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ARTIFICIAL INTELLIGENCE AND SUSTAINABILITY IN LAST-MILE DELIVERY

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Abstract

Last-mile delivery is the most critical and expensive segment of the supply chain, with significant environmental impacts, such as greenhouse gas emissions and noise pollution. To address these challenges, solutions like electric vehicles, local pickup points, and autonomous delivery technologies are emerging. Despite growing demand for efficient delivery, this segment faces persistent obstacles. Artificial intelligence offers promising opportunities to optimize last-mile logistics through improved inventory management, demand forecasting, and route planning, enhancing speed, efficiency, and customer satisfaction. However, adoption is hindered by high investment costs, data privacy concerns, and integration complexity. This paper presents a narrative literature review on AI applications in last-mile delivery, emphasizing sustainability. Findings highlight AI as a key enabler for greener, smarter logistics systems. The study also calls for interdisciplinary collaboration and policy support to accelerate AI adoption. Future research should focus on scalable solutions, ethical implications, and long-term impacts on urban environments and consumer behavior.

Keywords: *logistics, last-mile delivery, sustainability, AI*

1 INTRODUCTION

The growing emphasis on sustainable logistics has brought increased attention to its environmental impact, particularly in the last-mile delivery sector, which is a major contributor to carbon emissions and air pollution. [1] This stage of delivery represents the final stage of the supply chain, where goods are transported from production facilities to the end customer, and therefore it is the most challenging phase, since customer satisfaction depends directly on its efficiency. It is also the most expensive and inefficient part of the supply chain, requiring targeted improvements to enhance performance. [2]

The rapid growth of e-commerce and small-scale purchases has intensified environmental pressures in cities, leading to traffic congestion, increased greenhouse gas emissions, and noise pollution. [3] Fast shipping and reliable last-mile delivery strongly influence the purchasing decisions of customers. Therefore, growing consumer expectations and the necessity for firms to lower operational costs, further intensify the need for optimization in this stage of the supply chain.[2] The impact of the last mile extends beyond sales, relying on adequate infrastructure, urban planning, and sustainability measures, since transportation is a significant source of pollution. Current estimates indicate that last-mile delivery accounts for more than 30% of transport-related emissions in urban areas, with this share expected to rise by 2030 due to the continuous expansion of e-commerce. [4]

Traditional truck-based delivery methods face mounting challenges, including congestion, stricter environmental regulations, and rising fuel prices, which drive the transition toward greener alternatives such as electric vehicles, cargo bikes, and drones. These challenges highlight the urgent need to reassess last-mile logistics and adopt sustainable, eco-friendly practices. [2], [3] In Table 1, challenges in this part of the supply chain are shown, reflecting their influence on the efficiency of delivery.

Table 1. Challenges of the last-mile delivery [2]

Challenge	Influence
Cost efficiency	High shipping costs, more than 50%
Environmental impact	Negative effect on the environment- air and noise pollution
Urban congestion	Dense urban areas with limited infrastructure slow the delivery
Integration of technology	Challenges in synchronizing different technologies and implement them
Customer satisfaction	Growinf expectations, customers expect fast and reliable delivery

To remain competitive, alongside sustainability initiatives, modern logistics must embrace digitalization and innovative solutions. Artificial intelligence (AI) shows great potential, offering powerful tools for optimizing last-mile logistics through advanced route planning, demand forecasting, and dynamic scheduling. [5] At the same time, integrating electric vehicles (EVs) and other low-emission modes, such as cargo bikes and drones provides a direct path to decarbonization and noise reduction in urban areas. These innovations, supported by growing consumer preference for sustainable practices, are reshaping supply chains and driving the adoption of green delivery models, including micro-distribution hubs in dense city centers. [6] Ultimately, achieving sustainability in last-mile logistics requires not only technological solutions but also systemic

changes involving urban planning, policy support, and digital infrastructure.

The primary objective of this paper is to synthesize existing research and emerging trends to identify strategies for enhancing the sustainability of last-mile delivery without compromising customer satisfaction. Through a narrative literature review, the study examines current developments in last-mile logistics, focusing on approaches that reduce environmental impact while maintaining operational efficiency. Particular attention is given to the role of AI as a transformative tool for optimizing delivery processes.

2 METHODOLOGY

This paper employs a narrative literature review to synthesize recent research and emerging trends in sustainable last-mile delivery. The review focuses on studies published from 2021. onward to capture the latest developments in the field. Relevant literature was identified through systematic searches on Google Scholar using keywords such as: last-mile delivery, green last-mile delivery, sustainable last-mile delivery, AI in optimizing supply chain, green supply chain management, and AI in last-mile delivery.

The selection criteria prioritized papers that addressed sustainability in last-mile logistics, the role of AI in optimizing delivery processes, or both topics. The aim was to provide a comprehensive overview of current practices and innovations while highlighting interdisciplinary approaches. To ensure relevance, studies were chosen based on their contribution to understanding sustainability challenges, technological advancements, and consumer perspectives.

Connections among the reviewed studies were analyzed to identify citation patterns and thematic overlaps. These relationships are visualized in Figure 1, which illustrates the citation network and interlinkages between the selected papers, providing a structural overview of the research landscape.

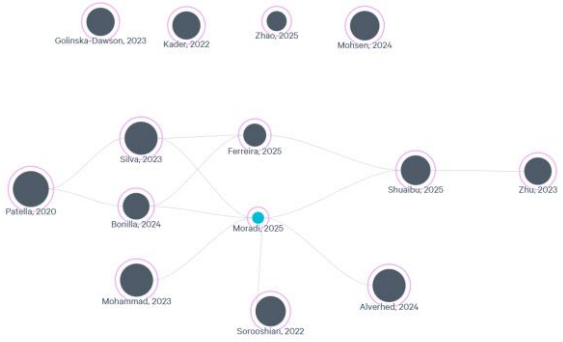

Fig. 1 Interconnection among selected studies

To illustrate the relationships among the reviewed studies, a citation network was created using Litmaps, an online tool for visualizing scholarly connections. The network highlights citation patterns and thematic clusters within the selected literature. However, one paper could not be represented in the visualization because it was not indexed in the Litmaps database. Despite this limitation, the figure provides a clear overview of the interconnections among most of the reviewed sources. Papers that are not connected to any other, represent a narrower focus, typically examining consumer adoption of emerging technologies or analyzing specific technological applications within the supply chain.

3. CURRENT TRENDS IN LAST-MILE DELIVERY

Last-mile delivery demand is projected to increase by 78% by 2030, accompanied by a 32% rise in emissions and a 21% increase in congestion. [7] While current practices focus on existing solutions, intelligent technologies are rapidly emerging and will play a central role in shaping future logistics systems. [8] These trends underscore the urgent need for sustainable and efficient solutions that minimize environmental impact while maintaining service quality.

To remain competitive and meet evolving consumer expectations, delivery companies are adopting a range of innovative solutions, including drones, autonomous robots, IoT-enabled systems, and AI-driven optimization, while simultaneously implementing green practices such as EVs, shared pickup stations, and cargo bikes. Despite their potential, some of these approaches, face significant barriers, including regulatory restrictions, inconsistent service quality, and technical limitations, which complicate widespread adoption. [1], [3] The next figure illustrates emerging technologies and alternatives for last-mile delivery aimed at improving efficiency and sustainability.

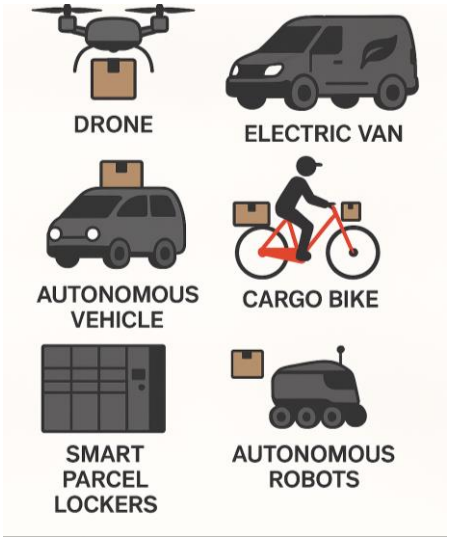

***Fig. 2** Last mile delivery alternatives*

3.1 Shared-pick up locations

Shared pick-up points, such as smart parcel lockers and other self-service collection stations, are becoming increasingly popular due to their convenience and ease of use. Typically installed in high-traffic locations like supermarkets, these solutions can lower operational costs by up to 12% and reduce emissions by approximately 18%. A key benefit of this model is reducing failed deliveries by allowing consumers to pick up packages at their convenience. The main challenge in installing parcel lockers lies in identifying suitable locations that are easily accessible, enhance logistical efficiency, and ensure profitability. However, to ensure long-term sustainability, further optimization of routing and location of parcel lockers is needed. AI tools can be effective in recognizing the optimal location of locker placement and delivery routing. [4], [9], [10]

3.2 Low-emission vehicles

The need for frequent, fragmented deliveries reinforces the shift toward smaller, electric-powered vehicles, cargo bikes, and other low-emission alternatives as a practical and eco-friendly solution for last-mile logistics. Although these vehicles typically have lower capacity and require more trips compared to traditional vans, they align well with the characteristics of e-commerce shipments, which are generally small and lightweight. Their use is particularly advantageous in dense urban areas. When combined with renewable energy sources, the environmental impact of these fleets decreases significantly, cutting greenhouse gas emissions and improving overall sustainability. [1]

3.3 Drones

Drones are still in the early stages of adoption for delivery services, but they offer a key advantage in parcel distribution by reaching areas that are difficult to access. Their use can significantly reduce traffic congestion, delivery times, costs, and environmental impacts. However, widespread acceptance remains limited due to challenges such as security concerns, privacy issues related to onboard cameras, and fears of job displacement, which raise social and regulatory barriers to implementation.[7], [10]

3.4 Delivery robots

Automation and digital connectivity are emerging as transformative forces in last-mile logistics. Autonomous delivery robots, along with AI-assisted electric vehicle fleets, are increasingly deployed in dense urban areas to enable faster, low-carbon deliveries. Robots can play a crucial role by automating short-distance and repetitive tasks, which helps reduce operational costs, delivery times, and greenhouse gas emissions. These systems also mitigate workforce shortages and improve reliability in congested environments. However, successful implementation faces challenges related to operations, infrastructure, regulatory compliance, and social acceptance, highlighting the need for supportive governance and a policy framework. [11]

4 POTENTIAL OF AI IN SUSTAINABLE LAST-MILE DELIVERY

The adoption of advanced technologies in last-mile delivery offers multiple benefits, including improved sustainability, enhanced operational performance, and overall efficiency. In this context, AI functions as a key technical facilitator for long-term sustainability, supporting companies in optimizing route management and broader operational workflows. To fully leverage these opportunities, businesses are encouraged to strategically invest in digital solutions that streamline route planning, enhance customer communication, and enable real-time monitoring of deliveries. [7].

Predictive analytics powered by AI helps forecast demand patterns, allowing efficient allocation of resources and reduction of empty runs. [7] Furthermore, AI supports the integration of urban consolidation centers by optimizing shipment grouping and scheduling, thereby reducing congestion and emissions in city centers. These applications demonstrate that AI not only enhances operational efficiency but also contributes significantly to environmental goals in green supply chain management. [5], [12] By processing extensive datasets in real-time, AI offers critical insights and predictive capabilities that significantly enhance the efficiency of urban logistics operations. [12]

Beyond routing, AI supports automation through autonomous vehicles, drones, and robots, reducing labor costs and improving efficiency. Although fully AI-driven last-mile systems remain in early development, concepts such as parcel pooling and autonomous delivery are emerging as promising innovations. [7] However, for AI to truly revolutionize last-mile delivery, it must move beyond isolated applications and be integrated into a comprehensive, adaptive framework that addresses both operational efficiency and environmental sustainability. [5]

4.1 Challenges

Although sustainable practices are largely policy-driven, AI integration beyond basic software applications remains mostly experimental in current research. Most studies rely on simulations or localized pilots, with limited evidence on large-scale deployment. [11] Moreover, gaps persist in the integration of human decision-making with autonomous systems, as logistics operators must balance algorithmic recommendations with contextual knowledge and social considerations. [1] Furthermore, the development of robust regulatory frameworks is essential to facilitate the widespread adoption of green last-mile delivery solutions, especially those leveraging advanced AI and EV technologies. [5]

5 CONSUMER WILLINGNESS TO PAY FOR GREEN DELIVERY

Consumer perception is a critical determinant in the adoption of green last-mile delivery solutions. While environmental awareness among consumers is rising, willingness to pay for eco-friendly delivery remains inconsistent. [13] Key factors influencing this willingness include income level, environmental consciousness, and perceived convenience. Research indicates that consumers are more likely to choose sustainable options when the additional cost is marginal and when benefits are clearly communicated. Understanding these behavioral patterns is essential for designing effective green delivery strategies and pricing models. [13], [14] For instance, while smart parcel lockers provide notable sustainability benefits that consumers acknowledge and are willing to use, they remain hesitant to pay a premium for such services, indicating mixed signals regarding willingness to pay. [15] To strengthen consumers' intention to choose greener delivery options, green marketing strategies should clearly communicate and demonstrate the benefits of these choices. [16] This approach ensures that green logistics initiatives are not only environmentally sound but also economically viable and socially acceptable.

6 CONCLUSION

As urban areas face increasing congestion and transportation remains a major contributor to pollution, the need for systemic change in last-mile delivery is undeniable. Current practices, such as the use of electric

vehicles, parcel lockers, and cargo bikes, demonstrate progress toward greener logistics, while emerging technologies like drones and autonomous robots are being tested for future scalability. The future of sustainable logistics lies in combining green transportation modes with intelligent technologies, creating adaptive frameworks that ensure efficiency, competitiveness, and environmental responsibility.

AI stands out as a transformative enabler in this transition. Its ability to optimize routing, analyze large datasets, predict demand, and support real-time decision-making positions AI as a critical tool for improving operational efficiency and reducing emissions. By integrating AI-driven strategies with sustainable delivery models, companies can achieve both environmental compliance and customer satisfaction.

Future research should therefore focus on developing scalable AI ecosystems that harmonize environmental, economic, and social dimensions of urban logistics. Such systems would require open data standards, cross-sectoral collaboration, and adaptive governance models capable of regulating emerging technologies while promoting innovation. Addressing these challenges will determine whether AI fulfills its potential as a genuine catalyst for the sustainable transformation of last-mile logistics.

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