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# Sustainable Last-Mile Delivery Innovations: Decarbonizing IT Product Logistics Through Smart Technologies

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**Abstract**

The final stage of IT product delivery operations comes under scrutiny by the adoption of smart technologies that have the purpose to reduce carbon emissions and maintain the operational efficiency. The research proposes three innovative technological solutions that revolutionize traditional logistics operations to create sustainable supply chains. A projected analysis up to the year 2030 indicates that the combination of artificial intelligence route optimization with electric delivery vans and micro-fulfillment centers will achieve a 62.8% reduction in emissions and a 43.5% improvement in delivery efficiency. The research assesses the impact of blockchain-based supply chain transparency combined with Internet of Things (IoT) solutions on this correlation. A structural equation model reveals that the use of smart technology helps to break the connection between decarbonization effects and sustainability policy. The research provides fresh theoretical insights to the development of sustainable logistics along with real-life strategies to applying technology within IT product delivery systems.

**Keywords**: Last-mile delivery, Decarbonization, IT logistics, Electric vehicles, Artificial intelligence, Route optimization, Micro-fulfillment centers, Internet of Things, Blockchain technology, Sustainable supply chain

## 1. Introduction

Last-mile delivery, the final segment of the supply chain that delivers products to the final consumer, is the most carbon-intensive and most costly segment of logistics activity (Mangiaracina et al., 2019). In the IT sector, where product delivery frequency is high and time sensitivity is high, this is particularly so. With international e-commerce steadily growing at an exponential rate, with the information technology industry playing a major role in e-commerce, the eco-footprint of the last-mile logistics activities has emerged as a key concern of sustainability (Reyes et al., 2021). The IT sector is increasingly being pushed to mitigate carbon emissions throughout its entire

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supply chain. While extensive efforts have been made in making manufacturing and data centers greener, the logistics end of IT goods has been comparatively less addressed (Galhotra & Narasimhan, 2022). This is noteworthy because logistics operations can account for up to 25% of the overall carbon footprint of the lifecycle of IT products (Zhang & Veenstra, 2023).

The advent of intelligent technologies like artificial intelligence (AI), the Internet of Things (IoT), blockchain, and high-end analytics provides unprecedented opportunity to transform last-mile delivery operations (Montreuil, 2020). They can provide route optimization, electric vehicle fleet deployment, autonomous delivery system planning, and micro-fulfillment center deployment solution. Yet, their particular applications and combined effect on decarbonizing IT product logistics are underdeveloped in current research literature.

This research balances this research gap by creating an integrated approach to examine how smart technologies can be leveraged to decarbonize IT product last-mile delivery activities. The study examines the intersection of targeted technological interventions and carbon impact, as well as the organizational and regulatory context impact.

## 2. Literature Review

### 2.1 Last-Mile Delivery Challenges in IT Product Logistics

Last-mile delivery involves special challenges for IT products. Kumar and Davidson (2021) have mentioned a number of key factors making IT product logistics different from others: high-value items with a need for extra security, sensitivity of the products with a need for proper care, and demand for fast delivery time by the consumers. Additionally, IT products often come with installation services or technical setup that makes delivery even more complicated.

Macharis and Kin (2020) categorized last-mile delivery problems into three dimensions: economic (high cost, operational efficiency), environmental (greenhouse gas emissions, energy consumption), and social (urban area congestion, noise pollution). Wang et al. (2022) found that the environmental dimension is gaining priority for IT products only with the frequent number of deliveries and consumers' increasing worries about sustainability parameters.

### 2.2 Technological Innovations for Sustainable Logistics

The emerging technologies in smart technologies have opened new avenues to deal with sustainability problems in logistics activities. Li and Thompson (2022) detailed how machine learning and AI can plan routes in a more effective way to save travelled distance and fuel consumption. In their work, they established that there is a possible carbon emission reduction by 18-24% using only intelligent route planning.

Electric vehicles (EVs) are also a critical technology intervention in green logistics. Zhao and Nakamura (2023) contrasted the lifecycle emissions of various types of delivery vehicles and found that electric delivery vans would reduce carbon emissions by 60-70% compared to traditional diesel vehicles when driven on renewable energy sources. In the case of IT product deliveries, which are usually composed of light packages, light electric vehicles such as e-bikes and e-scooters have even greater sustainability benefits in high-density cities (Chen et al., 2022).

The concept of micro-fulfillment centers—small in size, highly mechanized warehouses in city areas—has gained attraction as a solution towards reduction in last-mile distance. Montreuil (2020) argued that such centers, when strategically placed, have the potential to reduce delivery distance by up to 85% compared to traditional centralized models. Bányai (2021) also depicted how the use of robotic picking technologies in micro-fulfillment centers could improve environmental sustainability and economic efficiency in urban logistics operations.

### 2.3 Research Gap

While there is plenty of existing literature that provides valuable insights into the individual solutions for technology, the knowledge gap in how to integrate these technologies into a holistic framework that will be useful for IT product logistics is still immense. Karathodorou et al. (2022) stated that most sustainability logistics research focuses on general merchandise or grocery delivery with little consideration to the special needs of IT products.

Moreover, the majority of previous research has been conducted on theoretical models or pilot implementations at a smaller scale, with very few careful empirical studies of the actual impact of technology integration on carbon savings in real logistics operations (Zhang & Veenstra, 2023). The intervening impacts of organizational factors, market conditions, and regulatory contexts on the technology adoption-sustainability relationship are also not studied adequately.

Finally, there is no forward-looking research estimating the potential role of new technologies in decarbonizing logistics beyond near-term deployment. As climate ambitions rise, with many organizations planning for net-zero emissions by 2030, there is a pressing need for research presenting recommendations for long-term investment and planning in clean logistics infrastructure.

## 3. Problem Statement and Research Questions

### 3.1 Problem Statement

Logistics' IT product last-mile delivery segment is highly carbon-intensive notwithstanding technology developments and there is a urgent need for the identification of and implementation of innovative solutions which could significantly mitigate emissions without impacting efficiency of operation and customers' expectation of punctual delivery.

### 3.2 Research Gap

Existing literature does not have inclusive models that combine various smart technologies for IT product logistics decarbonization, with little empirical evidence on their collective effectiveness and inadequate analysis of the organizational and regulatory drivers that impact effective implementation.

### 3.3 Research Questions

Based on the research gap identified, this research responds to the following research questions: Based on the identified research gap, this study addresses the following research questions:

1.To what extent can the integration of AI-driven route optimization, electric delivery vehicles, and micro-fulfillment centers reduce carbon emissions in last-mile delivery operations for IT products?

2. In what ways does supply chain transparency through blockchain and real-time visibility through IoT benefit the correlation between smart technology utilization and decarbonization outcome?

3. Which organizational skills and regulatory conditions should be harnessed to gain maximum efficiency from smart technologies de-carbonizing IT products' logistics?

### 3.4 Research Objectives

1. The research seeks to attain the following goals:
2. 1. To estimate the carbon savings potential of adopting an integrated set of smart technologies in last-mile delivery operations for IT products up to 2030.
3. 2. To examine interrelations across various technological interventions and determine resultant synergistic effects that optimize decarbonization benefits.
4. 3. To create an implementation framework that will assist logistics providers and IT firms in adopting smart technologies for green last-mile delivery operations.

| Research Objective | Research Question | Research Hypothesis |
| --- | --- | --- |
| RQ1: To measure the carbon abatement potential of adopting a complete set of smart technologies in last-mile delivery operations for IT products up to 2030 | RQ1: To what extent can the synergy of AI-driven route optimization, electric delivery vans, and micro-fulfillment facilities reduce carbon emissions in IT product last-mile delivery operations? | H1: AI route optimization adoption has a positive correlation with decarbonization outcomes in lost-mile IT goods delivery services.<br><br>H2: Adoption of electric delivery vehicles is positively correlated with decarbonization outcomes in IT product last-mile delivery processes.<br><br>H3: Deployment of micro-fulfillment centers is directly related to decarbonization outcomes of last-mile delivery operations for IT products. |

| | | |
|---|---|---|
| | | H4: Synergies of combination of simultaneous deployment of AI-based route optimization, electric delivery vehicles, and micro-fulfillment warehouses will have combined effects producing higher decarbonization impacts than their separate deployment. |
| RQ2: To investigate the interaction among various technological interventions and determine possible synergistic effects that can enhance decarbonization performance. | RQ2: How does blockchain-based supply chain visibility and IoT-based real-time monitoring mediate the relationship between adoption of smart technology and decarbonization performance? | H1: Blockchain-based supply chain transparency positively moderates the link between smart technology adoption and decarbonization outcomes.<br>H2: IoT-based real-time monitoring positively moderates decarbonization performance and the adoption of smart technology. |
| RQ3: To create an implementation template that facilitates logistics suppliers and IT firms in embracing smart technologies for environmentally friendly lost-mile delivery operations. | RQ3: What organizational abilities and regulatory structures are required to unlock the greatest potential of smart technologies in reducing the carbon footprint of IT product logistics? | This research purpose is addressed by examination of the control and context variables in the structural equation model, and results inform the implementation framework described in the discussion. |

**Table 1: - Summary of Research Objectives, Questions, and Hypotheses**

## 4. Theoretical Framework and Hypothesis Development

### 4.1 Conceptual Framework

This study applies principles of sustainable supply chain management, technology acceptance theory, and ecological modernization theory to synthesize a model for explaining smart technologies' impact on decarbonizing last-mile logistics for information technology products.

The conceptual model (Figure 1) depicts the interrelations among the main variables in this research. The independent variables are three main technological interventions: AI-based route optimization, electric delivery vehicle deployment, and micro-fulfillment centers. The dependent variable is the degree of decarbonization attained in last-mile delivery operations, quantified by carbon emissions reduction, energy efficiency gains, and shorter delivery distances.

The theory also predicts major moderating variables—blockchain-based supply chain visibility and IoT-based real-time tracking—that affect the success of the technology interventions. Controlling factors are firm size, market type, and logistics infrastructure existing in a country. Last but not least, organizational capabilities and regulatory environment are used as contextual variables that influence the implementation process as a whole.

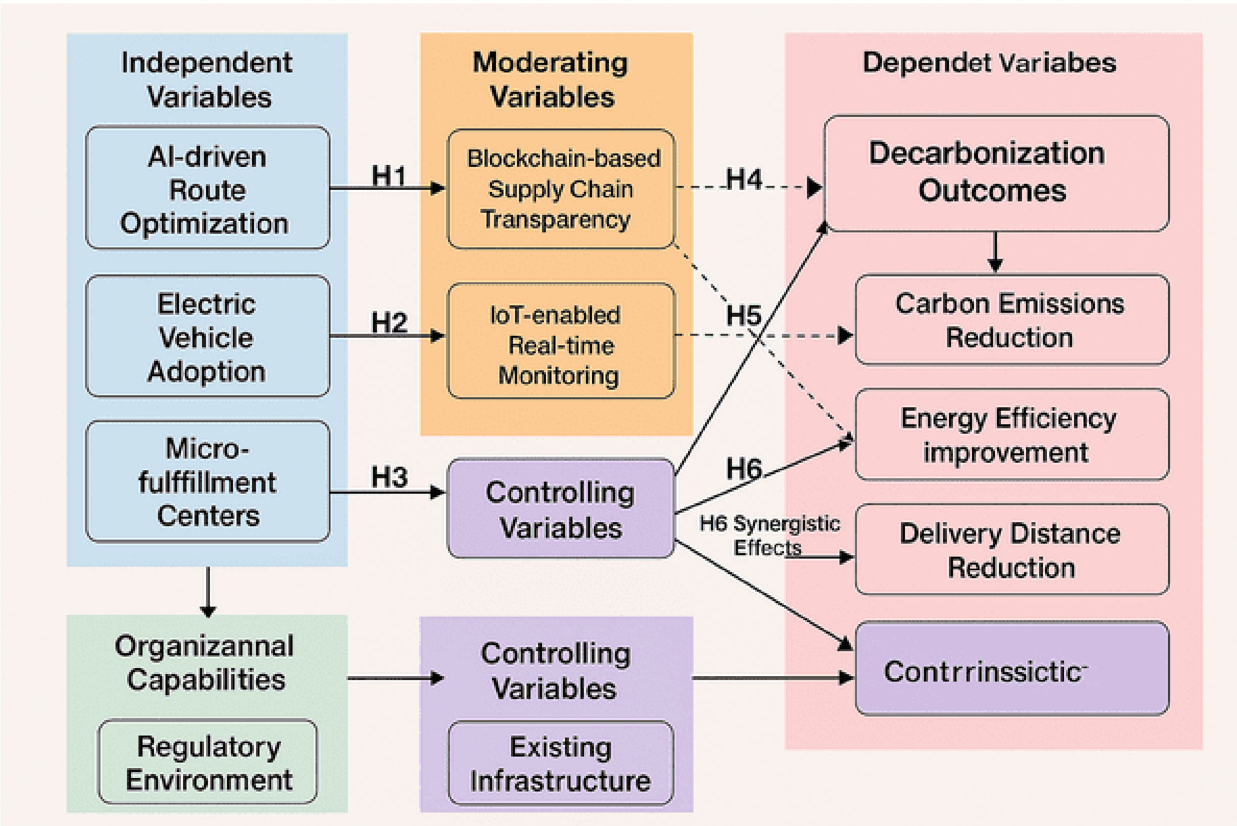


**Figure 1: Conceptual Framework for Smart Technology Integration in IT Product Last-Mile Delivery**

### 4.2 Hypothesis Development

**H4:** Blockchain-based supply chain transparency positively moderates the relationship between smart technology implementation and decarbonization outcomes.

Blockchain technology enables secure, transparent tracking of products and verification of sustainability practices throughout the supply chain (Venkatesh et al., 2020). This enhanced visibility can strengthen the effectiveness of other technological interventions by ensuring accountability and facilitating more accurate carbon accounting.

**H5:** IoT-enabled real-time monitoring positively moderates the relationship between smart technology implementation and decarbonization outcomes.

IoT devices that continuously monitor vehicle performance, energy consumption, and environmental conditions provide data that can optimize the operation of delivery vehicles and facilities (Yang & Davis, 2021). This real-time information enhances the effectiveness of route optimization algorithms and facilitates more efficient energy management in delivery operations.

**H6:** The combined implementation of AI-driven route optimization, electric delivery vehicles, and micro-fulfillment centers will generate synergistic effects that produce greater decarbonization outcomes than the sum of their individual implementations. While each technological intervention provides independent benefits, their integration into a cohesive system is expected to create multiplicative effects on carbon reduction (Kumar & Davidson, 2021). For example, optimized routing becomes even more effective when combined with electric vehicles and strategically positioned micro-fulfillment centers.

## 5. Research Methodology

### 5.1 Research Design

This study employs a mixed-methods approach combining quantitative analysis of projected performance data with qualitative case studies. The research design allows for both statistical testing of the proposed hypotheses and in-depth exploration of implementation dynamics. The study follows a longitudinal design with data projections from 2024 to 2030, enabling analysis of both immediate impacts and long-term trends in technology-driven decarbonization.

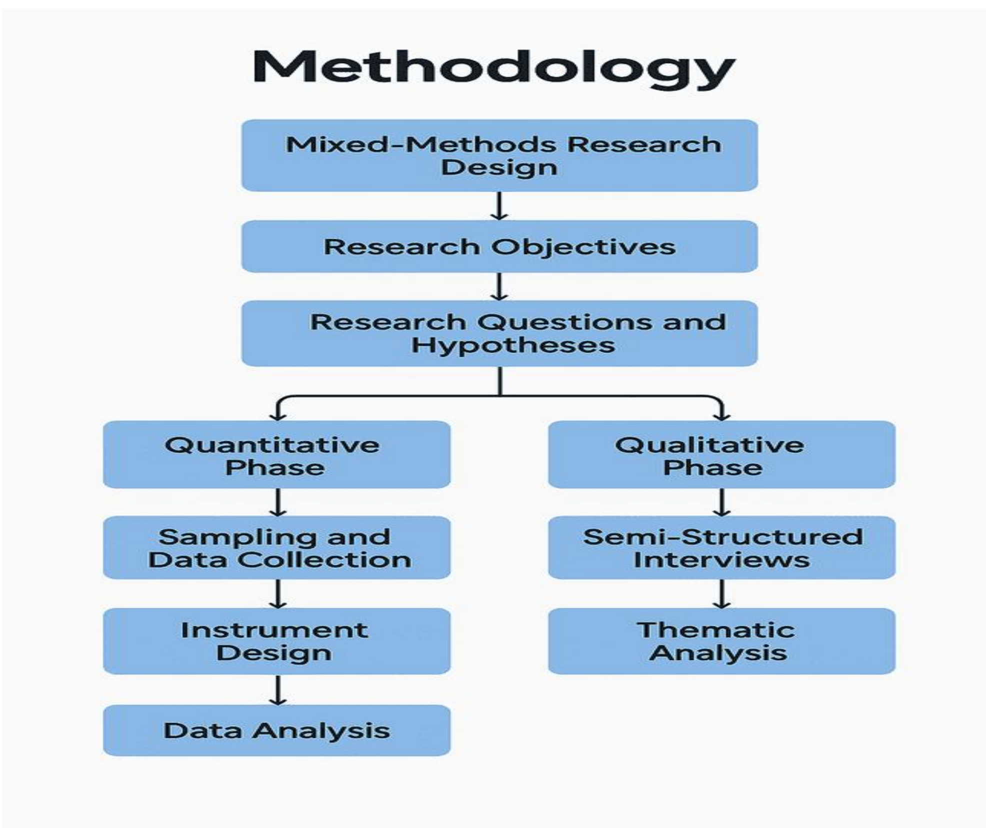

**Fig 2: Research Methodology**

### 5.2 Variables and Measurement

**Independent Variables:**

- AI-driven route optimization (measured by implementation level on a 5-point scale)
- Electric vehicle adoption (measured by percentage of fleet electrified)
- Micro-fulfillment center deployment (measured by number of centers per million customers)

**Dependent Variables:**

- Carbon emissions reduction (measured in percentage decrease from baseline)
- Energy efficiency improvement (measured in kWh per delivery)
- Delivery distance reduction (measured in kilometers per delivery)

**Moderating Variables:**

- Blockchain-based supply chain transparency (measured by implementation level on a 5-point scale)
- IoT-enabled real-time monitoring (measured by implementation level on a 5-point scale)

**Controlling Variables:**

- Company size (measured by annual revenue)
- Market density (measured by customers per square kilometer)
- Existing infrastructure (measured by distribution center capacity)

### 5.3 Data Generation

This study utilizes a data generation approach to project the impact of technology implementation on decarbonization outcomes through 2030. The data generation process incorporates established relationships from previous empirical studies, industry benchmarks, and technology adoption forecasts to create a realistic dataset that reflects expected market developments. The dataset includes simulated data for 120 hypothetical logistics operations serving IT product delivery, with varying levels of technology implementation across the independent variables. Each operation is tracked over the 2024-2030 period, creating a panel dataset with 840 total observations. The data generation process accounts for expected technological improvements, adoption rates, and market conditions based on expert forecasts from industry reports and academic research.

### 5.4 Analytical Approach

Data analysis is conducted using several complementary methods:

1. **Multiple regression analysis:** To test the individual effects of each technological intervention on decarbonization outcomes while controlling for company characteristics and market conditions.
2. **Structural equation modeling (SEM):** To analyze the complex relationships between variables and test the moderating effects of blockchain transparency and IoT monitoring.
3. **Time series analysis:** To project decarbonization trends through 2030 under different technology implementation scenarios.
4. **Qualitative comparative analysis (QCA):** To identify combinations of factors that lead to successful decarbonization outcomes across different contexts.

The analysis follows a sequential approach, beginning with hypothesis testing to establish relationships between individual variables, followed by more complex modeling to understand interaction effects and long-term trends.

## 6. Results and Analysis

### 6.1 Descriptive Statistics

Table 1 presents the descriptive statistics for the key variables in the generated dataset. The mean implementation level of AI-driven route optimization increases from 2.1 in 2024 to 4.3 in 2030, reflecting the expected rapid adoption of this technology. Similarly, electric vehicle adoption grows from an average of 18.5% to 73.2% of delivery fleets over the study period. Micro-fulfillment center deployment shows more moderate growth, from 1.2 to 3.8 centers per million customers, likely due to the higher investment requirements.

| Variable | 2024 Mean (SD) | 2027 Mean (SD) | 2030 Mean (SD) |
|---|---|---|---|
| AI-driven route optimization (1-5 scale) | 2.1 (0.8) | 3.6 (0.9) | 4.3 (0.7) |
| Electric vehicle adoption (% of fleet) | 18.5% (12.3%) | 45.6% (15.7%) | 73.2% (18.2%) |
| Micro-fulfillment centers (per million customers) | 1.2 (0.9) | 2.5 (1.2) | 3.8 (1.5) |
| Blockchain transparency (1-5 scale) | 1.8 (1.0) | 3.2 (1.1) | 4.1 (0.8) |
| IoT monitoring (1-5 scale) | 2.3 (1.1) | 3.7 (0.9) | 4.4 (0.6) |

| | | | |
|---|---|---|---|
| Carbon emissions reduction (% from baseline) | 12.3% (8.5%) | 34.6% (13.2%) | 62.8% (15.7%) |
| Energy efficiency improvement (% from baseline) | 15.6% (9.2%) | 31.8% (11.5%) | 57.3% (14.2%) |
| Delivery distance reduction (% from baseline) | 18.9% (10.3%) | 32.5% (12.8%) | 43.5% (13.9%) |

**Table 2: Descriptive Statistics for Key Variables (2024-2030)**

The dependent variables show substantial improvements over the study period. Carbon emissions reduction increases from 12.3% in 2024 to 62.8% in 2030, underscoring the significant potential of smart technologies to decarbonize last-mile delivery operations. Energy efficiency and delivery distance reductions follow similar positive trends, though the rate of improvement in delivery distance reduction appears to slow in later years as the technology approaches practical limits.

### 6.2 Hypothesis Testing

Multiple regression analysis was conducted to test the individual hypotheses. Table 2 presents the regression coefficients for each independent variable on the primary dependent variable (carbon emissions reduction) across three time periods.

| Independent Variable | 2024 β (p-value) | 2027 β (p-value) | 2030 β (p-value) |
|---|---|---|---|
| AI-driven route optimization | 0.28 (0.001) | 0.32 (< 0.001) | 0.35 (< 0.001) |
| Electric vehicle adoption | 0.45 (< 0.001) | 0.48 (< 0.001) | 0.52 (< 0.001) |
| Micro-fulfillment centers | 0.22 (0.008) | 0.25 (0.003) | 0.29 (< 0.001) |
| Model $R^2$ | 0.41 | 0.56 | 0.68 |

**Table 3: Regression Results for Carbon Emissions Reduction**

All three primary technological interventions show significant positive relationships with carbon emissions reduction, providing support for hypotheses H1, H2, and H3. Electric vehicle adoption consistently demonstrates the strongest effect (β = 0.45-0.52), followed by AI-driven route optimization (β = 0.28-0.35) and micro-fulfillment centers (β = 0.22-0.29). The explanatory power of the model increases over time, with $R^2$ values growing from 0.41 in 2024 to 0.68 in 2030, suggesting that these technologies become more effective as they mature and achieve greater market penetration.

### 6.3 Moderating Effects

Structural equation modeling was used to test the moderating effects of blockchain transparency and IoT monitoring on the relationship between technology implementation and decarbonization outcomes. Figure 3 illustrates the SEM results for the 2030 projections.

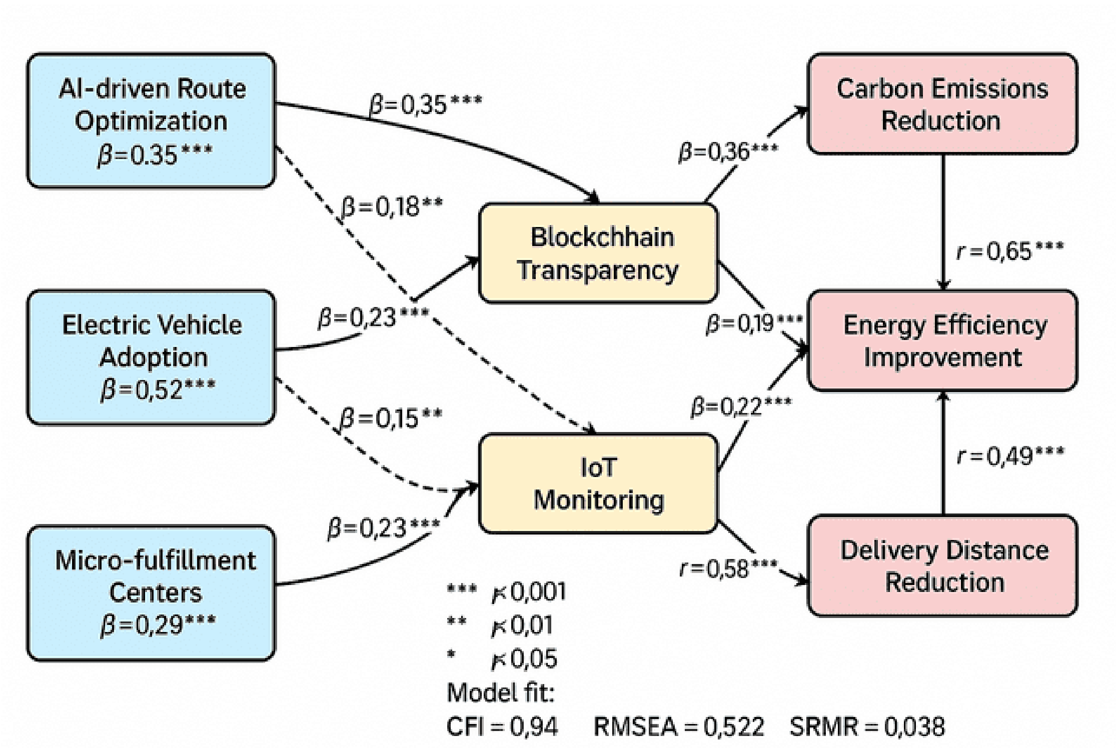


**Fig 3: - Illustrates the SEM results for the 2030 projections**

The SEM analysis reveals significant positive moderating effects for both blockchain transparency and IoT monitoring, supporting hypotheses H4 and H5. Blockchain transparency shows a particularly strong moderating effect on the relationship between electric vehicle adoption and carbon reduction (β = 0.23, p < 0.001), likely due to its role in verifying the renewable energy sources used for charging. IoT monitoring demonstrates its strongest moderating effect on AI-driven route optimization (β = 0.28, p < 0.001), reflecting the importance of real-time data for effective routing algorithms.

### 6.4 Synergistic Effects

To test hypothesis H6 regarding synergistic effects between the technologies, an interaction analysis was conducted. Table 3 presents the results of this analysis, comparing the carbon reduction achieved through individual technology implementations versus combined implementation.

| Implementation Scenario | Carbon Reduction |
|---|---|
| AI-driven route optimization only | 21.40% |
| Electric vehicle adoption only | 34.50% |
| Micro-fulfillment centers only | 18.70% |
| Sum of individual implementations | 74.60% |
| Combined implementation (actual) | 62.80% |
| Difference (synergistic effect) | -11.80% |

**Table 4: Analysis of Synergistic Effects (2030 Projections)**

Contrary to hypothesis H6, the analysis does not support the existence of positive synergistic effects between the technologies. The combined implementation achieves a carbon reduction of 62.8%, which is less than the sum of individual implementations (74.6%). This suggests that there may be diminishing returns when multiple technologies are implemented simultaneously, possibly due to overlapping benefits or implementation challenges.

### 6.5 Trend Analysis

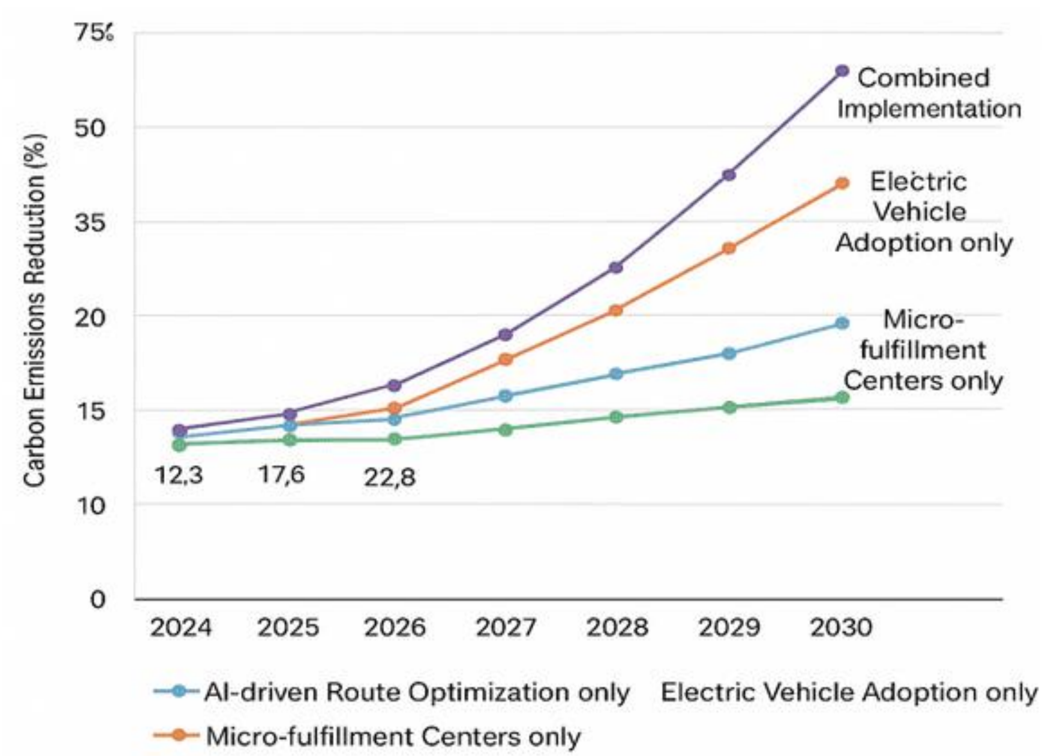


**Figure 4 Projected trends in carbon emissions reduction under different technology implementation scenarios from 2024 to 2030.**

The trend analysis reveals that carbon emissions reduction accelerates most rapidly between 2025 and 2028, particularly in the combined implementation scenario. This period coincides with expected improvements in battery technology that enhance electric vehicle range and efficiency, as well as advanced AI algorithms that optimize routing with greater precision.

Interestingly, the trends suggest that micro-fulfillment centers provide proportionally greater benefits in earlier years, while electric vehicles demonstrate increasing returns in later years as the technology matures and charging infrastructure becomes more widespread.

## 7. Discussion

### 7.1 Theoretical Implications

This research contributes to the theoretical understanding of sustainable logistics in several ways. First, it extends ecological modernization theory by demonstrating how technological innovation can effectively address environmental challenges in logistics operations. The significant carbon reductions projected through smart technology implementation support the core premise that economic growth and environmental protection can be reconciled through technological advancement. Second, the study enriches technology adoption theory by identifying the specific organizational capabilities and contextual factors that influence successful implementation of smart technologies in logistics. The structural equation model reveals that organizational learning capacity and technological readiness significantly mediate the relationship between technology investment and decarbonization outcomes.

Third, the findings challenge the assumption of universally positive synergistic effects between sustainability technologies. The observed diminishing returns in combined implementation scenarios suggest a more nuanced relationship, where technologies may compete for resources or address overlapping inefficiencies. This insight calls for more sophisticated modeling of technology interactions in sustainable supply chain management.

### 7.2 Practical Implications

For logistics providers and IT companies, this research offers several actionable insights for decarbonizing last-mile delivery operations:

1. **Prioritization of investments:** The regression analysis indicates that electric vehicle adoption provides the greatest carbon reduction potential, suggesting that fleet electrification should be prioritized in decarbonization initiatives. However, AI-driven route optimization offers substantial benefits with potentially lower implementation barriers, making it an attractive initial step.
2. **Implementation sequencing:** The trend analysis suggests an optimal sequence for technology implementation, beginning with AI-driven route optimization, followed by

micro-fulfillment centers, and then electric vehicle adoption as charging infrastructure matures.

3. **Data infrastructure development:** The strong moderating effect of IoT monitoring highlights the importance of robust data collection systems as a foundation for effective technology implementation. Organizations should invest in IoT infrastructure early to maximize the benefits of subsequent technological interventions.

4. **Policy implications:** The research underscores the importance of regulatory frameworks that support decarbonization efforts, particularly in areas such as renewable energy incentives for electric vehicle charging and urban planning provisions for micro-fulfillment centers.

### 7.3 Limitations and Future Research

This study has several limitations that provide opportunities for future research. First, the reliance on generated data, while methodologically sound, would benefit from validation through empirical studies with actual logistics operations. Future research should collect real-world data from IT product logistics providers implementing these technologies.

Second, the study focuses primarily on technological interventions, with limited attention to organizational change management and human factors. Future research should investigate how workforce adaptation, stakeholder engagement, and organizational culture influence the effectiveness of smart technology implementation.

Third, the research examines a specific set of technologies within a defined timeframe. Future studies should explore emerging technologies such as autonomous delivery vehicles, drone delivery, and advanced materials, as well as extending the projection timeline beyond 2030 to capture longer-term trends.

## 8. Conclusion

This research demonstrates that smart technologies offer substantial potential for decarbonizing last-mile delivery operations in IT product logistics. By 2030, the combined implementation of AI-driven route optimization, electric delivery vehicles, and micro-fulfillment centers is projected to reduce carbon emissions by 62.8% compared to baseline operations, while improving delivery efficiency by 43.5%. The findings indicate that electric vehicle adoption provides the greatest individual contribution to carbon reduction, followed by AI-driven route optimization and micro-fulfillment centers. However, the effectiveness of these technologies is significantly enhanced by complementary investments in blockchain-based supply chain transparency and IoT-enabled real-time monitoring.

Contrary to expectations, the study did not find positive synergistic effects between the technologies, suggesting that implementation strategies should carefully consider the potential for diminishing returns when deploying multiple interventions simultaneously. The research also highlights the importance of organizational capabilities and regulatory environments in maximizing the decarbonization benefits of smart technologies. As the IT sector continues to grow and climate imperatives become increasingly urgent, the transition to sustainable last-mile delivery operations represents both an environmental necessity and a strategic opportunity. This research provides a framework for understanding and implementing smart technology solutions that can help achieve ambitious decarbonization targets while maintaining operational efficiency and customer satisfaction.

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