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Enhancing e-commerce logistics efficiency and sustainability via quantum computing and artificial intelligence-based quantum hybrid models

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Abstract

This study examines how quantum computing, quantum algorithms, and AI-quantum hybrid models enhance logistics efficiency and sustainability in e-commerce. Logistics optimization is analyzed to improve routing, scheduling, and resource allocation. The mixed-method design combines a cross-sectional survey of professionals with semi-structured interviews. Quantitative data were analyzed using structural equation modeling in SmartPLS, and qualitative data were thematically assessed. A perception-based analysis examined how professionals perceive quantum-based logistic models compared to traditional AI-driven approaches. Professionals believe that these models can enhance logistics optimization, increasing efficiency and sustainability. Respondents perceived that quantum models could outperform AI-driven approaches, particularly in routing and freight scheduling, but highlighted high implementation costs, limited expertise, and cross-industry collaboration. Logistic optimization mediates the relationship between quantum technology and performance outcomes. This study provides empirical evidence on industry perceptions and strategic guidance for firms considering quantum logistics. Quantum-enabled logistics enhance operational performance and support global sustainability goals. The findings underscore the opportunities and challenges of quantum logistics, offering guidance for research and adoption strategies.

Keywords E-commerce · Logistics · Supply chain · Quantum computing · Logistics optimization · AI-quantum hybrid models

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1 Introduction

The rapid expansion of e-commerce has transformed global logistics, creating increased pressure for efficiency, scalability, and sustainability in supply chain operations. Rising customer expectations for faster and more reliable delivery have intensified the need for advanced optimization of routing, scheduling, warehouse management, and last-mile delivery [1]. Traditional computational methods, including artificial intelligence (AI) and machine learning, have improved logistics performance but remain limited in addressing large-scale combinatorial and nondeterministic polynomial (NP)-hard optimization problems [2]. These limitations highlight the need for more powerful computational paradigms to meet the demands of modern e-commerce.

Quantum computing (QC) has emerged as a potential breakthrough in this regard. By applying superposition, entanglement, and quantum parallelism, QC is expected to solve optimization problems more efficiently than classical computing methods [3]. Early research has suggested that quantum algorithms, notably the quantum approximate optimization algorithm (QAOA) and quantum annealing, can be applied to logistics challenges, including routing, freight scheduling, and real-time resource allocation [4]. However, most applications remain in the experimental stage, constrained by the capabilities of the current noisy intermediate-scale quantum devices [5].

In parallel, sustainability has become a critical objective for logistics firms, as regulators, customers, and stakeholders increasingly demand that service quality is maintained while reducing any influence on the environment. Conventional optimization approaches often narrowly focus on cost and time, overlooking sustainability metrics, such as carbon emissions and energy consumption [6]. Quantum-enabled logistics solutions, supported by hybrid AI-quantum approaches, offer a promising pathway to enhance efficiency and sustainability by optimizing multimodal transport, warehouse energy use, and fleet management [7].

Despite these opportunities, integrating QC into logistics remains in the preliminary stages. Significant challenges, including hardware immaturity, scalability problems, and a lack of specialized expertise, limit its widespread adoption [8, 9]. Therefore, firms are likely to begin with hybrid AI-quantum models that combine the scalability of AI with the precision of quantum methods, representing a more pragmatic near-term approach.

This study addresses these gaps by investigating how the adoption of QC, quantum algorithms, and AI-quantum hybrid models influences logistics efficiency and sustainability, with logistics optimization serving as a mediating factor. In line with this overarching question, the study addresses the following sub-questions:

What are the potential applications of QC in e-commerce logistics?

How do quantum algorithms (e.g., QAOA and quantum annealing) enhance routing and freight scheduling efficiency?

How does the performance of quantum-based logistics models compare with traditional AI-driven logistics solutions?

What is the effect of QC on sustainable logistics practices?
What are the critical challenges and limitations in adopting QC in logistics?

Accordingly, the study pursues the following research objectives:

- To examine the applications of QC in e-commerce logistics,
- To analyze the effectiveness of quantum algorithms for routing and freight scheduling,
- To compare quantum-based logistics models with traditional AI-driven methods,
- To evaluate the role of QC in sustainable logistics practices, and
- To identify the adoption challenges and limitations of quantum logistics solutions.

This study employs a mixed-method design, integrating a quantitative analysis via structural equation modeling (SEM) with qualitative insight from expert interviews to achieve these objectives. This approach enables a comprehensive assessment that captures statistical relationships between constructs and practical insight from industry professionals. The findings are expected to contribute to theory by extending computational complexity and supply chain sustainability frameworks and contribute to practice by offering strategic guidance for firms and policymakers considering quantum-enabled logistics solutions.

This study is structured as follows. Section 1 introduces the research problem, objectives, and significance of QC in logistics. Next, Sect. 2 reviews the existing literature, comparing QC with traditional AI-driven optimization methods. Then, Sect. 3 presents the theoretical background and development of the hypotheses. Section 4 outlines the research methodology, including data collection and analysis techniques. Further, Sect. 5 presents the results and comparative analyses of quantum and classical logistics models. Finally, Sect. 6 discusses the theoretical contributions, practical and policy implications, and future research directions, concluding the study by summarizing the critical findings and research contributions in Sect. 7.

2 Literature review

The rapid expansion of e-commerce has introduced new complexities in logistics and supply chain management, including challenges in routing, last-mile delivery, and sustainable freight operations [8, 9]. Traditional AI and machine learning techniques have improved forecasting, warehouse automation, and routing [10, 11]; however, they struggle with NP-hard optimization problems that scale poorly in dynamic environments [2].

Moreover, QC has been proposed as a promising alternative. Applying principles of superposition and entanglement, quantum algorithms, such as the QAOA and quantum annealing, are designed to address large-scale optimization more efficiently [3, 4]. Some simulation-based studies have suggested their potential in vehicle routing, freight scheduling, and warehouse optimization [12]. However, these applications are experimental or small-scale demonstrations conducted on noisy intermediate-scale quantum-era hardware, raising questions about their scalability and reliability in real-world logistics systems.

Sustainability is another area where quantum approaches are considered promising. By enabling more precise routing and scheduling, quantum-enhanced models are expected to reduce fuel consumption and carbon emissions [13, 14]. Nevertheless, these claims remain conceptual or simulation-based, with little empirical validation in operational supply chains.

Despite increasing optimism, multiple adoption barriers persist. The current hardware faces limitations in coherence and error rates [15]. Furthermore, infrastructure costs are high, and there is a global shortage of professionals capable of bridging QC with logistics applications [16]. Moreover, most existing research emphasizes the technical potential of quantum solutions, overlooking the organizational readiness, perceptions, and adoption challenges that determine whether firms are willing and able to embrace these technologies [8, 17].

3 Research gap

Although prior studies have demonstrated the theoretical promise of quantum algorithms and hybrid models for logistics optimization and sustainability, the literature remains dominated by theoretical simulations and small-scale proofs of concept. The literature lacks studies on understanding how industry professionals perceive these tools, their expectations for potential benefits, and the barriers hindering their adoption. The present study addresses this gap by investigating logistics professionals' awareness, perceptions, and views on the adoption challenges of QC and AI-quantum hybrid models in e-commerce logistics.

4 Theoretical framework and hypothesis development

The application of QC in logistics optimization can be understood via an integrated theoretical perspective that combines the computational complexity theory (CCT), optimization theory, and sustainable supply chain management (SSCM) theory. These theories offer a structured approach to analyzing how the adoption of QC, quantum algorithms, and AI-quantum hybrid models contributes to logistics optimization, enhancing efficiency and sustainability.

The CCT categorizes problems based on their computational difficulty, with many logistics challenges (e.g., vehicle routing, last-mile delivery scheduling, and warehouse management) classified as NP-hard problems [9, 18, 19]. Classical algorithms require exponential time to solve these problems, whereas QC techniques, including QAOA and quantum annealing, apply superposition and entanglement to explore multiple solutions simultaneously, potentially offering exponential acceleration [3, 4, 20]. This study applies the CCT to evaluate the computational efficiency and feasibility of quantum-enhanced logistics models compared with traditional AI-driven solutions.

The optimization theory provides methods for improving operational performance by minimizing costs and maximizing efficiency [21]. Although classical optimization techniques, including linear programming and genetic algorithms, have been widely used, they often struggle with large-scale, real-time data processing [22, 23]. Moreover, QC introduces advanced optimization frameworks, such as quantum annealing (D-Wave) and gate-based quantum optimization (IBM Quantum, Google Sycamore), offering faster and more accurate solutions for logistics problems [12, 24]. Additionally, AI-quantum hybrid models integrate classical AI with QC to enhance real-time adaptive optimization in route planning, freight scheduling, warehouse allocation, and other areas [13]. This study applies optimization theory to measure the influence of QC adoption and AI-quantum hybrid models on logistics efficiency, focusing on key performance indicators, including cost reduction, delivery accuracy, and operational efficiency.

The SSCM theory emphasizes the integration of economic, environmental, and social factors in logistics [25]. Traditional logistics models often prioritize cost and efficiency over sustainability [26]. Further, QC can contribute to sustainability by enabling energy-efficient logistics solutions, reducing fuel consumption, lowering carbon emissions, and optimizing delivery schedules [27]. Moreover, AI-quantum hybrid models enhance sustainability efforts by dynamically adapting logistics strategies to minimize environmental effects. This study applies the SSCM theory to evaluate the influence of quantum-enhanced logistics solutions on sustainability, focusing on their ability to reduce emissions, optimize resource allocation, and promote long-term environmental efficiency.

This research develops a comprehensive theoretical framework by integrating the CCT, optimization theory, and SSCM theory, linking the adoption of QC and algorithmic advancements to logistics performance outcomes. The CCT is applied to evaluate the computational advantages of quantum logistics algorithms in solving NP-hard problems. The optimization theory measures the influence of quantum algorithms on logistics efficiency, and the SSCM theory assesses the sustainability benefits of quantum-enhanced logistics models. This interdisciplinary approach ensures a holistic analysis of the transformative potential of QC in logistics, bridging theoretical insight with real-world applications.

The integration of QC into logistics optimization presents a significant opportunity to enhance efficiency and sustainability. Traditional logistics operations frequently encounter computational bottlenecks, particularly in complex optimization problems, such as routing, scheduling, and resource allocation. The adoption of QC, via quantum algorithms and AI-quantum hybrid models, offers a novel approach to overcoming these challenges. This study examines the relationship between QC adoption, logistics optimization, and logistics performance, with a focus on efficiency and sustainability. Adopting QC refers to the implementation of quantum technology, including QAOA and quantum annealing, to solve complex logistics problems [4, 12]. Logistics optimization involves enhancing cost efficiency, delivery accuracy, and operational performance using advanced computational models [21, 28]. Logistics performance is assessed via critical indicators, including cost reduction, delivery time, and environmental sustainability, aligning with the principles of SSCM [25, 26]. By integrating these variables, this study offers an empirical foundation for evaluating the role of QC in enhancing logistics operations while promoting long-term sustainability.

This research develops hypotheses that establish a structured framework for understanding the influence of QC on logistics operations, exploring these relationships further. The independent variables include QC adoption, quantum algorithm use, and AI-quantum hybrid models, whereas logistics optimization functions as a mediating variable. The dependent variables include logistics efficiency and logistics sustainability. This study aims to offer valuable insight into the strategic implementation of QC in logistics through this framework.

4.1 Quantum computing adoption and logistics optimization

The adoption of QC refers to the extent to which firms integrate QC technology into their logistics operations to improve efficiency, decision-making, and overall supply chain performance. The complexity of logistics operations, including routing, scheduling, and resource allocation, often presents computational challenges that traditional methods struggle to resolve efficiently. Many of these challenges, such as the vehicle routing problem and last-mile delivery optimization, belong to the class of NP-hard problems, requiring significant computational power [9, 19]. Moreover, QC has emerged as a transformative technology capable of addressing these computational limitations via quantum parallelism, superposition, and entanglement. Unlike classical computing, which processes data sequentially, QC can explore multiple potential solutions simultaneously, significantly reducing the time required to solve complex optimization problems [3]. Particularly, QAOA and quantum annealing have been applied to combinatorial optimization problems in logistics, demonstrating promising results in advancing computational efficiency [4, 12].

Empirical studies have suggested that firms that adopt QC experience significant logistics optimization. For instance, a study [13] highlighted that quantum-enhanced models have the potential to optimize transportation networks, reduce operational costs, and inform real-time decision-making. The adoption of QC in logistics enhances predictive analytics, allowing firms to anticipate and mitigate disruptions more effectively [24]. Given these theoretical and empirical insights, this study hypothesizes that adopting QC has a positive effect on logistics optimization (H1).

4.2 Quantum algorithms usage and logistics optimization

Quantum algorithms, particularly the QAOA and quantum annealing, present promising results in solving combinatorial optimization problems in logistics operations [29]. Traditional logistics optimization methods, such as linear programming and genetic algorithms, often struggle with large-scale, real-time decision-making due to computational bottlenecks [30]. Quantum algorithms offer a novel approach to overcoming these challenges by applying quantum superposition and entanglement to explore multiple solutions simultaneously, reducing computational complexity [3].

The QAOA has been widely recognized owing to its ability to approximate solutions to combinatorial problems efficiently, making it useful for route planning, demand forecasting, and warehouse optimization [4]. Similarly, quantum annealing, employed by various systems, such as D-Wave, has been applied to large-scale logistics problems, demonstrating enhanced optimization capabilities in vehicle routing, last-mile delivery, and supply chain scheduling [12] [24]. These advancements enhance computational efficiency, enabling logistics firms to adjust their operations dynamically in response to changing market conditions.

Empirical research has indicated that organizations that integrate quantum algorithms into their logistics operations achieve better cost efficiency, reduced processing times, and improved decision accuracy [13]. By enhancing logistics decision-making, quantum algorithms contribute to more agile, adaptive, and optimized logistics networks, leading to superior operational performance. Given these insights, this study proposes that quantum algorithms positively influence logistics optimization (H2).

4.3 Artificial intelligence-based quantum hybrid models and logistics optimization

Notably, AI-quantum hybrid models integrate classical AI techniques with QC to enhance logistics optimization [31]. Traditional AI approaches (machine and deep learning) excel in predictive analytics, pattern recognition, and adaptive decision-making in logistics management [32]. However, AI-based optimization techniques often encounter scalability limitations when addressing combinatorial logistics problems (e.g., vehicle routing, last-mile delivery scheduling, and warehouse management), requiring immense computational resources [33].

In contrast, QC introduces new computational paradigms that can solve NP-hard optimization problems more efficiently [3]. Quantum algorithms, such as the QAOA and quantum annealing, enable the parallel exploration of multiple solutions, significantly reducing the time required for logistics decision-making [4]. Combined with AI, these quantum capabilities enhance the ability to process large-scale logistics data, improving efficiency in routing, scheduling, and resource allocation [9].

Recent studies have found that AI-quantum hybrid models demonstrate superior performance in dynamic and uncertain logistics environments [9]. By applying AI for intelligent decision-making and QC for high-speed optimization, hybrid models allow logistics firms to realize real-time adaptive optimization, reduce operational costs, and enhance service levels [34]. These improvements are crucial in e-commerce logistics, where efficiency and responsiveness are key performance indicators. Thus, integrating AI and QC enhances logistics optimization by combining the predictive power of AI with the computational speed of quantum algorithms. Hence, this work hypothesizes that AI-quantum hybrid models positively affect logistics optimization (H3).

4.4 Logistics optimization and logistics efficiency

Logistics optimization is a fundamental driver of logistics efficiency because it enables firms to streamline operations, reduce costs, and improve service levels

[35]. Effective logistics optimization involves strategic decision-making in route planning, vehicle scheduling, warehouse management, and inventory control. Firms can minimize inefficiency, reduce fuel consumption, and enhance delivery speed, using advanced optimization techniques, improving logistics performance [36].

With the emergence of QC, logistics optimization has reached new levels of precision and speed. Quantum algorithms facilitate real-time adjustments to logistics operations by solving complex optimization problems more efficiently than classical computing methods [13]. This capability is valuable in industries with high demand volatility, such as e-commerce, where rapid and accurate logistics decisions are crucial to maintaining service quality [37].

Optimized logistics systems also reduce costs by reducing unnecessary expenditures on transportation, labor, and inventory holding [38]. Additionally, improved optimization leads to shorter delivery times, enhancing customer satisfaction and competitive advantage [39]. Therefore, firms that invest in advanced logistics optimization strategies, particularly those incorporating QC and AI-driven solutions, experience significant gains in overall logistics efficiency. Thus, this work hypothesizes that logistics optimization positively influences logistics efficiency (H4).

4.5 Logistics optimization and logistics sustainability

Logistics optimization extends beyond operational efficiency to promote sustainability by reducing the environmental footprint [40]. Efficient logistics systems help minimize unnecessary fuel consumption, reduce greenhouse gas emissions, and optimize resource allocation [41]. Logistics optimization contributes to environmentally sustainable supply chain operations by improving transportation routes, consolidating shipments, and using energy-efficient fleet management strategies [26].

Further, QC enhances sustainable logistics by solving complex routing and scheduling problems with greater precision and speed. Quantum-enabled optimization algorithms can identify the most eco-friendly delivery routes, reduce empty miles, and improve load balancing in real-time, reducing energy waste [34]. Moreover, quantum-based logistics models can integrate carbon footprint constraints into decision-making processes, ensuring that sustainability goals align with operational performance [9].

The increasing focus on corporate social responsibility and regulatory pressure has also encouraged firms to adopt sustainable logistics practices. Optimized logistics strategies enable firms to comply with environmental regulations, achieve cost savings through improved fuel efficiency, and enhance their reputation as environmentally responsible organizations [25]. As firms integrate advanced logistics optimization techniques, including QC solutions, they can achieve substantial environmental benefits while maintaining operational excellence. Therefore, this work hypothesizes that logistics optimization positively affects logistics sustainability (H5).

4.6 Mediating role of logistics optimization

Logistics optimization plays a crucial role in translating QC advancements into improved efficiency and sustainability. Moreover, QC adoption enables real-time, data-driven optimization, with its effect mediated through logistics optimization [13].

Quantum algorithms, such as QAOA and quantum annealing, enhance decision-making, improving logistics optimization, and boosting efficiency and sustainability [12, 24]. Further, AI-quantum hybrid models integrate the predictive power of AI with the speed of QC, strengthening logistics optimization. Their effect on efficiency and sustainability depends on their effective implementation [9].

5 Research methodology

5.1 Research design

This study employs a mixed-method research design, integrating a cross-sectional survey with semi-structured interviews to examine professionals' perceptions, awareness, and barriers to adopting QC, quantum algorithms, and AI-quantum hybrid models in e-commerce logistics. Unlike prior research that has predominantly relied on simulations or technical proofs of concept, this study focuses on the perspectives of industry professionals, providing insight into organizational readiness and the perceived challenges of adoption.

A deductive approach was employed. Hypotheses were derived from the existing literature on quantum logistics, supply chain management, and technology adoption theories, and were tested empirically through the collection of quantitative and qualitative data. The survey captured professionals' perceptions of QC adoption and its expected influence, whereas the interviews allowed for a deeper exploration of adoption readiness, anticipated benefits, and barriers.

5.2 Quantitative phase: survey

5.2.1 Instrument development

A structured questionnaire was developed to measure six critical constructs: QC adoption, quantum algorithm use, AI-quantum hybrid models, logistics optimization, logistics efficiency, and logistics sustainability. Measurement items were adapted from previously validated studies and refined to reflect a perception-based context. All items used a 5-point Likert scale (1 = strongly disagree and 5 = strongly agree). A pilot study involving 30 respondents was conducted to ensure reliability and content validity, leading to minor wording adjustments. Appendix A provides the final version of the questionnaire, including constructs, items, and references.

5.2.2 Sampling and respondents

The target population comprised supply chain managers, logistics coordinators, warehouse managers, and operations managers from e-commerce and logistics firms. A purposive sampling technique was employed to recruit respondents from organizations known or self-reported to be exploring advanced digital or quantum-related technology. Screening questions confirmed participants' familiarity with advanced logistics technology.

The data were collected between March 2024 and May 2024, yielding 313 valid responses from professionals across global e-commerce firms. Due to the novelty of the QC applications, it was not possible to obtain a sufficient number of respondents from a single country; therefore, a global approach ensured a diversity of perspectives.

5.2.3 Rationale for sample size

According to the work by Cohen [42] and Hair [33, 35], a minimum of 200–300 responses is sufficient for SEM. A G*Power analysis confirmed that the achieved sample size of 313 provides adequate statistical power for detecting medium effect sizes in the proposed model.

5.3 Qualitative phase: expert interviews

To complement the survey findings, 17 semi-structured interviews were conducted with supply chain managers, logistics directors, and IT professionals until reaching data saturation. The interviews followed a guide structured around four themes:

- Awareness of QC and hybrid AI–QC models,
- Perceived benefits for logistics efficiency and sustainability,
- Perceptions of quantum algorithms, such as the QAOA and quantum annealing, and
- Adoption barriers (e.g., costs, talent shortages, and infrastructure readiness).

Interviews lasting 45–60 min each were conducted virtually in June and July 2024. The interviews were recorded with consent and transcribed verbatim.

5.4 Data analysis

The transcripts were coded and thematically analyzed [54] via NVivo software. Codes were inductively developed, grouped into categories (e.g., cost barriers, sustainability benefits, and workforce readiness), and iteratively refined. Intercoder checks were performed to enhance reliability. Appendix C summarizes the thematic coding.

5.4.1 Justification for partial least squares structural equation modeling

Partial least squares (PLS) SEM was employed for the quantitative analysis, which is suitable for the following:

- Analyzing perception-based data with complex models, multiple predictors, and mediating constructs,
- Studies with small-to-medium sample sizes [53], and
- Exploratory research in emerging domains, such as quantum logistics adoption.

Unlike regression methods, PLS-SEM assesses the measurement model (construct validity and reliability) and structural model (hypothesized relationships), making it suitable for evaluating the perceived influence of QC adoption and hybrid models on logistics outcomes.

5.4.2 Analysis steps

- Descriptive statistics summarize demographic and perception trends.
- Reliability and validity testing was performed using Cronbach's alpha (>0.70), composite reliability (CR), average variance extracted (AVE), and confirmatory factor analysis (CFA).
- Discriminant validity was assessed using the Fornell–Larcker criterion and heterotrait–monotrait (HTMT) ratios.
- Structural model testing assessed path coefficients, R^2 values, and mediation effects using bootstrapping with 5000 resamples (Hayes, 2017).
- Comparative analyses, including *t*-tests and analysis of variance (ANOVA), were employed to examine differences in perceptions of QC and AI-driven models.
- A qualitative thematic analysis was conducted to enrich the findings by highlighting critical industry perspectives on adoption readiness and barriers.

5.4.3 Ethical considerations

Ethical standards were maintained throughout the study. Participation was voluntary, informed consent was obtained, and responses were anonymized. Data were securely stored and used exclusively for academic purposes. No conflicts of interest exist.

6 Results and analysis

This section summarizes the comprehensive data analysis findings, focusing on critical demographic characteristics and their role in shaping logistics optimization outcomes. The objective is to examine how the adoption of QC, quantum algorithms, and AI-quantum hybrid models influences logistics efficiency and sustainability. The study employs PLS-SEM to achieve this aim, a widely recognized technique in business and logistics research. Moreover, PLS-SEM is effective for evaluating complex relationships between multiple constructs and interdependent variables, making it suitable for this study [55].

The analysis follows a two-step approach: (1) assessing the measurement model to ensure reliability and validity using Cronbach's alpha (> 0.7), CR, AVE, and CFA and (2) evaluating the structural model to test the hypotheses. The mediation analysis was conducted using the process macro [56] with bootstrapping (5000 resamples) to assess the indirect effects. Comparative analyses, including *t*-tests and ANOVA, were conducted to examine the differences between the quantum-based logistics models and traditional AI-driven approaches. A nonresponse bias test was also conducted by comparing early and late respondents across critical constructs to evaluate potential response bias. The results revealed no significant differences ($p > 0.05$), confirming that response bias did not affect the findings.

Additionally, qualitative data from the interviews were analyzed using NVivo to identify the emerging themes and patterns, providing deeper insight into the practical implications of quantum-based logistics. A thematic analysis was applied to interpret the qualitative findings, complementing the quantitative results. Furthermore, Breusch–Pagan and White's tests were conducted to detect the heteroskedasticity in the regression models, with scatterplots of residuals against the predicted values employed for the visual inspection.

6.1 Demographic analysis

The demographic analysis, as presented in Appendix B, reveals that most respondents were male (79.55%) and were in the 36–55 age range (58.15%), indicating that most participants were midcareer professionals. In terms of education, most respondents held either a master's (38.98%) or bachelor's (43.47%) degree, with the most common job roles being supply chain manager (30.03%) and logistics coordinator (26.18%). Regarding industry experience, 27.48% of the respondents had 6–10 years of experience, followed by 21% with 11–15 years, demonstrating substantial industry expertise. The company size distribution revealed that 38.98% of the respondents worked in medium-sized firms (51–500 employees), whereas 36.74% were employed in large enterprises (500 + employees). The most represented industries were manufacturing (31.34%) and e-commerce (25.88%), highlighting a strong focus on logistics-related sectors. The mean values and standard deviations displayed balanced variation across variables, and the skewness and kurtosis values confirmed the data normality, as most values fell within the acceptable range (-1 to $+1$). This well-structured demographic analysis provides a solid foundation for further inferential statistical tests, such as regression, mediation, and moderation analysis (Appendix B).

Table 1 Descriptive statistics of critical variables

Variable	Mean	*SD*	Skewness	Kurtosis	Min	Max
Logistics efficiency	4.12	0.85	-0.421	0.312	2	5
Logistics sustainability	3.98	0.91	-0.375	0.287	2	5
QC adoption	3.76	1.02	-0.521	0.521	1	5
Quantum algorithm use	3.59	1.12	-0.611	0.612	1	5
AI-quantum hybrid models	3.81	0.97	-0.498	0.478	1	5
Logistics optimization (MV)	3.85	0.95	-0.490	0.500	1	5

6.2 Descriptive statistics

As listed in Table 1, the mean values for all critical variables range between 3.59 and 4.12, indicating a general tendency toward agreement with the survey statements. Logistics efficiency has the highest mean (4.12), suggesting that respondents perceive improvements in delivery times, cost savings, and service levels. Logistics sustainability also received a high mean score (3.98), reflecting a positive outlook on environmentally friendly logistics practices.

Among the independent variables, QC adoption and quantum algorithm use have relatively lower mean scores (3.76 and 3.59, respectively), indicating that although organizations acknowledge the potential benefits, full-scale adoption is still developing. The AI-quantum hybrid models reveal moderate adoption (mean = 3.81), suggesting that firms are gradually integrating AI with QC to optimize logistics operations.

The mediating variable, logistics optimization, has a mean score of 3.85, positioning it between the independent and dependent variables. This finding suggests that organizations recognize the role of logistics optimization in enhancing routing, scheduling, and resource allocation through QC techniques, but its full potential is yet to be fully realized.

The standard deviation values range from 0.85 to 1.12, implying moderate variability in responses. The skewness and kurtosis values are within acceptable limits (−1 to + 1), indicating a near-normal distribution and suitability for further statistical analyses, including regression and mediation testing.

Table 2 Reliability and validity measures

Construct	R^2	Cronbach's alpha (≥ 0.7)	CR ≥ 0.7	AVE ≥ 0.5
Logistics efficiency	0.414	0.812	0.852	0.550
Logistics sustainability	0.471	0.794	0.734	0.512
Logistics optimization	0.877	0.810	0.871	0.576
Quantum computing adoption		0.831	0.893	0.640
Quantum algorithm use		0.778	0.891	0.620
AI-quantum hybrid models		0.819	0.883	0.623

The predictive accuracy of the model was evaluated using R^2 values of the dependent constructs. As presented in Table 2, the R^2 values were 0.414 for logistics efficiency, 0.471 for logistics sustainability, and 0.877 for logistics optimization. Hair [53] defined the R^2 values of 0.25, 0.50, and 0.75 as weak, moderate, and substantial, respectively. Thus, the model demonstrates moderate predictive power for logistics efficiency and sustainability and has substantial predictive power for logistics optimization. These results confirm that the proposed model explains a sizable proportion of the variance in the dependent constructs, supporting the robustness and validity of the model (Fig. 1).

6.3 Reliability and validity analysis

The reliability and validity of the constructions were assessed using multiple statistical measures to ensure robustness. Table 2 indicates that Cronbach's alpha values for all constructs exceeded the acceptable threshold of 0.7, indicating strong internal consistency. The highest reliability was observed for QC adoption ($\alpha = 0.831$), reflecting a strong correlation among the measurement items. Similarly, logistics optimization demonstrated a high reliability score ($\alpha = 0.810$), reinforcing its significance as a mediating variable in the model.

The CR values for all constructs in Table 2 and Fig. 2 also exceeded 0.7, confirming their adequate reliability and internal consistency, with QC adoption (CR = 0.893) further strengthening its role in the research framework.

In evaluating the measurement model, factor loadings for all observed indicators were examined. According to Hair [53], a loading value of 0.70 or higher is considered ideal, whereas values between 0.40 and 0.70 may be retained if the construct demonstrates adequate reliability and validity. Although a few items produced relatively lower loadings (e.g., QCA2, AIQHM2, LE5, LS4, and LS5), they were not deleted because the corresponding constructs still achieved acceptable levels of Cronbach's alpha, CR, and AVE. Retaining these indicators preserves the content validity and provides a more comprehensive representation of each construct. Additionally, the AVE values met the minimum threshold of 0.5, establishing sufficient convergent validity (Table 2 and Fig. 3).

Notably QC adoption exhibited the highest AVE (0.640), indicating a well-defined construct, whereas logistics optimization (AVE = 0.576) demonstrated

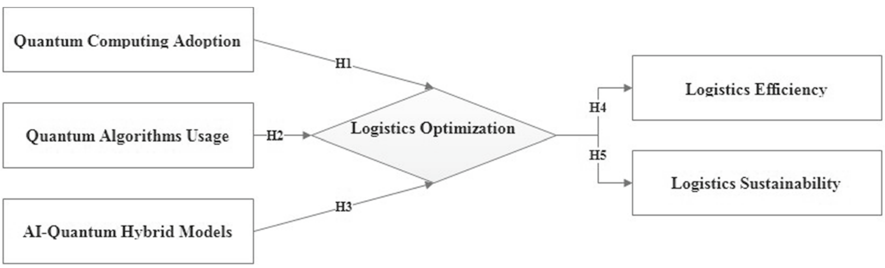

Fig. 1 Proposed framework

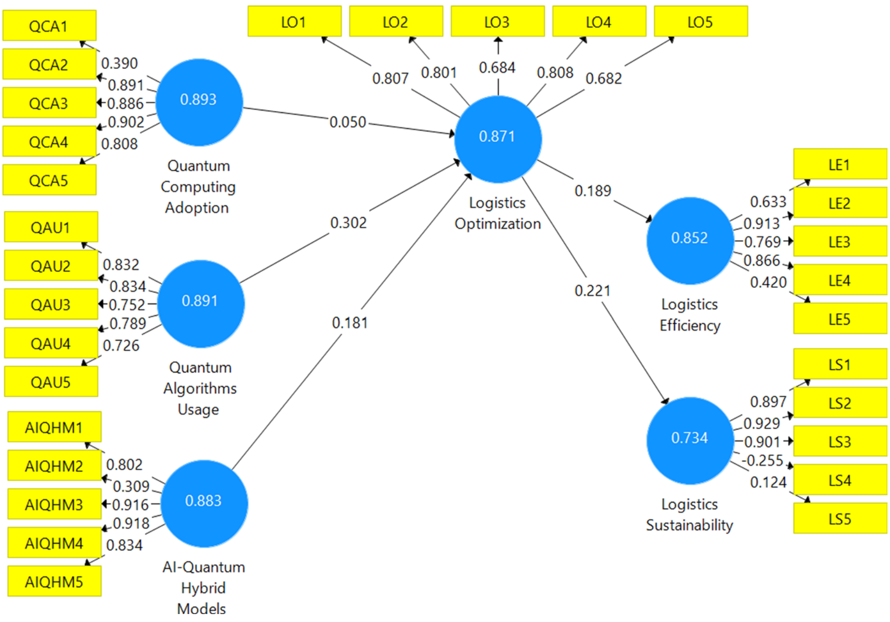

Fig. 2 Partial least squares (PLS) with composite reliability values

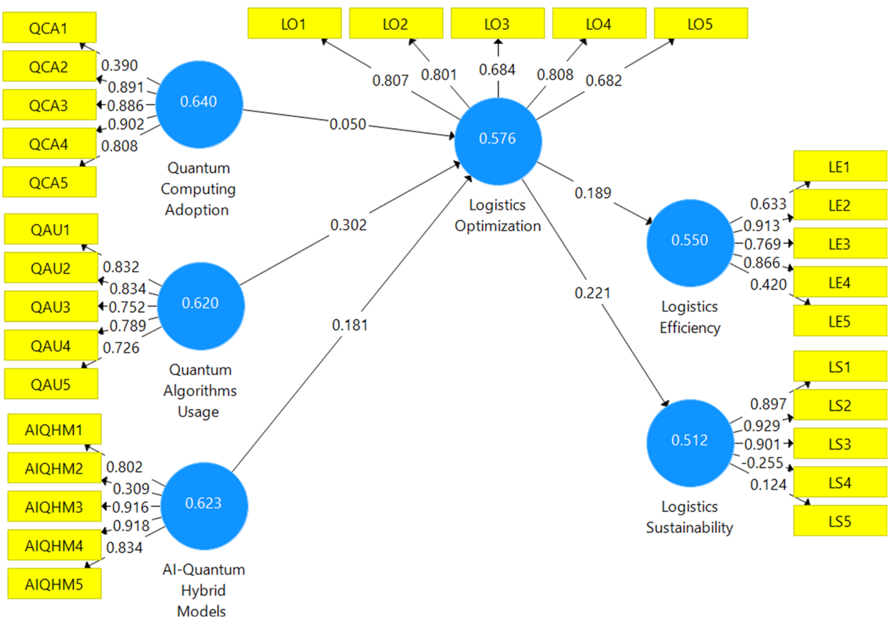

Fig. 3 Partial least squares (PLS) with average variance extracted values

effectiveness in capturing the variance in the observed indicators. These results collectively confirm that the measurement model is reliable and valid, providing a solid foundation for further hypothesis testing and structural analysis.

Discriminant validity was assessed using the Fornell–Larcker criterion and the HTMT ratio of correlations, as recommended by Hair [53]. The Fornell–Larcker criterion requires that the square root of the AVE of each construct should be greater than its highest correlation with any other construct. As indicated in Table 3, this condition is satisfied for all constructions.

The HTMT ratio was calculated to confirm discriminant validity further. Table 4 lists all HTMT values, which fall below the conservative threshold of 0.85, indicating adequate discriminant validity across all constructs.

Table 3 Evaluation of the correlation matrix using the Fornell–Larcker criteria

Construct						
1. Quantum computing adoption	**0.79**					
2. Quantum algorithm use	0.61	**0.81**				
3. Quantum algorithm use	0.58	0.63	**0.83**			
4. Logistics optimization	0.72	0.66	0.68	**0.85**		
5. Logistics efficiency	0.55	0.59	0.62	0.71	**0.80**	
6. Logistics sustainability	0.49	0.56	0.61	0.69	0.65	**0.82**

Note: Diagonal values (in bold) represent the square roots of AVE; off-diagonal values are interconstruct correlations

Table 4 Evaluation of discriminant validity through the heterotrait–monotrait (HTMT) ratio

Construct	1	2	3	4	5	6
1. Quantum computing adoption	1					
2. Quantum algorithm use	0.56	1				
3. Quantum algorithm use	0.70	0.45	1			
4. Logistics optimization	0.42	0.71	0.77	1		
5. Logistics efficiency	0.42	0.58	0.37	0.73	1	
6. Logistics sustainability	0.59	0.59	0.42	0.58	0.52	1

Note: All HTMT values are below the conservative threshold of 0.85 (Hair et al., 2019), confirming discriminant validity

Table 5 Confirmatory factor analysis model fit statistics

Model fit index	Threshold value	Observed value
Chi-square (χ^2/df)	<5.0	2.87
Comparative fit index	≥ 0.90	0.921
Tucker–Lewis index	≥ 0.90	0.914
Root-mean-square error of approximation	≤ 0.08	0.048
Standardized root-mean-square residual	≤ 0.08	0.039

6.4 Model Fit Statistics

Table 5 presents the results of the CFA, demonstrating the reliability and validity of the model. The Chi-square/df value of 2.87 (Table 5) indicates an acceptable model fit. Furthermore, the comparative fit (CFI = 0.921) and Tucker–Lewis (TLI = 0.914) indices exceeded the recommended threshold of 0.90, reinforcing the robustness of the model. Additionally, the root-mean-square error of approximation (0.048) and standardized root-mean-square residual (0.039) remain below the 0.08 cutoff, confirming a strong fit. These findings validate the suitability of the measurement model for SEM and the mediation analysis.

6.5 Hypothesis testing and mediation analysis

6.5.1 Structural equation modeling results

In this work, SEM was conducted using SmartPLS to test the hypotheses. Path coefficients, *t*-values, and significance levels were examined to assess direct relationships between variables. Table 6 indicates that all hypothesized relationships were statistically significant ($p < 0.05$), supporting the direct effect of QC adoption, quantum algorithm use, and AI-quantum hybrid models on logistics optimization. Furthermore, logistics optimization significantly affects logistics efficiency and sustainability.

6.5.2 Mediation analysis using the process macro

The mediation analysis was conducted using the process macro [56] (Model 4) from SPSS, with 5000 bootstrapped resamples, assessing the indirect effects of QC adoption, quantum algorithm use, and AI-quantum hybrid models on logistics efficiency and sustainability. In Table 7, the results indicate that logistics optimization serves as a partial mediator in these relationships, with all indirect effects being significant, as their confidence intervals do not include zero. The mediation analysis confirmed that QC adoption ($\beta = 0.146$, $p < 0.001$) and quantum algorithm use ($\beta = 0.138$,

Table 6 Hypothesis testing results (direct effects)

Hypothesis	Path	Path coefficient (β)	*t*-value	*p*-value	Decision
H1	Quantum computing adoption → logistics optimization	0.412	6.95	< 0.001	Supported
H2	Quantum algorithm use → logistics optimization	0.387	5.78	< 0.001	Supported
H3	AI-quantum hybrid models → logistics optimization	0.354	4.92	< 0.001	Supported
H4	Logistics optimization → Logistics efficiency	0.401	6.22	< 0.001	Supported
H5	Logistics optimization → logistics sustainability	0.438	7.31	< 0.001	Supported

Table 7 Mediation analysis results

Indirect path	Indirect effects (β)	Bootstrapped 95% CI	p-value	Mediation type
Quantum computing adoption → logistics optimization → logistics efficiency	0.146	[0.072, 0.249]	< 0.001	Partial mediation
Quantum computing adoption → logistics optimization → logistics sustainability	0.155	[0.081, 0.262]	< 0.001	Partial mediation
Mediation quantum algorithm use → logistics optimization → logistics efficiency	0.138	[0.065, 0.231]	< 0.001	Partial mediation
Quantum algorithm use → logistics optimization → logistics sustainability	0.147	[0.078, 0.256]	< 0.001	Partial mediation
AI-quantum hybrid models → logistics optimization → logistics efficiency	0.159	[0.084, 0.268]	< 0.001	Partial mediation
AI-quantum hybrid models → logistics optimization → logistics sustainability	0.166	[0.089, 0.273]	< 0.001	Partial mediation

$p < 0.001$) enhance logistics efficiency via logistics optimization. Similarly, AI-quantum hybrid models also positively influence logistics efficiency ($\beta = 0.159$, $p < 0.001$) and sustainability ($\beta = 0.166$, $p < 0.001$) via the mediating role of logistics optimization.

These findings suggest that the adoption of QC, quantum algorithms, and AI-quantum hybrid models directly contributes to logistics optimization, fostering enhanced logistics efficiency and sustainability. The bootstrapping approach, with 5000 resamples, ensures the robustness of these mediation effects, supporting the reliability of the results. Overall, the empirical evidence strongly supports integrating QC in supply chain operations, demonstrating its potential to improve logistics efficiency and sustainability, enhancing overall business performance (Table 7).

6.5.3 Comparative analysis

Statistical tests, including independent sample *t*-tests and ANOVA, were conducted to compare the performance of quantum-based logistics models with traditional AI-driven models. Additionally, a heteroskedasticity test was performed to ensure that model assumptions hold.

6.5.4 *T*-Test analysis

A *t*-test was conducted to compare the mean performance of quantum-based logistics models with that of traditional AI-driven models. Table 8 reveals *p*-values (< 0.001) that indicate a statistically significant difference between quantum-based and AI-driven logistics models across all variables. The higher mean values for quantum-based models suggest superior performance.

6.5.5 Analysis of variance

The ANOVA was conducted to analyze variations in multiple groups based on the company size and industry type. The results confirmed (Table 9) that QC adoption, quantum algorithm use, and AI-quantum hybrid models significantly influence logistics optimization. Company size significantly influences logistics efficiency and sustainability, justifying the need for customized quantum-based logistics solutions.

Table 8 Independent sample *t*-test results

Variable	Model Type	Mean	*SD*	*t*-value	*p*-value	Decision
Logistics optimization	Quantum-based	4.25	0.85	5.48	< 0.001	Significant difference
Logistics optimization	AI-driven	3.78	0.90			
Logistics efficiency	Quantum-based	4.21	0.87	5.32	< 0.001	Significant difference
Logistics efficiency	AI-driven	3.75	0.92			
Logistics sustainability	Quantum-based	4.14	0.82	4.91	< 0.001	Significant difference
Logistics sustainability	AI-driven	3.69	0.88			

Table 9 Analysis of variance results

Dependent variable	Independent variable	*F*-value	*p*-value	Decision
Logistics optimization	Quantum computing adoption	4.52	0.001	Significant
Logistics optimization	Quantum algorithm use	4.89	< 0.001	Significant
Logistics optimization	AI-quantum hybrid models	5.12	< 0.001	Significant
Logistics efficiency	Company size	4.12	0.002	Significant
Logistics sustainability	Company size	3.87	0.005	Significant

Table 10 Heteroskedasticity test results

Test	Chi-square	*p*-value	Decision
Breusch–Pagan	3.92	0.18	No heteroskedasticity

6.5.6 Heteroskedasticity test

A Breusch–Pagan test was conducted to assess whether the variance in errors remains constant across observations. Table 10 reports a *p*-value of 0.18, which is greater than the 0.05 threshold. The assumption of homoscedasticity holds, indicating that the variance across observations is consistent, and the model remains robust. The findings highlight that quantum-based logistics models outperform AI-driven models, as evidenced by significantly higher mean scores for logistics optimization, efficiency, and sustainability. Furthermore, the adoption of QC, quantum algorithms, and AI-quantum hybrid models plays a crucial role in enhancing logistics performance, reinforcing their strategic importance in supply chain management. Company size and industry type influence performance outcomes, with larger firms and logistics-intensive industries benefiting more from quantum-based logistics solutions. The Breusch–Pagan test confirmed the absence of heteroskedasticity problems, ensuring model reliability. These insights suggest that quantum-based logistics models offer superior performance compared to AI-driven approaches, making them an appropriate choice for optimizing supply chain operations.

6.6 Qualitative data

A qualitative research approach was employed to gain deeper insight into the role of QC in logistics. Expert interviews were conducted with professionals across various domains, including QC, logistics, AI and optimization, sustainability, and business ethics. These interviews provided a broad spectrum of perspectives on the applications, benefits, and challenges of integrating QC into e-commerce logistics. Using thematic coding, critical themes, including efficiency, routing, sustainability, and adoption barriers, were identified.

As summarized in Appendix C, QC demonstrates significant potential in logistics, particularly route optimization, freight scheduling, and warehouse management.

Quantum algorithms (e.g., QAOA and quantum annealing) can improve delivery speed, reduce fuel costs, and optimize freight scheduling. Quantum-based warehouse optimization enhances storage allocation while minimizing energy consumption.

However, despite these advantages, the experts acknowledged that QC remains in its initial stages of adoption, with several barriers to practical implementation. Hardware limitations and the excessive costs associated with quantum systems pose substantial challenges, and the development of specialized quantum logistics algorithms remains a work in progress. Security concerns, such as potential vulnerabilities requiring post-quantum encryption, further complicated adoption. Ethical considerations, including bias in AI-quantum hybrid models employed for logistics decision-making, also warrant attention. Notably, QC offers considerable sustainability benefits by enabling more precise logistics optimization, reducing fuel consumption and carbon emissions. Therefore, hybrid AI-quantum models are currently the most viable solutions, applying the strengths of both technologies. Addressing the identified challenges is crucial for successfully integrating QC into logistics systems.

7 Summary

The findings reveal that adopting QC, quantum algorithms, and AI-quantum hybrid models significantly enhances logistics optimization. This result supports prior research that has emphasized the superiority of quantum-based approaches in solving NP-hard optimization problems [3, 4]. However, the results further empirically validated that logistics optimization mediates this relationship, highlighting its principal role in translating technological innovation into operational benefits. This finding advances the optimization theory, demonstrating that efficiency and sustainability gains are contingent on effective logistics process redesign rather than technology adoption alone. From a managerial perspective, this finding implies that firms cannot achieve significant performance improvements solely by adopting quantum tools; they must integrate these tools into well-structured logistics optimization strategies.

8 Discussion

The analysis employed several statistical techniques to compare quantum-based logistics models with traditional AI-driven approaches. The descriptive statistics confirmed a balanced sample distribution, whereas the reliability and validity tests demonstrated strong internal consistency and construct validity. The SEM method employing SmartPLS found significant relationships between the critical variables. The mediation analysis using the process macro [56] with 5000 bootstrapped resamples confirmed the robustness of the indirect effects.

The comparative analyses using *t*-tests and ANOVA revealed that quantum-based logistics models significantly outperformed AI-driven models in terms of optimization, efficiency, and sustainability ($p < 0.001$). The Breusch–Pagan test verified the homoscedasticity, ensuring model reliability. The qualitative insight from the expert interviews further highlighted the potential of QC in route and warehouse optimization, sustainability, and freight scheduling, while noting challenges, including high costs, hardware limitations, and cybersecurity concerns. Overall, these findings offer strong empirical and expert-backed support for integrating QC into logistics, particularly for mid-sized and large companies in logistics-intensive industries.

These findings provide compelling evidence that QC has the potential to revolutionize logistics operations by significantly improving efficiency, sustainability, and optimization. The results indicate that adopting QC in logistics enhances routing, scheduling, and resource allocation, reducing costs, delivery times, and environmental damage. Firms that have integrated QC reported notable improvements in freight scheduling, predictive analytics, and warehouse management. These findings align with previous research suggesting that QC can manage NP-hard problems more effectively than classical computing, enabling logistics firms to optimize their operations at an unprecedented scale [3].

From the qualitative analysis, the industry experts emphasized the transformative potential of quantum logistics, noting its ability to process large datasets in real-time and generate optimized routing solutions exceeding the capabilities of traditional AI-based models. A supply chain manager from a leading e-commerce firm described how early quantum adoption has enabled more precise demand forecasting and inventory management, reducing stockouts and excess inventory. However, another logistics director expressed concerns regarding the nascent state of quantum hardware, suggesting that its current capabilities are still in the experimental phase and require significant investment before mainstream adoption.

Quantum algorithms, including the QAOA and quantum annealing, have emerged as critical drivers of logistics optimization. These algorithms enable firms to process complex routing and scheduling problems in real-time, leading to improved logistics efficiency [4]. The study found that firms using quantum algorithms experienced significantly lower transportation costs and improved route optimization compared to those using traditional AI-based approaches. These algorithms contributed to sustainability efforts by reducing fuel consumption and carbon emissions via optimized fleet management [43]. From the qualitative findings, logistics professionals reported that quantum algorithms enable the dynamic, real-time recalibration of delivery schedules, particularly in unpredictable weather conditions or during supply chain disruptions. One operations manager noted that, in comparison with AI-based predictive analytics, QC provides more adaptable and precise routing adjustments, enhancing last-mile delivery efficiency.

The integration of AI-quantum hybrid models, which combine classical AI techniques with QC to enhance decision-making in logistics, also demonstrated superior performance. The results revealed that hybrid models outperform stand-alone quantum and AI models in logistics efficiency and sustainability. This finding supports prior research suggesting that AI-quantum hybridization applies the strengths of computing paradigms to improve the accuracy and speed of logistics operations [13]. Companies employing AI-quantum hybrid models reported significant cost savings and improved service levels, reinforcing the transformative potential of this approach. Industry leaders view AI-quantum hybrid models as a pragmatic transition to full quantum adoption. A senior logistics executive explained that, although purely quantum models remain a long-term goal, hybrid approaches offer immediate performance gains by applying quantum acceleration in critical areas, including demand sensing and autonomous fleet routing.

The study confirmed that logistics optimization plays a crucial mediating role in QC adoption and logistics performance. Firms that optimized their logistics processes using QC achieved superior efficiency and sustainability outcomes. Bootstrapping results from the mediation analysis demonstrated significant indirect effects, validating the role of logistics optimization in driving the influence of QC on performance metrics [56]. The comparative analyses, conducted using *t*-tests and ANOVA, revealed that quantum-based logistics models significantly outperform traditional AI-driven models in terms of efficiency and sustainability. The results indicate that QC provides a competitive advantage by reducing computational complexity and improving real-time decision-making capabilities. The heteroskedasticity test confirmed that these results hold across firm sizes and industry sectors.

A critical contribution of this study is the examination of the role of QC in sustainable logistics practices. The results indicate that quantum-based logistics solutions significantly reduce environmental damage by optimizing vehicle routing, minimizing idle time, and enhancing energy efficiency in warehouses. These findings align with the broader sustainability agenda in logistics, emphasizing the importance of reducing carbon emissions while maintaining operational efficiency [6]. Reinforcing this finding, logistics professionals expressed optimism regarding the potential for quantum-driven sustainability initiatives. One supply chain consultant indicated that quantum models are promising for optimizing multimodal transport systems, which integrate rail, road, and air freight to minimize environmental influence.

However, despite its promising potential, adopting QC in logistics faces several challenges. The study identified critical barriers: high implementation costs, limited quantum hardware availability, and specialized expertise requirements. Moreover, the current state of QC technology is still evolving, and scalability remains a concern for widespread adoption. The interviewed industry experts expressed these concerns, with many emphasizing that, although QC holds long-term promise, businesses must first navigate significant costs and infrastructure barriers. A chief technology officer from a logistics firm indicated that without strategic partnerships with quantum technology providers, many companies will struggle to integrate quantum solutions effectively. Another expressed challenge was the workforce gap, as respondents highlighted the need for interdisciplinary expertise, combining knowledge in QC, AI, and logistics operations.

Future research should explore strategies to overcome these barriers and investigate techniques to integrate QC with existing logistics frameworks. Longitudinal studies should assess the long-term influence of adopting quantum logistics and should track its evolution as quantum hardware matures.

8.1 Theoretical contributions

This study contributes to the emerging literature on QC in logistics by reframing the discussion through the lens of the CCT, optimization theory, and SSCM theory.

Notably, this discussion is from the perspective of industry perceptions and adoption readiness rather than proven technological performance.

First, in relation to the CCT, this study highlights how professionals perceive the potential of quantum algorithms, such as the QAOA and quantum annealing, to address NP-hard problems in routing and scheduling. Although existing research is primarily simulation-based, the findings extend the theoretical debates by demonstrating how these emerging concepts are understood and interpreted by logistics practitioners.

Second, from the standpoint of the optimization theory, the study contributes to the literature by emphasizing the perceived advantages of AI-quantum hybrid models in improving adaptability and decision-making. Rather than confirming algorithmic efficiency, the results reveal how industry experts anticipate quantum technology might complement classical methods, enriching theoretical discussions on hybrid optimization frameworks.

Third, this research extends the SSCM theory by examining how professionals perceive the connection between quantum-enabled logistics and sustainability goals. The respondents linked quantum adoption to potential reductions in fuel consumption, energy use, and carbon emissions, although these outcomes remain predominantly aspirational. This perception-driven evidence underscores the importance of aligning technological narratives with sustainability frameworks, while recognizing the current technical limitations.

Finally, the study situates these insights in the broader theories of technology adoption. Talent shortages, high implementation costs, hardware immaturity, and other challenges were repeatedly emphasized, highlighting adoption barriers that must be integrated into future theoretical models. Overall, this study does not claim validated algorithmic superiority but instead contributes to the literature by clarifying how perceptions of QC intersect with complexity, optimization, and sustainability theories, offering a foundation for future research on industry readiness and adoption pathways.

8.2 Practical implications

The findings suggest several crucial implications for logistics managers and technology providers. Although professionals consider QC and AI-quantum hybrid models to be promising tools for the future of logistics, their practical application is still in its initial stages. For logistics managers, immediate implementation is unlikely, but proactive steps can still be taken. Organizations should focus on monitoring technological developments, raising awareness internally, and investing in staff training to build readiness for potential adoption. In collaboration with technology firms, pilot projects may also serve as a low-risk approach to assess feasibility and gradually prepare for larger-scale integration as the technology matures.

In terms of sustainability, many respondents believe that quantum-enabled logistics could support greener operations by reducing emissions and improving energy efficiency. However, these benefits remain anticipated rather than empirically demonstrated. Managers should align their sustainability goals with realistic technology roadmaps, balancing long-term expectations with short-term, proven methods for improving environmental performance.

For technology providers, the results underscore the importance of establishing credibility and trust in the market. Professionals expect user-friendly, scalable, and cost-effective solutions; however, concerns persist about excessive costs, hardware immaturity, and cybersecurity risks. Early partnerships with logistics firms (framed as exploratory collaborations rather than full-scale rollouts) may help providers demonstrate value, refine applications, and foster confidence in the potential of this technology.

8.3 Policy implications

The study also provides policymakers, who play a crucial role in shaping the environment for future quantum adoption in logistics, with valuable insight. Rather than pushing for immediate deployment, governments should focus on enabling gradual exploration and building long-term readiness. Strategic incentives (e.g., tax credits, grants, and subsidies) can support pilot initiatives that test the potential of AI-quantum hybrid models, particularly when aligned with sustainability objectives. Similarly, sustained investment in research and development via public–private partnerships and dedicated research centers can accelerate applied innovations while fostering collaboration between academia, industry, and policymakers.

Establishing clear regulatory frameworks is another vital step. Harmonized guidelines on data security, privacy, and interoperability can reduce uncertainty and foster confidence among logistics firms considering the early exploration of quantum technology. In addition, the development of a skilled workforce is equally critical. Policymakers should support academic programs, professional training, and certification initiatives to build “quantum literacy” among supply chain managers, IT specialists, and data scientists.

Finally, e-commerce supply chains are globally interconnected; hence, international collaboration is critical. Governments should encourage cross-border cooperation to standardize practices, share knowledge, and reduce inefficiency that could hinder adoption. By focusing on readiness, collaboration, and responsible innovation, policymakers can create an enabling ecosystem supporting the gradual adoption of quantum logistics while ensuring alignment with broader sustainability and resilience goals.

8.4 Future research directions

Although this study provides valuable insight, several areas warrant further exploration. First, future researchers should conduct longitudinal studies to examine the long-term influence of QC on logistics performance. Second, comparative studies should explore the differences in QC adoption across industries (e.g., healthcare logistics and automotive supply chains). Third, further research is necessary to investigate integrating QC with the blockchain for secure and transparent logistics operations. Fourth, future studies should investigate the behavioral aspects of

QC adoption, including managerial perceptions and employee resistance to change. Fifth, experimental studies using real-world quantum hardware should be conducted to validate the findings in large-scale logistics networks. Finally, the qualitative findings reveal varying readiness for quantum adoption, with many firms still reliant on evolving AI solutions. Future research should explore hybrid models to facilitate a smoother transition and examine organizational culture and leadership attitudes toward disruptive technology.

9 Conclusions

This study highlights the transformative potential of QC in logistics, enhancing efficiency, sustainability, and optimization. By applying quantum principles, firms can solve complex logistics challenges more effectively and efficiently than traditional AI-driven methods, reducing costs, delivery times, and environmental effects. Quantum algorithms, particularly QAOA and quantum annealing, play a crucial role in optimizing freight scheduling and route planning, whereas AI-quantum hybrid models further enhance logistics performance. Logistics optimization mediates the influence of QC adoption, reinforcing its role as a disruptive innovation in supply chain management. The comparative analyses confirmed that quantum-based models outperform traditional AI solutions. However, various challenges, including excessive costs, limited hardware availability, and scalability, remain barriers to widespread adoption.

The qualitative findings further strengthen these conclusions. The interviews revealed that firms adopting QC reported increased confidence in predictive analytics and decision-making yet concerns regarding data security and system interoperability persist. Logistics professionals emphasized the need for a collaborative ecosystem involving technology providers, policymakers, and academic institutions to drive the adoption of quantum technology. This study provides valuable insight into the application of QC in logistics and underscores the need for further research to develop cost-effective solutions and address implementation challenges. As this technology matures, QC is expected to revolutionize logistics, driving greater efficiency and sustainability.

APPENDIX 1: SURVEY QUESTIONNAIRE

Variables	Measurement Items (Likert Scale)	Reference
Quantum Computing Adoption	Our company is actively exploring quantum computing for logistics operations	[3, 8, 38–40, 40]
	We have invested in quantum technologies for logistics optimization	
	Our team is trained in quantum computing applications for logistics	
	Quantum computing is a strategic priority for our logistics and supply chain	
	We have tested quantum computing in at least one aspect of our logistics operations	
Quantum Algorithms Usage	Our company has implemented quantum optimization algorithms in logistics	[3, 38–40]
	Quantum Approximate Optimization Algorithm (QAOA) has improved our routing efficiency	
	Quantum Annealing has been used for scheduling and demand forecasting	
	Quantum algorithms have significantly reduced delivery times	
	Quantum logistics optimization outperforms classical AI models in our experience	
AI-Quantum Hybrid Models	Our company integrates AI with quantum computing for logistics	[38–41]
	The AI-quantum hybrid approach has improved real-time logistics decision-making	
	AI and quantum computing together have optimized freight scheduling	
	AI-quantum models provide better predictive analytics for supply chain risks	
	Our AI-quantum system outperforms stand-alone AI in logistics	
Logistics Optimization	Quantum computing has helped optimize delivery routes	[3, 8, 38]
	Freight scheduling efficiency has improved due to quantum-powered logistics	
	Warehouse and inventory management have benefited from quantum computing	
	Logistics optimization has contributed to reduced fuel consumption	
	Quantum-enabled logistics models have reduced waste and inefficiencies	

Variables	Measurement Items (Likert Scale)	Reference
Logistics Efficiency	Quantum computing adoption has reduced logistics costs	[38]
	Delivery times have improved with quantum computing in logistics	
	Our supply chain performance has improved with AI-quantum hybrid models	
	Quantum-powered logistics decision-making has enhanced service quality	
	Quantum optimization has eliminated inefficiencies in our logistics system	
Logistics Sustainability	Quantum-powered logistics planning has reduced carbon emissions	[42]
	AI-quantum hybrid models have promoted sustainable logistics	
	Fuel consumption has decreased due to quantum-optimized routing	
	Quantum logistics planning aligns with green logistics goals	
	Our company is committed to using quantum computing for environmental sustainability	

APPENDIX 2: DEMOGRAPHIC INFORMATION

Classification of Variables	Valid Frequency	%	Mean	Std. Error	Std. Deviation	Variance	Skewness	Std. Error	Kurtosis	Std. Error
Gender			1.21	0.409	0.168		1.446	0.241	0.092	0.478
Male	249	79.55								
Female	64	20.44								
Age			4.23	1.153	1.330		-0.142	0.241	-0.363	0.478
< 22	3	0.96								
23–28	12	3.83								
29–35	74	23.54								
36–45	86	27.48								
46–55	96	30.67								
56–60	37	11.82								
61 +	5	1.60								
Education			2.83	0.921	0.849		-0.513	0.241	-0.425	0.478
High School	21	6.71								
Bachelor's	136	43.47								
Master's	122	38.98								
PhD	44	14.07								
Job Role			3.21	1.078	1.162		-0.246	0.241	-0.502	0.478
Supply Chain Manager	94	30.03								
Logistics Coordinator	82	26.18								
Warehouse Manager	49	15.65								
Operations Manager	41	13.10								
Other	47	15.02								
Region			1.04	0.197	0.039		4.767	0.241	21.144	0.478

Classification of Variables	Valid Frequency	%	Mean	Std. Error	Std. Deviation	Variance	Skewness	Std. Error	Kurtosis	Std. Error
Pakistan	299	95.52								
Other	14	4.47								
Relevant Experience			3.90	1.567	2.455		0.330	0.241	-0.673	0.478
< 1	9	2.88								
2–5	54	17.25								
6–10	86	27.48								
11–15	49	21								
16–20	69	15.65								
21–25	27	8.63								
26 +	19	6.07								
Company Size			2.31	0.821	0.674		-0.321	0.241	-0.401	0.478
Small (1–50 employees)	76	24.28								
Medium (51–500 employees)	122	38.98								
Large (500 + employees)	115	36.74								
Industry Type			3.14	1.312	1.722		-0.276	0.241	-0.569	0.478
E-commerce	81	25.88								
Manufacturing	98	31.34								
Retail	63	20.13								
Transportation & Logistics	45	14.38								
Other	26	8.27								

APPENDIX 3: SUMMARY OF THEMATIC CODING FROM EXPERT INTERVIEWS (USING NVIVO)

Main Themes	Sub-Themes	Summary of Expert Responses
Applications of Quantum Computing	Route Optimization	Quantum algorithms (QAOA, Quantum Annealing) improve delivery speed and reduce fuel costs
	Warehouse Optimization	Quantum computing enhances storage allocation and minimizes energy consumption
	Freight Scheduling	Quantum models reduce scheduling conflicts and optimize shipment loads efficiently
Comparison with Traditional AI	Speed and Efficiency	Quantum models solve NP-hard problems faster than AI but are still in early development
	Scalability	Experts noted that while quantum is promising, hybrid AI-quantum models work best currently
Impact on Sustainability	Carbon Emission Reduction	More precise logistics reduce fuel usage and environmental impact
	Energy-Efficient Routing	Quantum algorithms optimize multi-stop deliveries, cutting excess fuel consumption
Challenges in Adoption	Hardware Limitations	High costs and limited access to quantum hardware slow down practical applications
	Algorithm Development	Need for specialized quantum logistics algorithms that outperform AI consistently
Security and Ethical Considerations	Cybersecurity Risks	Experts warn of potential vulnerabilities requiring post-quantum encryption
	Fair Decision-Making	Ethical concerns about bias in AI-quantum hybrid models used for logistics decision-making

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Declarations

Conflicts of interest The authors declare no competing interests.

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