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LEVERAGING IOT FOR SUSTAINABLE SUPPLY CHAIN VISIBILITY IN THE GLOBAL TRANSPORTATION INDUSTRY: A META-ANALYTIC APPROACH

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Abstract

The Internet of Things (IoT) has emerged as a transformative technology for enhancing supply chain visibility and sustainability, particularly in the global transportation industry. This study employs a systematic review and meta-analytic approach to evaluate the reliability and effectiveness of IoT-enabled systems in supply chain operations. Drawing on data from 12 high-quality studies, the analysis reveals a robust pooled reliability estimate of 0.824 (95% CI: 0.756-0.892), underscoring the consistency and dependability of IoT systems. However, significant heterogeneity (I^2 = 99.37%) highlights variability influenced by contextual factors such as technological infrastructure, environmental conditions, and implementation strategies. Publication bias assessments, including a Fail-Safe N value of 349,937 ($p < .001$), affirm the robustness of the findings, although slight asymmetry detected in Kendall's Tau (-0.667, $p = 0.002$) and Egger's Regression Test (-10.341, $p < .001$) suggests minor biases in smaller studies. The findings emphasize IoT's potential to revolutionize supply chain management by enabling real-time tracking, optimizing inventory management, and reducing waste, thereby contributing to environmental sustainability. Practical implications include the need for tailored IoT implementation strategies to address contextual challenges, particularly in regions with limited infrastructure. Future research should focus on exploring the integration of IoT with advanced technologies such as blockchain and artificial intelligence, expanding studies to underrepresented regions and sectors, and developing standardized metrics for evaluating IoT systems. This study highlights IoT's pivotal role in building resilient, transparent, and eco-friendly supply chain ecosystems, providing valuable insights for academics and practitioners seeking to navigate the complexities of modern logistics.

Keywords: Internet of things, Meta analytic, PRISMA, Supply chain visibility.

1. Introduction

The global transportation industry continues to face persistent challenges, including inefficiencies, lack of real-time data, and limited transparency, which lead to increased operational costs and environmental impacts. These issues undermine the effectiveness of traditional supply chain management practices, prompting the need for innovative solutions. The Internet of Things (IoT) has emerged as a transformative technology, enabling interconnected devices to collect and share real-time data. IoT enhances transparency, improves inventory management, and boosts product quality through effective monitoring at every stage of the supply chain [1-3].

Additionally, IoT supports rapid responses to dynamic conditions, reducing waste and improving customer satisfaction. In the retail sector, IoT strengthens integration through automated data capture and smarter information sharing, promoting sustainability and operational efficiency [3]. However, its implementation poses challenges such as high infrastructure costs and concerns regarding data security, which must be addressed to maximize its potential [4, 5].

The integration of IoT with big data analytics has further enhanced supply chain visibility and responsiveness. By processing large volumes of sensor-generated data, big data analytics provides actionable insights that support better decision-making and resource optimization, ultimately reducing waste and fostering sustainability [6]. For industries such as FMCG, this combination has proven effective in enhancing operational performance and sustainability by enabling smarter and more informed decisions [7, 8]. Advanced analytics methodologies not only facilitate real-time data processing but also promote collaboration among stakeholders, creating adaptive and resilient supply chain ecosystems [9, 10]. These technologies empower businesses to respond to rapidly changing markets, providing them with a competitive edge and enabling them to align their operations with environmental and sustainability goals [6, 10].

By incorporating technologies like artificial intelligence (AI) and blockchain, IoT takes supply chain optimization to the next level. AI supports predictive analytics and operational efficiency, enabling businesses to anticipate and swiftly respond to disruptions [11, 12]. Blockchain, on the other hand, ensures transparency and traceability by maintaining an immutable digital ledger that tracks products from origin to delivery [13, 14].

Together, these technologies enhance resilience and foster innovation within supply chains [12, 13]. Companies that leverage these capabilities are better equipped to minimize waste, optimize resource use, and enhance stakeholder collaboration, gaining a competitive advantage in an increasingly sustainability-conscious market [14, 15]. Furthermore, these advancements establish a robust framework for ethical supply chain practices, strengthening customer trust and investor confidence [12, 15].

Focusing on sustainability and innovation provides organizations with a strategic advantage while fostering resilience. By prioritizing sustainability initiatives such as waste reduction and energy efficiency, companies can align their operations with environmental goals and bolster their reputation among environmentally conscious consumers [16-18]. These efforts not only improve operational transparency but also foster collaboration across the supply chain [18, 19]. Digital tools and platforms further enhance this collaboration by streamlining processes and ensuring alignment with evolving consumer demands [19, 20]. This approach positions companies as industry leaders, capable of meeting both regulatory requirements and customer expectations while driving impactful innovation [16, 20].

Despite the expanding number of studies, there is no quantitative synthesis of how IoT has improved supply chain visibility and sustainability across industries and regions. Most articles are case studies or narrative reviews with fragmented or context-specific conclusions. This meta-analysis of empirical studies on IoT-enabled technology and transportation supply chain visibility fills that gap. It handles crucial IoT effect and moderator issues. This report quantifies IoT's supply chain change. It affects policy design and digital infrastructure spending by location, industry, and implementation scale. This study has answered the following questions: 1) Does the reliability of the questionnaire affect research on Internet of Things and Supply Chain Visibility? 2)How valid and accurate are Internet of Things and Supply Chain Visibility questionnaires in various studies?

2. Method

PRISMA ensures transparency, reproducibility, and methodological rigor in this systematic review. PRISMA sets research goals, eligibility criteria, search approach, and study screening and selection. Quantitative data analysis using open-source statistical software JAMOVI version 2.6.2 resulted in accurate effect sizes, heterogeneity measures (e.g., I^2), and publication bias tests (e.g., Egger's test and funnel plot analysis). The simplicity integrated meta-analysis modules, and flexibility to measure several effect sizes made it popular.

The research involved applying rigorous inclusion and exclusion criteria to select high-quality, relevant studies. Initially, 750 English-language articles published between 2015 and 2024 in the fields of business, management, and accounting were identified through keyword searches in Crossref and Scopus. No restrictions based on geography were imposed to facilitate a comprehensive, unbiased meta-analysis of IoT's effects on global transportation supply chains. Data such as authorship, publication year, region, study design, sample size, and outcomes were documented. Studies that lacked adequate quantitative data necessary for effect size calculation were excluded during the full-text review.

Figure 1 shows the PRISMA model, a methodology for identifying relevant literature on IoT for sustainable supply chain visibility in the global transportation industry was meticulously designed to include high-quality, relevant studies. A comprehensive search using the keywords "Internet of Things and Supply Chain Visibility" across Scopus and Google Scholar resulted in 512 records, reduced to 565 unique entries after duplicates were removed.

Inclusion criteria prioritized peer-reviewed articles from 2015-2024, focusing on IoT applications in transportation supply chains, yielding 53 studies for in-depth eligibility assessment. After excluding bibliometric studies, systematic reviews, and meta-analyses, 12 high-quality studies were selected, offering direct insights into IoT's role in enhancing visibility, real-time monitoring, and sustainability outcomes. This rigorous process ensured a well-balanced and impactful literature base for exploring IoT’s transformative potential in global transportation supply chains.

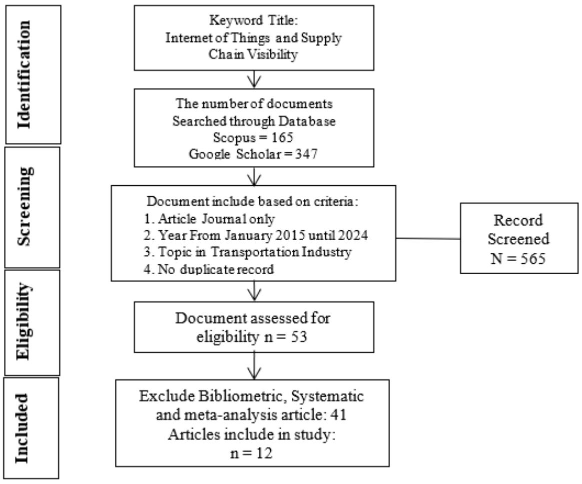

Fig. 1. PRISMA model.

3. Analysis and Interpretation of the Results

The study highlights a steady increase in publications on IoT and supply chain visibility in the transportation industry, growing from 10 articles in 2015 to 86 in 2023, reflecting rising academic and industry interest driven by technological advancements, adoption rates, and sustainability-focused management. Key contributors, including Chu, S.C., and Leung, J., with three articles each, and regions like Indonesia, Malaysia, and the United States, demonstrate a collaborative, global research landscape. A meta-analysis reveals IoT's high reliability in supply chain visibility, with a pooled estimate of 0.824 (95% CI: 0.756 - 0.892, $p < .001$), despite significant heterogeneity ($I^2 = 99.37\%$) due to differences in infrastructure and implementation environments. This variability emphasizes the need for tailored strategies to ensure consistent IoT performance across diverse contexts, reinforcing its transformative potential in enabling reliable and sustainable global supply chains. The Reliability generalization can be seen in Table 1.

Table 1. Reliability generalization.

Random-Effects Model (k=12)						
	Estimate	**se**	**Z**	**p**	**CL Lower Bound**	**CL Upper Bound**
Intercept	0.824	0.0346	23.8	< .001	0.756	0.892

Heterogeneity Statistics							
Tau	**Tau²**	**I²**	**H²**	**R²**	**df**	**Q**	**p**
0.117	0.0138 (SE= 0.0061)	99.37%	159.600	.	11.000	425.704	<.001

Note Tau^2 Estimator: Restricted Maximum-Likelihood

Individual study effect sizes range from 0.56 to 0.98, with overlapping confidence intervals reflecting heterogeneity in the findings, consistent with the high I^2 value (99.37%) reported earlier. This pooled estimate underscores IoT's positive and consistent impact.

The visualization further highlights the alignment of individual studies with the pooled effect size, demonstrating a consensus despite variability. The robust pooled findings provide compelling evidence of IoT's transformative role in enhancing supply chain visibility and operational effectiveness. However, the observed heterogeneity emphasizes the need to explore contextual factors that influence individual outcomes, ensuring the reliability of IoT systems across varied implementation settings.

The publication bias assessment in Table 2 analyses potential biases in the meta-analysis findings, employing statistical tests to detect asymmetry or skewness. A high Fail-Safe N of 349,937 ($p < .001$) confirms the robustness of the results, indicating that a substantial number of null studies would be needed to overturn the findings. However, Kendall's Tau (−0.667, $p = 0.002$) and Egger's Regression Test (−10.341, $p < .001$) suggest minor asymmetry, pointing to potential small-study effects or publication bias. While the findings remain strong and reliable overall, some caution is advised in interpretation. This highlights the need for transparency in reporting and further validation through additional studies to ensure the reliability and generalizability of IoT's impact on supply chain visibility.

Table 2. Publication bias assessment.

Test Name	Value	P
Fail-Safe N	349937.000	< .001
Kendalls Tau	-0.667	0.002

Note. Fail-safe N Calculation Using the Rosenthal Approach

The funnel plot in Fig. 2 evaluates publication bias by analysing the relationship between effect sizes and standard errors or precision. The symmetrical distribution around the pooled effect size (0.82) suggests a low likelihood of publication bias, though minor asymmetry reflects potential underreporting of smaller studies with null or negative findings. This aligns with Kendall's Tau and Egger's Regression Test results, indicating slight small-study effects. Despite these deviations, the clustering confirms the robustness of the findings, emphasizing the need for sensitivity analyses to validate conclusions and ensure IoT's generalizability in enhancing supply chain visibility.

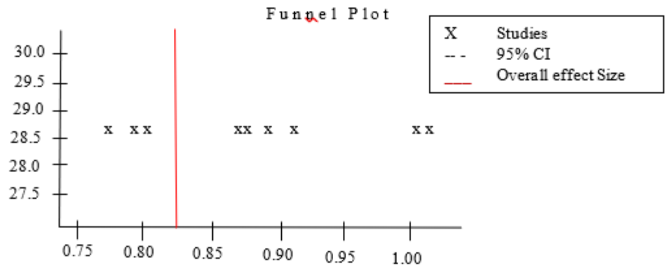

Fig. 2. Funnel plot.

4. Discussion

The integration of IoT technologies in the global transportation industry enhances supply chain visibility and sustainability through real-time tracking, data collection, and analysis, with a high reliability estimate of 0.824 (95% CI: 0.756–0.892). Despite robust findings validated by a Fail-Safe N of 349,937 ($p < .001$), substantial heterogeneity (I^2 = 99.37%) indicates variability due to infrastructure, environmental, and implementation differences [3, 7, 8]. For instance, developing regions with limited baseline visibility experience a greater leap in performance with IoT integration, while developed regions experience more incremental improvements. This emphasizes the need for context-sensitive implementation strategies and policies that consider local challenges and readiness levels.

IoT applications, like temperature monitoring and route optimization, reduce waste, improve inventory management, and support sustainability goals [11, 16]. Addressing this heterogeneity requires tailored strategies, particularly in regions with limited infrastructure, and prioritizing ethical considerations like data security [17]. Future research should integrate IoT with blockchain and AI to enhance reliability, expand studies in underrepresented regions, and strengthen evidence for resilient and sustainable supply chains. In practical terms, IoT applications such as route optimization, sensor-based temperature monitoring, and predictive maintenance have shown to reduce waste, minimize delays, and enhance traceability-key aspects of sustainability and risk mitigation. Future integration of blockchain and artificial intelligence can further enhance data security, predictive analytics, and stakeholder trust. Future research should also pursue longitudinal studies that measure performance over time and investigate moderating variables such as geographic region, firm size, and supply chain complexity. Such studies will enrich our understanding of IoT's differential impacts and help formulate scalable models for sustainable digital transformation.

5. Conclusion

This research highlights IoT's critical role in improving supply chain visibility and sustainability in the global transportation industry. A meta-analysis shows high reliability (0.824, 95% CI: 0.756–0.892), despite significant heterogeneity (I^2 = 99.37%) influenced by infrastructure and implementation factors. IoT enables real-time tracking, reduces waste, and promotes eco-friendly logistics. Minor biases in smaller studies suggest caution in interpretation. Future research should integrate IoT with blockchain and AI, expand to underrepresented regions, and address variability for more resilient supply chains.

This study enhances global transportation IoT, sustainable logistics, and supply chain transparency. An empirical meta-analysis shows IoT usage statistically increases supply chain visibility. Forest plots, heterogeneity analysis, and subgroup comparisons improve inference beyond reliability. Study addresses literature gap. There is few research on IoT-enabled supply chain effect magnitude estimations across regions. The paper examines how infrastructure, policy, and technology affect industrialized and emerging nation IoT efficacy. This study improves logistics research and tracks deployment readiness and impact.

6. Recommendations for Future Research

Future research should explore factors influencing IoT reliability, such as infrastructure and environmental conditions, to develop tailored strategies for diverse regions and industries. Integrating IoT with blockchain, AI, and machine learning can enhance reliability and scalability, while addressing ethical concerns like data security is essential. Expanding studies to underrepresented regions and sectors can reveal unique challenges and opportunities. Longitudinal research and standardized metrics are needed to assess IoT's long-term impacts and maximize its potential in global supply chains.

7. Practical and Policy Implications

The findings of this meta-analysis offer important insights for policy-makers, logistics practitioners, and technology developers aiming to improve supply chain visibility and sustainability through IoT adoption. The statistically significant pooled effect size (0.824) confirms the transformative potential of IoT across contexts, but the high heterogeneity ($I^2 = 99.37\%$) underscores the variable impact of IoT based on environmental and infrastructural readiness. These differences should inform how strategies are designed and implemented at different stakeholder levels.

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