisation and sustainability signals a growing awareness of QC’s role in enabling greener, smarter, and more traceable supply networks through advanced simulations and low-energy computing paradigms.

The Manufacturing & Operation perspective accounts for 7 studies, often focusing on production sequencing, scheduling, and factory-level resource allocation (Z.-S. Chen et al., 2025; Fedorov et al., 2023). These works explore how QC could offer performance gains over classical heuristics under conditions of complexity and uncertainty.

In contrast, Demand & Supply Planning remains underrepresented with only 3 studies. This gap suggests an opportunity for future research to investigate how QC might support probabilistic demand forecasting or dynamic network reconfiguration—especially in volatile markets (Gill et al., 2022).

The Other category (6 studies) includes those with cross-functional or theoretical contributions that do not fit neatly within a single operational domain but are still relevant to overall supply chain transformation.

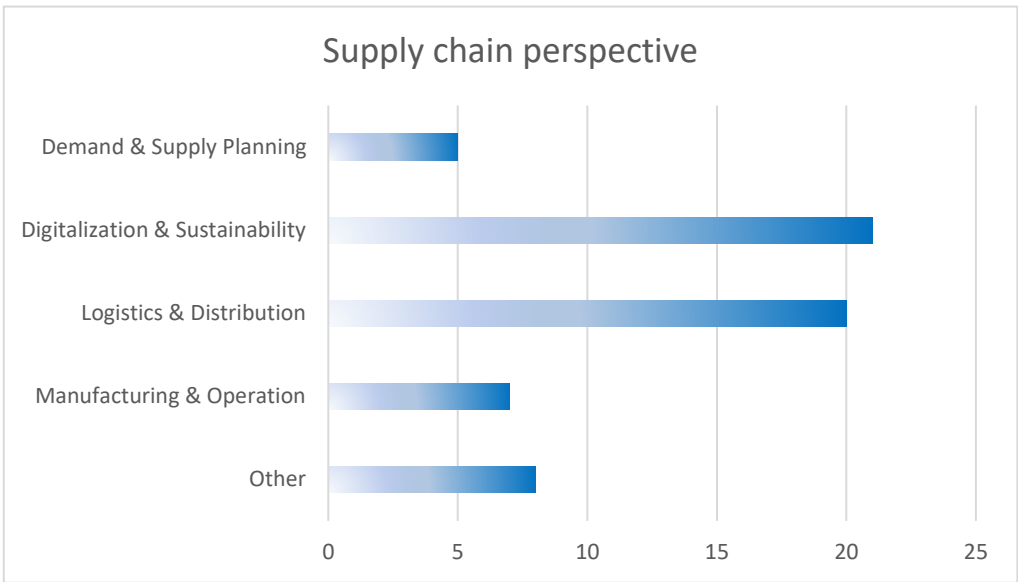


Figure 7. Supply chain perspective

4 Thematic Analysis

The thematic analysis presents the detailed interpretive findings on the potential of QC in SCM (Ghadge et al., 2023), as organised in the typology shown in Figure 8. This chapter focuses on tracing the implementation pathway of QC in SCM, synthesising quantum-technology drivers, delineating key barriers and challenges, and mapping current and prospective application domains across the supply chain.

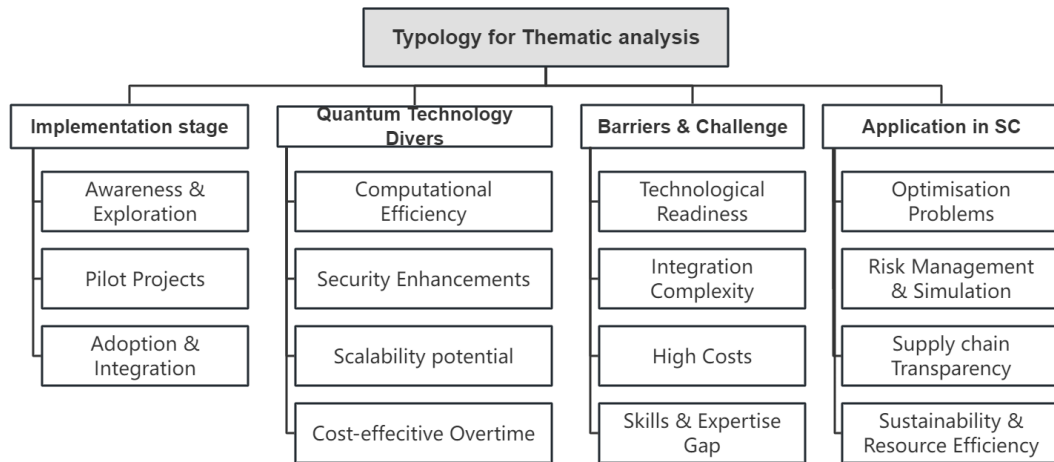


Figure 8. A framework for thematic analysis

4.1 Implementation level

This subsection outlines the pathway through which QC enters supply-chain practice. As indicated in Fig. 8, three stages—awareness & exploration, pilot projects, and adoption & integration—are characterised, with typical decision gates, governance mechanisms, resource requirements, and feedback loops that condition progression toward routinised use.

4.1.1 Awareness & Exploration

The awareness and exploration phase is characterized by theoretical modelling, early algorithm development, and the conceptual alignment of supply chain problems with quantum-compatible formulations. At this stage, the emphasis is not on direct implementation but on systematically identifying supply chain

challenges where quantum acceleration may offer meaningful benefits and clarifying how these challenges correspond to the evolving capabilities of quantum technologies (AbuGhanem, 2025; Maddikunta et al., 2022). A major research thrust in this phase is centred on combinatorial optimization problems, which are ubiquitous in supply chain settings (e.g., vehicle routing, multimodal network flow and inventory coordination). These problems are usually NP-hard, and the complexity increases rapidly, making it hard for traditional heuristics and meta-heuristics to balance solution quality and computational efficiency. Recently, in the context of quantum-compliant frameworks, we have explored revisiting network flow and routing problem characterizations using reformulated representations to possibly loosen the constraint-heavy nature of these problems (Ariño Sales & Palacios Araos, 2023; Niu et al., 2025). Likewise, routing analysis in urban distribution settings has shown that the mature methods are limited when the system becomes dynamic and suggested that quantum-enhanced frameworks rooted in annealing/adiabatic paradigms appear to be useful options for better adaptability and convergence (Pooja & Sood, 2025; Vu et al., 2023).

Beyond logistics and routing, this stage also engages with complex inventory and production planning problems under uncertainty. Models incorporating demand elasticity, deterioration, payment delays, and probabilistic variability highlight the nonlinear and multi-dimensional characteristics that render these problems computationally demanding (Ruidas et al., 2020; Shaikh et al., 2018). While still addressed using classical optimization, their structure aligns well with the mathematical forms that quantum and hybrid quantum-classical solvers are designed to tackle, marking them as suitable candidates for future quantum-based experimentation (Z. Chen & Sarker, 2017).

At a broader level, recent syntheses situate these advances within the wider trajectory of supply chain digitalization. Integrating QC with parallel developments in IoT, AI, and cyber-physical systems aligns with visions of autonomous, data-driven, and decentralized supply networks (Maddikunta et al., 2022). Concurrently, hardware-oriented assessments detail the constraints imposed by limited qubit counts, error rates, and noise, reinforcing the need for hybrid

evaluation strategies during this early stage (AbuGhanem, 2025). Reviews of annealing techniques and hybrid methodologies similarly underscore the importance of embedding quantum components into classical workflows to ensure realistic and incremental progress (Ajagekar et al., 2020; Hauke et al., 2020).

Initial research suggests that combinatorial optimization problems are intrinsically suited to quantum approaches, including annealing and hybrid quantum-classical techniques, which could provide a powerful channel out of the bounds of classical heuristics. Furthermore, the incorporation of QC as part of the general digitalization of supply chains serves ongoing evolution progress in AI, IoT, and Cyber-Physical systems advances to draw towards visions surrounding autonomous data-driven networks. Most importantly, this phase links theoretical quantum models to practical supply chain applications conceptually and methodologically, serving as an enabler for transforming decision-making, agility, and resiliency with the latest in SCM for the fast-changing.

4.1.2 Pilot projects

Pilot project initiatives serve as a critical transitional phase from conceptual awareness to practical adoption, enabling organizations to validate QC applications under semi-controlled or real-world conditions. These initiatives often highlight the feasibility, performance advantages, and early-stage limitations of quantum techniques in solving specific supply chain optimization problems.

The prevailing design pattern is a hybrid pipeline: large combinatorial instances are decomposed into tractable subproblems, quantum components are invoked as accelerators within classical workflows, and outputs are validated via simulation or digital twins so that solver behaviour can be read in operational terms (Ariño Sales & Palacios Araos, 2023; Weinberg et al., 2023). This architecture acknowledges the constraints of the current hardware generation while enabling disciplined comparisons against established baselines in representative supply chain settings (Liao et al., 2025).

A core theme in these pilots is resource-aware feasibility. For vehicle-routing problems with time windows and heterogeneous constraints, qubit-efficient formulations enlarge the class of instances that can be exercised on noisy intermediate-scale devices, while preserving rigorous head-to-head evaluations with strong classical heuristics (Leonidas et al., 2024). Complementary lines of work propose alternative formulations to navigate hardware limits—e.g., approaches designed for restricted connectivity or depth—that broaden the pilot design space without overcommitting to a single hardware trajectory (Gautam & Ahn, 2024). Beyond routing, early implementations extend to network-flow structures, where hybrid annealing workflows are benchmarked against classical methods on multicommodity flow to examine solution quality and time-to-solution trade-offs germane to logistics planning (Niu et al., 2025).

They provide proof-of-concept for computational acceleration as a whole, but they also illustrate important practical challenges, such as the limitations of hardware technology and algorithm calibration in addition to domain-specific formulations. Therefore, pilot projects should be seen as more than technical pilots but also serve as critical prerequisites to scaling up the technology and making strategic investments and capability development in new quantum-integrated supply chains.

4.1.3 Adoption & Integration

The adoption and application of QC into SCM represent a crucial dissemination point, where prior theoretical capability now converts to operational routine. This has reached a stage where enterprises are not simply exploring quantum solutions in abstract terms, but actually integrating them with foundational supply chain operations like logistics optimization, production scheduling and cybersecurity.

A dominant theme is the deployment of quantum-enhanced algorithms in solving logistics routing and scheduling problems, which are notoriously difficult due to their combinatorial complexity. Quantum annealing and variational quantum approaches have been successfully integrated into SCM workflows to address vehicle routing and task sequencing. For example, Azad et al. (2023)

implemented the Quantum Approximate Optimization Algorithm (QAOA) on IBM Qiskit to solve vehicle routing problems (VRP), demonstrating that quantum-classical hybrid solvers can compete with classical methods in real scenarios. Similarly, Bożejko et al. (2025) developed an exact hybrid scheduling algorithm combining branch-and-bound with quantum annealing on the D-Wave platform, significantly improving efficiency in delay-sensitive task scheduling. Complementing these, Osaba et al. (2024) explored quantum annealers to address real-world delivery constraints, confirming quantum models' applicability in operational logistics planning.

Beyond optimization, integration efforts are extending into the digital backbone of supply chain operations, particularly in ERP systems and data security infrastructures. As QC threatens classical cryptographic standards, organizations are beginning to implement post-quantum cryptographic protocols to safeguard supply chain data and digital transactions. Lin & Lin (2025) proposed the NSEA ERP architecture, integrating CRYSTALS-Kyber encryption and neuro-symbolic AI to enhance real-time resilience and decision automation in SCM. Likewise, Zhang et al. (2025) presented a quantum hybrid blockchain-based framework (QHB-DA) for ensuring data authenticity in Industry 4.0 supply chains, combining quantum-proof cryptographic signatures with blockchain traceability.

Integration is also occurring in sector-specific contexts such as prefabricated construction supply chains (PCSC). In this domain, QC is being explored to optimize the coordination of modular components, materials, and scheduling flows. Chen et al. (2025) examined PCSC environments and identified quantum-enhanced scheduling and logistics synchronization as promising levers to address fragmentation and complexity. Their findings highlight the potential for QC to reshape logistics-heavy, highly modular industries.

Another strategic driver for adoption is the pursuit of sustainability and green transformation within supply chains. As digitalization and decarbonization efforts converge, QC is being introduced not only to accelerate computation but also to reduce environmental inefficiencies. When Feng et al. (2022) pointed out that

quantum-enabled logistics and planning systems can indirectly cut emissions by saving energy of computational workloads and optimizing the delivery route in accordance with environmental constraints. Such applications are consistent with the ever-growing calls for your company to take greater responsibility in environmental matters. Again, besides those functional advantages, quantum-inspired optimization techniques So digitalization and the popularization of QC are closely related to this problem. have been applied in inventory and production systems. Take the Quantum-Inspire Particle Swarm Optimisation (QPSO) approach for example, which applies to perishable goods with time-dependent demand structure inventory management. Using quantum-inspired ideas, Chandra Das et al. (2020) designed an inventory model that combined new preservation technology with dynamic pricing to bring about an improvement in seconds- thinks actions. Similarly, Ning et al. (2016) demonstrated a dynamic quantum-added job-shop scheduling strategy adaptive to production constraints and fluctuating job priorities stalwarts in Industry 4.0 supply chains.

The adoption and integration phase is a critical inflection point from theoretical promise to practical reality, where QC has been shown in action impacting SCM. Logistics routing, scheduling, and inventory planning all have applications that show QC can solve the combinatorial bottlenecks with which classical methods struggle; integration into ERP systems, as well as in cybersecurity and blockchain implementations, secures digital infrastructure from newfound threats. Application in sectors like prefabricated construction highlights the QC's importance in aligning modular flows and green supply chain goals. Still, these moves are stymied by hardware limitations and hybrid model dependence. Importantly, this phase represents far more than just technical advancement; it also serves as foundational proof that QC is able to unlock efficiency gains, resilience, and agility. These attempts can address their inherent complexity and allow for pan-industry adoption at scale.

4.2 Quantum Technology Drivers

This subsection explains the technology-led incentives for QC in supply-chain management. Four drivers—computational efficiency, security enhancements,

scalability potential, and long-run cost effectiveness—are synthesised and linked to prevalent problem classes, indicating where near-term value is most plausible and which use cases attract early trials.

4.2.1 Computational efficiency

Computational efficiency factors mainly concern the use of quantum and quantum-inspired methods to accelerate otherwise intractable optimization subroutines that underpin routing, inventory, and production decisions. In last-mile logistics, hybrid annealing studies consistently report meaningful latency reductions: Ariño Sales & Palacios Araos (2023) decompose each vehicle tour into a ~2,500-variable QUBO solved on D-Wave’s hybrid engine, with best instances improving total travel distance by 4–7% relative to a tuned classical guided-local-search baseline. Similar patterns are reported in cross-dock routing (Weinberg et al., 2023), and in network-flow design, where Niu et al. (2025) show that a gate-model QAOA variant returns feasible multi-commodity assignments 35% faster than a tabu-search benchmark at identical solution quality.

Beyond routing, quantum heuristic innovation is apparent in inventory and scheduling meta-heuristics. Shaikh et al. (2018) embed quantum-behaved particle-swarm updates into a deteriorating-item EOQ model, halving convergence iterations; Ruidas et al. (2020) extend quantum-inspired swarms to dynamic pricing and carbon-tax settings, again reporting double-digit runtime gains. In scheduling, Ghosh et al. (2022) adapt ant-colony pheromone updates to qubit superposition states to achieve near-optimal flow-shop make spans within NISQ limits, while Leonidas et al. (2024) and Gautam & Ahn (2024) demonstrate qubit-efficient and path-integral formulations of the VRP that maintain solution quality under ≤ 100 -qubit budgets.

Critically, almost all efficiency studies pre-filter or cluster real data to fit present hardware, and many measure improvement against legacy heuristics rather than modern mixed-integer-programming baselines. Nonetheless, consistent signals across warehouse inbound batching (Gibbons et al., 1994), order-picking (Jung & Choi, 2021), location–routing hyper-heuristics (Zhao et al., 2020), and backorder forecasting via a hybrid quantum LSTM (Jahin et al., 2023) indicate that NISQ-

era hybrids can already deliver targeted acceleration for combinatorial sub-modules when embedded inside classical pipelines. Thus, the managerial question shifts from whether quantum accelerates raw solvers to how workflows are architected so that subroutine-level speedups cascade into end-to-end lead-time or throughput gains.

4.2.2 Security enhancements

Security enhancement factors mainly include cryptographic obsolescence risk and the corresponding design of quantum-safe protocols for supply-chain data integrity. Öztürk & Yildizbaşı(2020) identify blockchain adoption barriers—cost, technical skill, and regulatory ambiguity—that QC may exacerbate by increasing the risk of cryptographic obsolescence, while Koh et al.(2020)position transport blockchains as “trust mediators” that will ultimately require quantum-safe consensus once Shor-capable devices emerge. Technical pathways are elaborated in specialist work: Commey et al.(2024) review quantum-resistant hash-based signatures for IoT gateways; Mansoor et al.(2025)prototype lattice-based key exchange on constrained micro-controllers and find <15% handshake-latency overhead—tolerable for logistics telemetry; and Chaudhry et al.(2025) propose zk-DASTARK to extend zero-knowledge rollups with quantum-secure proofs for oracle integrity in smart contracts, reconciling shipping, customs, and insurance data.

At the same time, none of these studies demonstrates end-to-end deployment within a live logistics network; evidence remains simulation-centric or uses synthetic traffic. Cheung et al. (2021) caution that quantum-enhanced attackers may weaponize Grover-style search to accelerate route manipulation or inventory spoofing, implying that offensive and defensive capabilities will rise in tandem. Commercial analyses echo this dualism, arguing that vendor roadmaps should synchronize PQC migration with optimization pilots to avoid an “asymmetric-risk gap” (MacQuarrie et al., 2020; Naik et al., 2025). Thus, while less empirically mature than efficiency, security appears strategically time-sensitive: organizations that delay PQC retrofitting risk creating architectural dead-ends in which optimization gains are offset by expanded threat surfaces, underscoring

the need to move from conceptual frameworks to controlled field trials that quantify latency, bandwidth, and cost overheads of quantum-secure SCM communications.

4.2.3 Scalability potential

Scalability factors mainly refer to extending quantum advantage across multi-layer, network-wide supply chains by aligning problem encodings, orchestration strategies, and workforce/tooling readiness. A taxonomy mapping problem classes to qubit requirements projects that ~1,000-qubit error-mitigated devices can support regional routing portfolios, while ~10,000-qubit error-corrected platforms could enable simultaneous global optimization across sourcing, production, and distribution layers (Gill et al., 2022). These abstractions are grounded in algorithmic advances: VRP encodings can be compressed to $O(n \log n)$ qubits (Leonidas et al., 2024), and path-integral relaxations permit gradual qubit-budget scaling without loss of solution quality (Gautam & Ahn, 2024).

From the software angle, a fuzzy AHP survey ranks industrial pain points and finds software tooling and skills gaps outrank hardware access as perceived bottlenecks (AbuGhanem, 2025), a result corroborated by workforce-reskilling evidence that calls for curricula integrating operations research and quantum information science (Li, 2024). An algorithmic bridge with an adiabatic schedule-path optimizer shows runtime growing sub-linearly with qubit count, supporting hierarchical decomposition in full-scale SCM models (Zeng et al., 2016). Domain-specific work confirms partial scaling via partitioning: QAOA-based sub-optimizations iterate over progressively larger subnetworks for transport-network design (Dixit & Niu, 2023), and quantum-inspired tabu search scales warehouse-layout generation to >10,000 SKU positions by delegating local-search kernels to a 57-qubit emulator (Núñez-Merino et al., 2024). Yet qubit quality, interconnect topology, and error-correction overhead remain formidable barriers, and laboratory success may degrade under production noise (Fauseweh, 2024).

Breaking down the billion into qubit-efficient encodings, using hierarchical decomposition and quantum-inspired heuristics suggests such scaling up from local routing tasks to global sourcing-production-distribution orchestration should

be theoretically feasible. Yet workforce readiness and software tooling gaps currently eclipse hardware accessibility as real-world bottlenecks, suggesting that both technological breakthroughs are on par with organizational capability development. Although algorithmic improvements like scaling runtime sub-linearly and utilizing hybrid partitioning provide stepping stones to full-scale SCM integration, sustained difficulties in qubit quality, error correction, and noise mitigation limit the short-term applicability.

4.2.4 Cost-effective overtime

Cost-effectiveness and sustainability factors mainly concern whether quantum-accelerated methods translate simulated efficiency gains into economic value and emissions reduction over time. In logistics decarbonization, digital-twin initiatives have been linked to quantum-accelerated routing, suggesting that an 8% logistics-emission cut could yield multimillion-dollar carbon-tax savings on a European trade lane (Sarkis et al., 2020); modelling of Chinese freight VRPSDP shows that quantum-accelerated runs reach identical emission targets with 12% fewer vehicles (Ning et al., 2016); and in low-carbon multi-depot CVRPs, hybrid quantum heuristics reduce fuel cost by ~9% under large-scale backhaul scenarios (Huang et al., 2024). Inventory-centric studies offer additional economic signals: quantum-inspired EPQ models have been shown to lower combined production and holding cost across variable-price settings (Ruidas et al., 2020), and a green-production extension indicates that carbon-subsidy savings can amplify ROI under carbon-pricing regimes (Ruidas et al., 2023). Quantum LSTM backorder-prediction supports leaner safety-stock policies, cutting working capital by up to 6% (Emu et al., 2025). In warehouse automation, studies on inbound batching (Paul et al., 2021) and order-picking robots (Queiroz & Fosso Wamba, 2024) suggest labour-hour savings when quantum search accelerates task sequencing.

However, few studies provide full total-cost-of-ownership models; capital expenditure on quantum cloud credits, integration middleware, and specialist staff is frequently omitted, as are risk-adjusted discount rates for technology obsolescence. The need for stochastic ROI models that incorporate declining

qubit-hour prices and evolving carbon levies has been highlighted (MacQuarrie et al., 2020). Early hybrid trials suggest that tactical deployment—such as late-cut routing or daily stock-level re-optimization—may pay back within three operating cycles (Weinberg et al., 2023), but hard financial data remain scarce. Thus, preliminary simulations indicate cost and sustainability upside, yet rigorous longitudinal dashboards and end-to-end digital twins—capturing fuel burn, labour, inventory, and compliance costs—are needed to convert theoretical efficiency into CFO-ready ROI narratives.

4.3 Barriers

This subsection delineates the constraints limiting diffusion of QC in supply-chain contexts. Key challenges include technological readiness, integration complexity, high costs, and skills and expertise gaps. These are treated as socio-technical and organisational factors that shape both the pace and the pattern of adoption.

4.3.1 Integration complexity

The current QC stack for SCM is fragmented across hardware paradigms and rapidly evolving software layers, which complicates end-to-end integration from modelling to execution and monitoring. Reviews of the ecosystem underline heterogeneous toolchains, unstable interfaces, and shifting hardware roadmaps—conditions that impede reproducibility and long-term maintainability for logistics optimization workflows (Gill et al., 2022). From a platform perspective, vendor-specific performance characteristics and calibration practices further increase coupling costs. Longitudinal accounts of IBM's systems show how processor generations, control stacks, and performance metrics evolve quickly, requiring organizations to re-validate pipelines as backends change (AbuGhanem, 2025). Evidence from logistics use cases illustrates why hybrid orchestration is unavoidable. Large multi-truck routing instances cannot be fully embedded on near-term hardware; instead, firms rely on iterative decomposition and quantum–classical annealing to keep problems within feasible resource envelopes while feeding results back into realistic supply chain simulations (Chand et al., 2018). Backend-specific encodings intensify integration complexity: qubit-efficient formulations for vehicle routing reduce qubit

counts but demand bespoke mappings, transpiration, and benchmarking across IBM, Rigetti, and IonQ devices, with comparisons to strong classical solvers (Leonidas et al., 2024). For annealing-based approaches, performance is sensitive to schedule design, necessitating additional layers of schedule/path optimization and device calibration—capabilities not yet routine in SCM IT stacks (Zeng et al., 2016). Domain-specific studies reinforce this integration burden. Last-mile logistics prototypes combining adiabatic/annealing ideas with classical heuristics demonstrate value only when tuned for concrete operational constraints, adding translation steps between business rules, QUBO/CQM models, and solver settings (Ariño Sales & Palacios Araos, 2023). Similarly, quantum treatments of transport network design and multicommodity flows require bi-level or mixed-integer formulations that must be specialized for the quantum backend and then reconciled with enterprise data flows (Dixit & Niu, 2023; Niu et al., 2025). In sum, immature and shifting hardware–software ecosystems raise integration risk and technical debt for mission-critical SCM, making portability and reliability contingent on hybrid designs, backend-specific encodings, and continuous re-validation.

4.3.2 Technological readiness

Even with pilots in place, operationalization depends on robust interfacing between quantum routines and the existing SCM stack (ERP/MES/APS/WMS). Hybrid logistics workflows must ingest heterogeneous data, transform it into backend-compatible models (e.g., QUBO/CQM or qubit-efficient encodings), manage queued jobs on cloud services, and reintegrate outputs into transaction systems with auditable provenance and latency guarantees. Case evidence shows that scalable routing solutions rely on iterative decomposition and orchestration across quantum and classical solvers, followed by validation in high-fidelity supply chain simulations (Yuan et al., 2023). Qubit-efficient vehicle-routing approaches demonstrate feasibility on NISQ devices, yet require backend-specific mappings and benchmarking across multiple providers, which increases the integration surface and the need for platform-aware expertise (Leonidas et al., 2024). Transport network design studies similarly reveal the

importance of end-to-end verification: bi-level formulations solved via annealing need careful comparison with incumbent heuristics, and their stochastic outputs must be reconciled with service-level and compliance requirements (Dixit & Niu, 2023). Beyond optimization, digitalization research underscores data governance and sustainability trade-offs when embedding advanced computation into supply chains, pointing to the need for clear policies on data quality, access, and environmental impact of computation (Shaikh et al., 2018). Security and interoperability are additional bottlenecks. Logistics cybersecurity reviews document a limited use of real operational data and highlight exposure from internet risks that expand when sensitive operational data is piped into hybrid quantum–classical services (Chaudhry et al., 2025). In parallel, blockchain initiatives in transport show promise for provenance and auditability, but also introduce their own maturity and integration hurdles that must be reconciled with quantum pilots in shared data pipelines (Koh et al., 2020). Security-focused reviews of blockchain-based IoT propose zero-knowledge proofs and post-quantum cryptography to harden data flows, indicating where SCM integrators should plan controls as quantum experimentation scales (Commey et al., 2024).

Consequently, the technological readiness is not only “quantum algorithms” but also API orchestration, data engineering, verification/validation, and secure deployment across legacy infrastructure. Without these competencies, organizations face operational risk, vendor lock-in, and limited ability to A/B test quantum components against classical baselines before scale-up.

4.3.3 Skills & Expertise gap

The obstacles to the application of QC in SCM do not only depend on hardware, but also on people. Workforce studies show that Industry 4.0/5.0 transformations require extensive reskilling across analytics, software, and cyber-physical systems; a significant share of essential skills by the mid-2020s did not appear on earlier job descriptions, implying sizable upskilling gaps inside operations and logistics teams (Li, 2024). Industry 5.0 surveys echo the need for cross-disciplinary competence human-centric integration of advanced computation with domain expertise suggesting that organizations must build teams conversant in

both operations research and emerging computation to realize benefits (Adel, 2022; Maddikunta et al., 2022). Quantum-specific literacy deepens this challenge. Foundational reviews catalogue steep learning curves across hardware models, software toolchains, and algorithmic choices, and emphasize persistent NISQ limitations that must be understood to select feasible encodings, set baselines, and interpret results (Gill et al., 2022). In SCM contexts, near-term advantage typically arises from carefully engineered hybrids rather than monolithic quantum runs; teams must design problem decompositions, choose encodings, and orchestrate evaluation against strong classical solvers. Case studies in logistics demonstrate that quantum routines add value when paired with classical heuristics and realistic simulations, reinforcing the need for practitioners who can bridge algorithm engineering with operations modelling (Weinberg et al., 2023). At the same time, “quantum-inspired” approaches are gaining traction in operations and logistics, offering a pragmatic pathway for capability building while true quantum hardware matures. Their adoption still requires literacy in novel encodings and benchmarking but can serve as a training ground for teams preparing to evaluate quantum backends within SCM (Núñez-Merino et al., 2024). Complementary advances in explainable decision support for supply chains highlight the importance of transparent analytics and governance, competencies that will also be essential for quantum-enabled decision systems (Olan et al., 2025). Overall, shortages of trained professionals and limited quantum literacy remain first-order readiness constraints, slowing credible road-mapping and the translation from proofs-of-concept to operational value in SCM settings.

4.3.4 High initial cost

Total cost of adoption remains high relative to uncertain, domain-specific gains in SCM. Analyses of the commercial landscape characterize QC as an emerging market with evolving business models and partnerships that can spread risk but also complicate procurement and capability planning; until stability improves, organizations should expect exploratory rather than definitive ROI (Naik et al., 2025). From a hardware trajectory, detailed accounts of IBM’s processors and

performance metrics show meaningful progress alongside persistent challenges in scaling, noise, and control—factors that translate into recurring expenditure for access, benchmarking, and integration as platforms iterate (AbuGhanem, 2025). On the algorithmic side, state-of-the-art reviews of many-body simulations emphasize resource demands and error-sensitivity on digital quantum computers, underscoring why robust performance often requires circuit tailoring, error-mitigation, and repeated calibration activities that add engineering cost before any operational value is realized (Fauseweh, 2024). In SCM applications, recent case studies report benefits arising from hybrid designs with problem-specific encodings and decomposition. However, these architectures incur hidden costs in algorithm engineering, data preparation, solver calibration, and continuous re-tuning as SDKs and backends evolve (Da Silveira et al., 2017; Hauke et al., 2020). Moreover, for transport network design and multicommodity flows, comparisons to strong classical heuristics are essential to justify spending; early results suggest promise but also variability, reinforcing the need for rigorous baselines and controlled pilots before scaling (Dixit & Niu, 2023; Niu et al., 2025). Cloud access can reduce CapEx, yet OpEx persists: metered usage, queue times, and specialist staffing for orchestration and validation. Coupled with volatile roadmaps and uncertain advantage over classical methods in production settings, these factors create financing and governance hurdles for SCM leaders seeking predictable returns. Accordingly, high upfront and lifecycle costs remain a central barrier, motivating narrow proofs-of-concept, staged integration, and cautious commitments until stable, repeatable gains are demonstrated in real supply chain environments.

4.4 Applications in supply chain

QC has recently moved from theoretical exploration toward early pilot implementations in SCM. While still in a nascent stage, existing studies demonstrate that quantum algorithms can address some of the most computationally intensive challenges across different industries. As shown in Table 2, applications span from manufacturing and production scheduling, where quantum-inspired optimization improves job-shop and machine scheduling

(Amaro et al., 2022; Bożejko et al., 2025; Ning et al., 2016), to transportation and logistics, where routing and delivery problems are reformulated for quantum solvers (Azad et al., 2023; Beheshti et al., 2015; Dixit & Niu, 2023; Osaba et al., 2024; Weinberg et al., 2023). In retail and inventory management, quantum approaches enhance resilience and optimize stock control under uncertainty (Chandra Das et al., 2020; Lin & Lin, 2025), while in pharmaceutical and healthcare supply chains, quantum-safe cryptography and blockchain frameworks strengthen data authenticity and traceability (Chaudhry et al., 2025; Zhang et al., 2025). Furthermore, automotive supply chains and cross-industry initiatives illustrate how quantum technologies can improve fleet routing (Weinberg et al., 2023), enhance enterprise resource planning, and support green and secure supply chain finance (Awan et al., 2022; Cheung et al., 2021; Feng et al., 2022; Li, 2024; Lin & Lin, 2025; Naik et al., 2025). These applications, although still at proof-of-concept scale, collectively indicate the emerging potential of QC to transform industry-specific supply chain practices.

Table 2. Pilot quantum computing applications

Industry Application	Project / Study Name	Description	Reference
Manufacturing & Production Scheduling	Steel Job-Shop with VQAs (F-VQE, VQE, VarQITE, QAOA)	Applied variational quantum algorithms to steel job-shop scheduling; F-VQE showed faster convergence and better optimality on real hardware.	Amaro et al., 2022
	Flexible Job-Shop via QMPSO	Dynamic rescheduling strategy with quantum-behaved PSO; improved stability and reduced makespan in benchmark manufacturing cases.	Ning et al., 2016
	Single-Machine Scheduling with QA	Used D-Wave quantum annealer inside branch-and-bound for tardiness minimization; reduced runtime vs classical.	Bozejko et al., 2025
Transportation & Logistics	Scenario-Based Routing (QUBO)	Modeled stochastic, time-dependent shortest path for traffic/logistics routing; quantum solver showed promising scaling.	Dixit et al., 2024
	Vehicle Routing with QAOA (IBM Qiskit)	VRP formulated as Ising Hamiltonian and solved via QAOA on NISQ devices; highlighted optimizer and depth trade-offs.	Azad et al., 2023
	Parcel Delivery (Q4RPD, D-Wave hybrid)	Real-world Spanish package delivery with heterogeneous fleet; hybrid solver handled 2D packing + priority constraints.	Osaba et al., 2024
	Automotive Fleet Routing (Aisin Corp.)	Large automotive supplier; decomposed multi-truck VRP solved iteratively with QA/SA; validated in realistic SC simulation.	Weinberg et al., 2023

	VRP with Time Windows (Q-MOGA)	Quantum-inspired GA optimized multi-objective VRP with prioritized time windows in logistics case study.	Beheshti et al., 2015
Retail & Inventory Management	Inventory Control with Preservation Tech (QPSO)	Inventory system with deterioration, price-dependent demand, and preservation technology; solved with QPSO to minimize losses.	Chandra Das et al., 2020
	ERP Resilience with NSEA (PQC + Neuro-Symbolic AI)	ERP for manufacturing/retail integrating quantum-safe cryptography; improved resilience (63% faster recovery, 62.9% fewer overruns).	Lin & Lin, 2025
Pharma & Healthcare Supply Chains	Quantum Hybrid Blockchain (QHB-DA)	Blockchain for authenticity and data security in Industry 4.0 pharma chains; integrates DAG + PQC for tamper-resistance.	Zhang et al., 2025
	zk-DASTARK	Post-quantum zero-knowledge proof system securing data feeds for healthcare smart contracts; tested on IOTA.	Chaudhry et al., 2025
Automotive Supply Chains	Multi-Truck Routing (Aisin Corp.)	Demonstrated quantum annealing for just-in-time auto parts routing with large fleets.	Weinberg et al., 2023
Cross-Industry Security & Finance	Post-Quantum ERP	ERP resilience with quantum-safe modules; aligns 92% with SAP schema.	Lin & Lin, 2025
	Cybersecurity in Logistics	Review of quantum-era risks to blockchain and logistics IT; calls for early adoption of PQC.	Cheung et al., 2021
	Quantum Finance & Blockchain Review	Identified use of QC for portfolio optimization, fraud detection, and post-quantum blockchain for supply chain finance.	Naik et al., 2025

Green & Circular SC (GSCI, CAB2IN)	Frameworks integrating QC as enabler for eco-design, recovery, and digitalization toward sustainability.	Feng et al., 2022; Liu et al., 2023
Workforce Reskilling	Highlighted need for reskilling, upskilling, and digital readiness for adopting quantum technologies in SC.	Li, 2024; Awan, 2022

5 Future Research and Conceptual Framework

This chapter presents a conceptual framework for understanding how quantum computing may be adopted in supply chain management. The framework draws on insights from the review and organises them into stages of acceptance, processes of implementation, possible areas of application, and the wider supply chain network. It highlights the conditions that support adoption as well as the barriers that may slow progress. The purpose is not to offer a fixed model, but to provide a structured view that can guide pilot projects and later integration. The chapter also identifies research gaps that remain in the current literature. These gaps point to the need for more empirical studies, industry-specific analysis, and closer attention to organisational and policy factors. Together, the framework and the discussion of gaps lay the ground for future work that can turn potential into practice.

5.1 Conceptual framework

As shown in Figure 9, the proposed framework is structured into four levels that capture the main dimensions of adoption in supply chain management. These levels include the path of technology acceptance, the stages of implementation, the areas of application, and the position of these applications within the wider supply chain network. Together, they provide a coherent view of how quantum computing can move from initial awareness to industry-wide use.

At the technology acceptance level, the framework describes a gradual path of adoption. Firms first move through awareness and sensemaking as they learn what technology is and why it may matter. They then deepen understanding through exploration, scanning tools, and trial ideas with small internal exercises. Strategic alignment follows, where possible uses are checked against business goals such as efficiency, resilience, and sustainability. Feasibility and partnering then become central, because most firms will need outside expertise and access to platforms to turn ideas into proof-of-concepts. Pilot experimentation allows a first test in real decisions, for example in routing, scheduling, or forecasting, with clear baselines and simple success criteria. If pilots show value, organizational

integration embeds methods into planning routines and IT systems so that results are available to line managers and not only to specialists. When these steps are held on a scale, industry-wide diffusion and institutionalization become possible through shared standards and benchmarks that reduce uncertainty for buyers and partners. This staged path echoes the logic used in prior implementation frameworks while keeping the focus on supply-chain decision making rather than technical detail.

Then the implementation process level shows three main stages. In the initiation stage, interest is pushed by new knowledge, early pilots from pioneers, and in some cases, policy support, yet progress is slowed by immature tools and by the effort needed to translate abstract models into specific operational tasks. In the adoption-decision stage, managers are drawn by expected gains in optimisation and risk analysis and by the fit with ongoing digital programmes, while they also face obstacles linked to integration work, skills and training gaps, and data quality and security concerns. In the implementation stage, teams seek operational efficiency and competitive improvement and often link goals to environmental targets, but they must still handle high cost, uncertain returns, limited scalability, and possible vendor lock-in. Reading adoption through drivers and barriers at each stage aligns with how earlier supply-chain technology frameworks organise evidence and clarifies where many projects stall and what conditions help them proceed.

The third level groups application areas that are most visible in the literature and in early practice. Logistics and distribution show opportunities in vehicle routing, multimodal planning, and cross-dock design. Manufacturing and operations point to job-shop and flow-shop scheduling and to resource allocation across machines or lines. Demand and supply planning includes forecasting that combines classical models with quantum components and inventory policies that must respond to uncertainty. Digitalisation and sustainability link quantum adoption to cybersecurity in enterprise systems and to analysis that supports greener logistics and trustworthy data exchange with partners. These domains reflect

where current studies concentrate and where practitioners can pilot without changing the full architecture of the firm.

Finally, the network level places these applications on the end-to-end chain from procurement and sourcing to manufacturing, distribution and warehousing, retailers and customers, and reverse logistics. This view reminds us that value is created when methods travel across organisational borders and when upstream and downstream partners can act on shared insights. It also stresses that pilots should be chosen with a clear place in the network to avoid isolated proofs of concept that cannot scale. In sum, the framework links a practical acceptance path with a staged process view, anchors use cases in familiar supply-chain domains, and maps them to the physical and information flows of the network. It is conceptual by design and should be read as a guide for structured experimentation and later empirical testing.

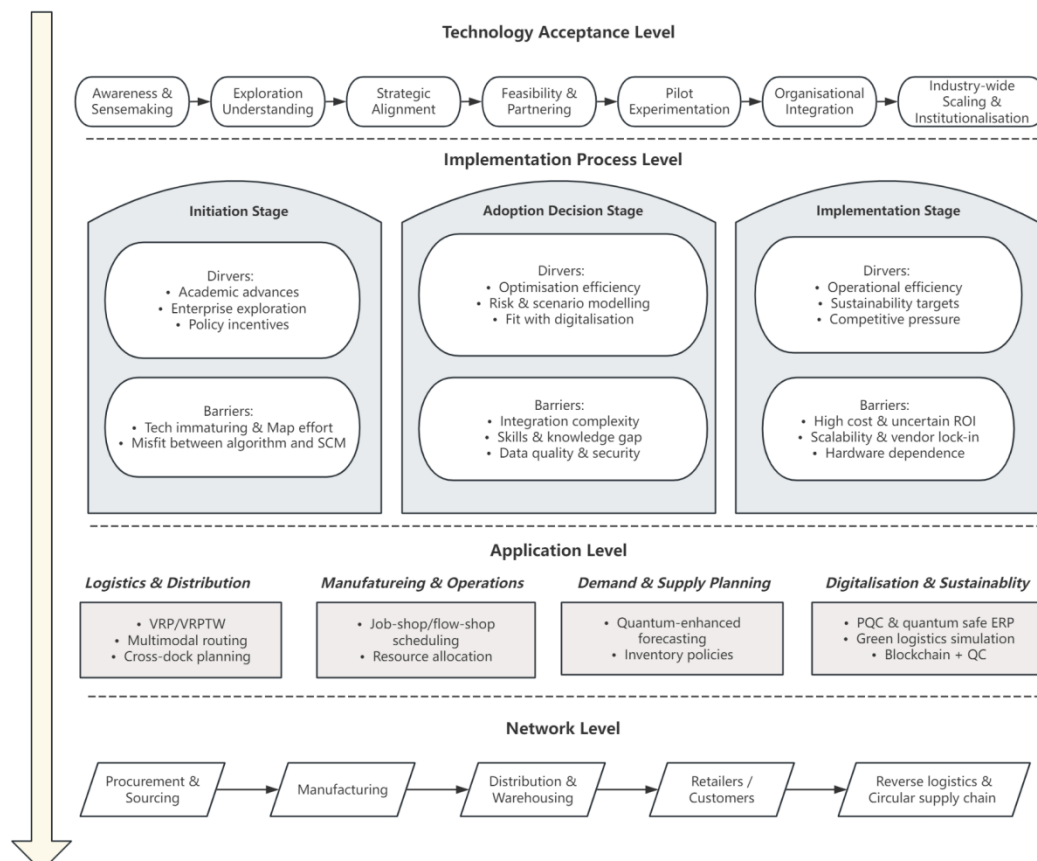


Figure 9. Conceptual framework for QC implementation in SCM

5.2 Future Research Directions

- Need for empirical evidence and real-world validation.

Although the framework gives a clear picture of possible adoption, it also highlights important research gaps. Current work on QC in SCM is still at an early stage. Most studies are conceptual or based on small experiments. There is very little empirical evidence about how the technology performs in practice. More case studies and pilot projects are needed to test the framework and provide lessons from real-world contexts. Without such evidence, it is hard to know if theoretical gains in optimisation or simulation can bring real improvements in efficiency, resilience, or sustainability (Mousa & Shirazi, 2024; Shamsuddoha et al., 2025).

- Industry-specific differences in supply chains

Another gap is that most research does not consider differences between industries. SCM in pharmaceuticals, automotive, food, and fashion has very different structures and needs, but these differences are rarely studied in QC. For example, pharmaceutical supply chains must ensure strong regulation and cold-chain control, while automotive supply chains deal with complex supplier tiers and just-in-time systems. Food supply chains are sensitive to perishability and safety, while fashion supply chains face fast product cycles and unstable demand. These features suggest that the role of quantum computing may look very different in each industry. Current research often treats supply chains as if they were the same, which may hide important insights(et al., 2024). Future research should provide industry-specific studies to identify where quantum tools can add real value.

- Bridging technical advances with management and leadership

There is also a lack of work that connects technology and management. Many studies focus on algorithms but pay less attention to culture, leadership, governance, and skills (Phillipson, 2025). However, adoption does not depend on technical performance alone. It also depends on whether firms can build the right management support and skills to use these

tools. Leadership commitment, training, and cross-team collaboration often decide if a pilot can scale into normal operations. Current research does not link these factors with technical progress, which creates a gap. Stronger collaboration between technical fields and management research will be needed. Without this, quantum projects may remain as experiments that never reach wider use.

- Quantum data structures for secure information sharing

A further underexplored area concerns quantum data structures for supply chain information sharing. Current research does not study how quantum information theory may change the way firms share data. Supply chains already face challenges of trust, privacy, and competition when they share data. Quantum-secure structures such as entangled databases, quantum blockchain, or quantum contracts may offer new ways to ensure transparency and protection at the same time (Naik et al., 2025). This could support more reliable sharing of logistics and inventory data across competing firms. Future studies should examine how these structures can work in practice, and what benefits or risks they may bring. This would extend SCM research from optimisation problems into the field of data sharing and information systems.

- Integrating quantum machine learning with behavioural SCM

Another promising direction is bridging quantum machine learning and behavioural supply chain research. SCM research increasingly studies human behaviour, such as bias, trust, and cooperation. But current quantum ML models are not designed to capture these features. Classical models often assume rational behaviour, but in practice supply chain actors make decisions that are influenced by bounded rationality or trust relationships. Quantum-inspired models may allow researchers to describe these non-linear and interdependent behaviours in a new way. For example, entanglement could be used to represent how trust between two firms depends on their shared history, or how one partner's forecast bias influences others in a network (Fedorov et al., 2023). Linking this with work

on “quantum cognition” could open new ways to study contracts, negotiations, and collaboration in supply chains.

- Policy, standards, and ecosystem support for adoption

The role of policy and ecosystem support is underexplored. Issues such as training, standards, shared platforms, and regulation could strongly influence adoption. Governments, industry groups, and partnerships may help reduce barriers and spread knowledge. Without such support, single firms may face high costs, lack of skills, and uncertainty about interoperability. Research that studies these ecosystem factors can help explain how collective action will shape the speed and scale of QC adoption (Aken, 2004; Rad, 2021).

In short, the proposed framework is a first step that organises what is known and points to what is missing. Future research should test it in practice, adapt it to different industries, and connect technical progress with management and policy insights. This will be important for turning QC in supply chains from a promising idea into a practical reality.

6 Conclusion

6.1 Discussion

This study set out to review the current state of QC in SCM and to build a conceptual framework based on the literature. The descriptive analysis gave an overview of research trends, including publication growth, country distribution, and research methods. It showed that interest in QC for SCM is rising quickly, but still limited compared to other digital technologies.

The thematic analysis explored both the drivers and the barriers for QC adoption. Drivers include faster computation, better security, potential for scaling, and long-term cost benefits. These factors explain why companies and researchers are paying attention to QC. At the same time, barriers such as integration complexity, immature technology, high costs, and lack of skills are slowing progress. This shows that adoption is not only a technical issue but also a question of organisation, resources, and skills.

The review also identified different stages of implementation. At present, most efforts are at the awareness and pilot project stage. Some hybrid quantum-classical pilots in logistics, scheduling, and inventory show encouraging results, but real integration into daily operations remains rare. This pattern is similar to other new technologies, where early trials come before large-scale use.

Applications of QC in SCM are emerging in several areas. Logistics and distribution, such as routing and transport planning, are the most developed. Manufacturing scheduling, quantum-secure cryptography, and sustainable operations are also gaining attention. However, demand and supply planning is still less explored, which leaves a gap for future research. Another important point is that research is concentrated in a few countries with strong investment and infrastructure, showing that national strategies influence how the field develops.

In conclusion, QC in SCM is still in an early stage. Growth is clear, but progress is uneven and many challenges remain. The need for higher efficiency, resilience, transparency, and security will continue to drive interest. External forces such as regulation, competition, and sustainability pressure may further push adoption.

The conceptual framework developed in this study connects drivers, barriers, implementation stages, and applications, offering a guide for both researchers and practitioners. Future work should test this framework with real cases, explore industry-specific needs, and study how management and policy factors can support adoption.

6.2 Contribution to theory and practice

This study advances both theoretical and practical understanding of QC in SCM. Firstly, while previous studies tended to emphasize routing and network optimisation, this review consolidates fragmented insights and positions QC as a transformative technology for logistics, manufacturing, planning, and digital sustainability.

Secondly, the analysis identifies technological drivers, implementation stages, and adoption barriers that shape the pathway from conceptual awareness to practical integration. The proposed conceptual framework extends supply chain innovation theory by describing potential applications for QC in SCM, thereby offering a structured lens through which academics can further investigate emerging quantum-enabled supply chain models.

Thirdly, the review contributes to managerial practice by offering actionable insights into how QC can be piloted and scaled within supply chains. Evidence from pilot projects and hybrid approaches provides guidance for supply chain managers on where quantum advantages may realistically emerge in the near term and what socio-technical conditions must be in place to capture value.

Finally, the findings carry implications for policymakers and ecosystem stakeholders. The study highlights the importance of regulatory readiness, quantum-safe standards, and cross-industry collaboration to enable the diffusion of QC applications. By outlining future research directions, such as sector-specific studies, quantum-secure data structures, and behavioural modelling, the review sets a foundation for scholars, practitioners, and policymakers to collectively shape the way of QC application in SCM.

6.3 Limitations of the study

This study has several limitations. First, although the systematic literature review used a clear and repeatable process, only 61 articles were included. Because quantum computing in supply chains is still new and covers many fields, some related studies may have been missed, especially those outside the main management and operations journals. The choice of keywords and inclusion rules also includes some subjectivity, even though we tried to reduce this through several screening steps and extended search strings.

Second, the study mainly looked at conceptual and pilot-level applications. Most of the reviewed works are still at the theoretical or proof-of-concept stage. As a result, the findings may not fully show how quantum computing performs in real supply chain settings. It is also not clear if these approaches can be scaled to complex, multi-tier networks.

Third, this research only included academic papers written in English. Grey literature, industry white papers, and non-English studies were not considered. This may limit the coverage of practice-oriented insights and knowledge from other regions. In addition, while the study covered different industries, it did not look deeply into sector-specific issues, such as perishability in food supply chains or modularity in construction. These differences may affect adoption patterns but were not studied in detail.

Finally, the study did not analyse technical details such as hardware limits, links with existing IT systems, costs, and regulatory challenges. These are important barriers but need more focused research. Future studies should build on the framework proposed here and examine pilot projects and industry cases to test feasibility, assess organizational readiness, and apply the framework in practice.

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Appendices

Appendix A Ethical approval letter



10 May 2025

Dear Miss Zhang ,

Reference: CURES/25087/2025

Project ID: 28575

Title: Potential of Quantum Computing for supply chain management: A systematic literature review

We are pleased to inform you that you have successfully declared that your research project is a **Literature Review – based solely on openly available literature which is in the public domain, and you are undertaking desk-based research not involving any other form of data or information.**

You have also confirmed that your project **does not meet** any of the literature review specified exceptions, listed both within the relevant section of the CURES form and below:

- 1) Your supervisor has requested that you apply for approval through CURES because:
 - The journals or data are in a sensitive area (please discuss this with your supervisor)
 - The project will be embargoed i.e. **will not be publicly available via the Cranfield library immediately or longer term**
- 2) Approval is/will be specifically required by another external body e.g. journal publishers

Therefore, **you do not require ethical approval** and your CURES application will be automatically closed.

Please keep a copy of this letter safe, if this exception is in relation to your thesis project, you will need to include a copy with your final thesis submission.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B List of Select Papers

Paper number	Title	Author(s)
1	A case study of variational quantum algorithms for a job shop scheduling problem	Amaro, David; Rosenkranz, Matthias; Fitzpatrick, Nathan; Hirano, Koji; Fiorentini, Mattia
2	A Fuzzy Inventory Model for a Deteriorating Item with Variable Demand, Permissible Delay in Payments and Partial Backlogging with Shortage Follows Inventory (SFI) Policy	Shaikh, Ali Akbar; Bhunia, Asoke Kumar; Cárdenas-Barrón, Leopoldo Eduardo; Sahoo, Laxminarayan; Tiwari, Sunil
3	A Multifaceted Analysis of Intelligent Vehicle Route Optimization	Pooja; Sood, Sandeep Kumar
4	A novel dynamic scheduling strategy for solving flexible job-shop problems	Ning, Tao; Huang, Ming; Liang, Xu; Jin, Hua
5	A novel offloading approach of IoT user perception task based on quantum behavior particle swarm optimization	Chen, Lu; Zhang, De-Gan; Zhang, Jie; Zhang, Ting; Wang, Wen-Jing; Cao, Ya-Hui
6	A novel quantum algorithm for ant colony optimisation	Ghosh, Mrityunjay; Dey, Nivedita; Mitra, Debdeep; Chakrabarti, Amlan
7	Adiabatic quantum computing impact on transport optimization in the last-mile scenario	Ariño Sales, Juan Francisco; Palacios Araos, Raúl Andrés
8	An application of preservation technology in inventory control system with price dependent demand and partial backlogging	Chandra Das, Subhash; Zidan, A.M.; Manna, Amalesh Kumar; Shaikh, Ali Akbar; Bhunia, Asoke Kumar

9	An EPQ model with stock and selling price dependent demand and variable production rate in interval environment	Ruidas, Subhendu; Seikh, Mijanur Rahaman; Nayak, Prasun Kumar
10	An interval-valued green production inventory model under controllable carbon emissions and green subsidy via particle swarm optimization	Ruidas, Subhendu; Seikh, Mijanur Rahaman; Nayak, Prasun Kumar; Tseng, Ming-Lang
11	Applying Quantum Computing to Solve Multicommodity Network Flow Problem	Niu, Chence; Rastogi, Purvi; Soman, Jaikishan; Tamuli, Kausik; Dixit, Vinayak
12	Barriers to implementation of blockchain into supply chain management using an integrated multi-criteria decision-making method: a numerical example	Öztürk, Cihat; Yildizbaşı, Abdullah
13	Big data driven supply chain design and applications for blockchain: An action research using case study approach	Sundarakani, Balan; Ajaykumar, Aneesh; Gunasekaran, Angappa
14	Blockchain in transport and logistics—paradigms and transitions	Koh, Lenny; Dolgui, Alexandre; Sarkis, Joseph
15	Complete the Last Mile Delivery Problems in the Quantum Computing	Liao, Pei Yen; Bhie, Santos Jay; Ou, Chia-Ho; Chen, Chih-Yu; Chang, Ching-Ray
16	Cybersecurity in logistics and supply chain management: An overview and future research directions	Cheung, Kam-Fung; Bell, Michael G.H.; Bhattacharjya, Jyotirmoyee

17	Digitalization and the greening of supply chains	Sarkis, Joseph; Kouhizadeh, Mahtab; Zhu, Qingyun Serena
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