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EMERGING TECHNOLOGIES IN GREEN AND SUSTAINABLE LOGISTICS MANAGEMENT

CAMILA DOS SANTOS PANTOJA
UEPA - UNIVERSIDADE DO ESTADO DO PARÁ

MAYANE TAISSA TRINDADE RODRIGUES
UEPA - UNIVERSIDADE DO ESTADO DO PARÁ

ALINE DE OLIVEIRA FERREIRA
UEPA - UNIVERSIDADE DO ESTADO DO PARÁ

IGOR DE JESUS LOBATO POMPEU GAMMARANO

HÉLIO RAYMUNDO FERREIRA FILHO
UEPA - UNIVERSIDADE DO ESTADO DO PARÁ

Introdução
Sustainability, seen as a systemic concept integrating economic, social, cultural and environmental aspects, has become a strategic necessity beyond ethics. In this scenario, green logistics and sustainable supply chains stand out, addressing waste and freight impacts. Adopting such practices reduces costs, mitigates environmental effects, and enhances competitiveness, though barriers remain. This study asks: how can emerging technologies support their consolidation?

Problema de Pesquisa e Objetivo
This study analyzes how emerging technologies can consolidate green logistics, enhancing sustainability and competitiveness. It seeks to identify applicable technologies, evaluate their economic, social, and environmental benefits, and examine barriers to adoption. Based on these findings, it aims to propose guidelines and recommendations to strengthen the integration of technological solutions in favor of sustainable logistics practices.

Fundamentação Teórica
Logistics manages flows of goods, services, and information, optimizing resources and ensuring efficiency. Green logistics focuses on reducing environmental impacts through emission control, waste reduction, and sustainable technologies. Sustainable logistics goes further, integrating environmental, social, and economic dimensions, promoting responsible practices, innovation, and alignment with the SDGs.

Metodologia
The research is exploratory, qualitative, and descriptive, conducted through an integrative literature review on sustainable logistics and emerging technologies. Data were collected from 2020–2025 in major databases, academic repositories, and institutional reports. Criteria favored recent and rigorous studies. Analysis considered applications, company size, contributions, and barriers, resulting in seven categories of emerging technologies identified in the literature.

Análise e Discussão dos Resultados
Emerging technologies like IoT, cloud computing, Big Data, and AI drive green logistics, improving efficiency, traceability, and sustainability, though adoption is harder for small firms due to costs and infrastructure. Waste management, through reverse logistics and monitoring systems, supports the circular economy, yet faces barriers of cost and awareness, while offering economic and environmental benefits.

Considerações Finais
Emerging technologies like IoT, AI, Big Data, and 3D printing strengthen green logistics, but adoption depends on company size, resources, and data quality. Large firms lead, while SMEs face barriers such as costs, skills gaps, and cultural resistance. Advancing requires innovation, policies, and collaboration to ensure competitiveness and sustainability.

Referências
ALMEIDA, J. M. Una revisión sistemática de las ventajas de la implementación de la logística verde em las industrias de Latinoamérica em las últimas décadas: una revisión de la literatura científica. 2021. Disponível em: . Acesso em: 02 jul. 2025. ANTT. Agência Nacional de Transportes Terrestres. Disponível em: https://www.gov.br/antt/pt-br. Acesso em: 04 ago. 2025.

Palavras Chave
Artificial intelligence, Emerging technologies, Reverse logistics

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1 INTRODUCTION

Growing concerns about environmental conditions have broadened the debates on sustainability, understood as a systemic concept that integrates economic, social, cultural and environmental dimensions. More than an ethical duty, it represents an essential business strategy to respond to legal and market requirements (Letunovska *et al*., 2023; Silva, 2016; Butt *et al*., 2023).

In this context, green logistics and sustainable supply chain management assume a prominent role, especially in the face of problems related to waste management and the impacts of freight transport (Sarkis, Zhu and Lai, 2011).

The adoption of sustainable practices demonstrates economic viability, by reducing costs and minimizing environmental effects, while strengthening organizational competitiveness. However, the consolidation of these practices still requires overcoming barriers such as high initial costs, cultural resistance and permanent need for innovation. Therefore, this study aims to answer: how can emerging technologies contribute to the consolidation of green logistics in the contemporary business environment?

2 THEORETICAL FOUNDATIONS

2.1 LOGISTICS

Logistics is understood as a multidisciplinary field focused on the planning and management of the flow of goods, services, and information. It is fundamental for optimizing operations, reducing costs, and enhancing customer satisfaction. Its relevance is widely discussed in literature, which highlights its strategic role, especially in the distribution and transportation of goods (Oliveira; Estender, 2012).

According to a widespread definition, logistics is the discipline that studies, in an organization (such as a private company, a public administration, a non-profit association, amilitary corps), the management and implementation of the operations concerning the flow of tangible goods (materials, food and medical supplies, refuse, equipment, weapons, etc.) from their sources (suppliers, mines, crop fields, etc.) to their points of utilization or consumption or disposal (retailers, landfills, army units, etc.) to meet the objectives of the organization (Ghiani; Laporte; Musmanno, 2022).

These authors state that to manage all these resources, it is necessary to incorporate a vision of a logistics system A logistics system is a set of interacting infrastructures, equipment, and human resources whose objective is, as whole, the execution of all the functional activities determining the flow of materials among a number of facilities.

2.2 GREEN LOGISTICS

Green logistics is defined as the study of the environmental effects of all activities involved in transportation, storage, and handling of physical products as they move through supply chains in both forward and reverse directions. It assesses the nature and scale of these effects and explores different ways to reduce them (McKinnon *et al*., 2015). This involves reducing carbon emissions, minimizing waste, conserving resources, and employing innovative technologies to create a more sustainable and environmentally conscious logistics ecosystem (Wilson, 2023). Unlike traditional logistics, which prioritizes cost and efficiency without

considering environmental consequences, green logistics integrates sustainability as a core principle.

Green logistics refers to the set of practices and strategies aimed at reducing the environmental impacts of logistics activities (Virgílio, 2022). It seeks to integrate sustainability throughout the supply chain by adopting processes that prioritize energy efficiency, waste reduction, and the use of renewable resources (Sharma, 2025).

The primary goal of green logistics is to create an eco-friendly supply chain that balances economic efficiency with environmental and social responsibility. This includes adopting cleaner energy sources, reducing greenhouse gas (GHG) emissions, implementing circular economy principles, and leveraging technology to enhance sustainability (Carter, 2025). Green logistics is the integration of economic efficiency and socio-environmental responsibility to reduce emissions, resource consumption, and waste generation, thereby supporting climate change mitigation and aligning with sustainable development and the circular economy (Solano et al., 2021; Oliveira; Mendes, 2024).

2.3 SUSTAINABLE LOGISTICS

Sustainable logistics is a strategic approach that integrates the principles of sustainable development into logistics operations, considering environmental, social, and economic aspects, aiming at an efficient and responsible supply chain that preserves natural resources and the well-being of future generations (Sarkis, Zhu, and Lai, 2011; Silva, 2016). Unlike green logistics, which focuses mainly on reducing environmental impacts, sustainable logistics takes a broader view, incorporating social responsibility and economic viability (Butt *et al*., 2023).

This approach includes practices such as ethical supplier management, valuing labor, using clean technologies, and promoting transparency and responsible innovation (Letunovska *et al*., 2023). This model represents an evolution of the traditional model, balancing economic performance, social justice, and environmental preservation, contributing to the fulfillment of the Sustainable Development Goals (SDGs) and strengthening organizational competitiveness and resilience (Mukherjee *et al*., 2024; Pinho *et al*., 2024).

Considering that sustainable logistics seeks to reconcile environmental, social, and economic aspects, going beyond reducing environmental impacts to also promoting social benefits. This more comprehensive approach can induce institutional, political, and economic changes that favor income distribution, better working conditions, and quality of life, contributing to a more socially balanced environment (Sarkis, Zhu, and Lai, 2011; Solano *et al*., 2021).

3 METHODOLOGY

The research is exploratory, qualitative, and descriptive in nature, based on an integrative literature review, which is appropriate for gathering and synthesizing knowledge on sustainable logistics and emerging technologies (Sarkis; Zhu; Lai, 2011; Mukherjee et al., 2024). Data collection was carried out between 2020 and 2025 in scientific databases (Scopus, Scielo, ScienceDirect, Google Scholar, CAPES), academic repositories (BDTD/CAPES, UFPA, USP, UFMG), and institutional reports from organizations such as SEBRAE, IBGE, UN, and ANTT (Letunovska et al., 2023). The inclusion criteria considered recent publications with methodological rigor, while duplicates or superficial studies were excluded. The analysis of the selected works considered applications, company size, contributions, and barriers, allowing the identification of seven main categories of emerging technologies, presented in Table 1 (Mukherjee et al., 2024; Sarkis; Zhu; Lai, 2011).

Table 1 - Analysis of Emerging Technologies in Green and Sustainable Logistics (2020-2025).

Technology	Main Applications	Contributions	Main Barriers	Sourcee
IoT and Cloud Computing	Real-time traceability and control	Reduction of waste and energy consumption	Infrastructure and systems integration	Mukherjee *et al.* (2024); Pinho *et al.* (2024)
Artificial Intelligence	Demand forecasting and predictive maintenance	Greater efficiency and lower CO_2 emissions	Costs and shortage of professionals	Mukherjee *et al.* (2024); Corrêa et al. (2020)
Big Data	Predictive analytics and logistics planning	Accurate planning and reduction of failures	Dependence on quality data	Leite *et al.* (2014); Pinho et al. (2024)
3D printing	On-demand and decentralized production	Less transportation and reduced waste	Low adoption and high cost	Corrêa *et al.* (2020)
Drones and Autonomous Vehicles	Fast deliveries and in hard-to-reach areas	Reduced emissions and agility	Legal limitations and costs	Pinho *et al.* (2024); Virgilio (2022)
RFID	Product monitoring	Increased traceability	Investment in labels/readers	Leite *et al.* (2014)
Waste Management Systems	Reverse logistics and selective collection	Impact and cost reduction	Lack of infrastructure and culture	Butt *et al.* (2023); Letunovska *et al.* (2023)

Source: Developed by the authors, based on Mukherjee *et al.* (2024), Pinho *et al.* (2024), Leite *et al.* (2014), Corrêa *et al.* (2020), Butt *et al.* (2023), Letunovska *et al.* (2023), Virgilio (2022).

4 ANALYSIS AND DISCUSSION OF RESULTS

4.1 EMERGING TECHNOLOGIES

Emerging technologies are essential for green logistics, promoting efficiency and reducing environmental impact. IoT, cloud computing, Big Data, and artificial intelligence form the basis of Logistics 4.0, optimizing processes and reducing resource consumption and emissions (Pinho *et al.*, 2024). IoT and cloud computing are technologies with the greatest investment potential, enabling efficient tracking and planning, while integration with RFID increases traceability in the supply chain (Mukherjee *et al.*, 2024; Leite *et al.*, 2014).

Small businesses face barriers to adopting these technologies, requiring public policies and cultural changes (Wang, Zeng, and Li, 2022; Pinho *et al.*, 2024). 3D printing, although not widely used, can reduce transportation through local production, while Big Data and AI enable predictive analytics and automation, however, they depend on infrastructure and technical qualifications, making their application in small businesses difficult (Leite *et al.*, 2014).

Artificial intelligence applied to logistics contributes to sustainability through intelligent routing systems, demand forecasting, and predictive maintenance, reducing fuel consumption and waste (Mukherjee *et al.*, 2024). However, adoption faces challenges such as costs, lack of infrastructure, and cultural resistance, especially in small and medium-sized enterprises (Pinho *et al.*, 2024). Nevertheless, AI shows great potential to transform sustainable logistics, aligning with current environmental and economic goals (Mukherjee et al., 2024).

4.3 WASTE MANAGEMENT

Waste management is an essential pillar of green logistics, focusing on the control, reuse, and correct disposal of waste in the supply chain, in line with the circular economy and social and environmental responsibility (Butt *et al.*, 2023). Reverse logistics, which involves

reintegrating products and materials into the production cycle through recycling and reuse, is enhanced by emerging technologies such as IoT sensors and tracking systems, which enable real-time monitoring and better planning (Letunovska et al., 2023).

Environmental management software also helps in complying with standards such as the National Solid Waste Policy (PNRS). However, challenges such as insufficient infrastructure, low awareness, and high costs for small businesses still hinder implementation. Even so, waste management offers opportunities to reduce costs, strengthen institutional image, and achieve environmental goals.

5 FINAL CONSIDERATIONS

This study shows that emerging technologies, such as IoT, artificial intelligence, Big Data, and 3D printing, offer great opportunities to improve and increase the use of green logistics as a tool to reinforce sustainable actions by companies. However, the adoption and implementation of these technologies depend on the size of the company, available financial resources, and the quality of data.

Large corporations are leading the transformation process, but these barriers must be overcome so that small businesses can also benefit and implement changes in their organizational structures. Waste management, through reverse logistics and technological monitoring, is essential activity for sustainability. Thus, consolidating green logistics requires technological innovation, effective public policies, and organizational engagement to ensure competitiveness and socio-environmental responsibility.

However, some relevant obstacles have been identified, such as the lack of integration between information systems, high costs of technological implementation, lack of skilled labor, and internal cultural resistance. For future research, it would be interesting to explore in more detail the reality of small and medium-sized enterprises, analyze the economic impact of adopting green technologies, investigate public policies that encourage sustainable innovation, and study collaborative supply chain models that can expand the reach of green logistics in different sectors.

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