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Digital Transformation of Postal Logistics Supply Chains toward Sustainability and Efficient Management from a Web 4.0 Perspective

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ABSTRACT

The development of sustainable supply chains in postal logistics has become a critical challenge and strategic priority in the context of accelerated digital transformation. The adoption of Web 4.0 technologies, including artificial intelligence, the Internet of Things, Blockchain, and advanced analytics, enables the transition from traditional logistics models to intelligent, adaptive, and data-driven processes. They simultaneously support management efficiency, environmental responsibility, and social sustainability. These technologies facilitate predictive planning, route optimization, enhanced transparency, and improved resource management. They result in reduced operational costs and greenhouse gas emissions, as well as increased reliability and quality of postal services. The integration of Web 4.0 technologies with sustainable operational practices, such as the use of electric vehicles, smart warehousing systems, and environmentally friendly packaging solutions, generates a synergistic effect that improves overall system efficiency, reduces the environmental footprint, and enhances customer experience. This paper provides a systematic overview of Web 4.0 technologies and sustainability-oriented practices in postal logistics, identifies their key benefits and implementation challenges. The research also demonstrates how their combined application supports long-term resilience, competitive advantage, and the transformation of postal logistics supply chains toward intelligent and sustainable systems.

1. Introduction

Contemporaneous postal systems are facing multiple challenges arising from increasing customer demands, intensified competition, and the growing requirements for sustainable business practices [1]. Traditional models of postal logistics are largely characterized by rigid structures and limited optimization capabilities, leading to higher resource consumption, increased operational costs, and a larger environmental footprint [2]. In this context, the development of sustainable supply chains in the postal services sector has become an imperative, as it enables the rationalization of service processes, the reduction of greenhouse gas emissions, and the improvement of service quality, while

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simultaneously balancing economic and environmental objectives of postal systems [1]. In parallel, digital transformation and the integration of advanced technologies represent a significant opportunity for the modernization of postal operations. Web 4.0 technologies, encompassing decentralized digital platforms, artificial intelligence (AI), advanced analytical tools, and blockchain, enable the creation of adaptive and intelligent supply chains [3]. These technologies support predictive resource planning, optimization of transport routes, the implementation of autonomous transport systems, and transparent shipment tracking, thereby significantly contributing to operational efficiency and environmental sustainability of postal services.

The implementation of Web 4.0 technologies in postal logistics not only improves performance and reduces costs but also enables the integration of sustainable practices into daily operations related to the fulfillment of stochastic customer demands. Transparency enabled by blockchain, combined with analytics and AI, contributes to improved resource management, waste reduction, and enhanced energy efficiency [3]. At the same time, the integration of decentralized platforms allows for more agile and flexible adaptation to demand fluctuations, which is particularly important for global postal networks operating in a dynamic and competitive environment [1,4]. The objective of this paper is to analyze the potential application of Web 4.0 technologies in the development of sustainable postal logistics supply chains, identifying key benefits, challenges, and limitations of their implementation. The paper also formulates guidelines for strategic digital transformation in this domain, emphasizing the synergy between technological innovation and sustainability principles. Particular emphasis is placed on the application of predictive logistics, autonomous transport systems, and blockchain technologies to establish efficient, transparent, and sustainable postal logistics supply chains.

2. Implementation of Sustainable Technologies and Practices in Postal Logistics

The implementation of sustainable technologies and practices in postal logistics represents a pivotal phase in the transition from traditional logistics models toward intelligent, digitally enabled, and environmentally responsible service systems. The alignment of technological innovation with the principles of sustainable development allows for the simultaneous enhancement of operational efficiency, service reliability, and the reduction of adverse environmental impacts [4]. In this context, sustainability is not treated as an isolated objective, but as an integral component of the overall digital transformation of postal logistics systems.

Particular emphasis is placed on the integration of Web 4.0 technologies, including AI, the Internet of Things (IoT), and blockchain, with sustainability-oriented operational practices. These practices encompass energy efficiency optimization, the deployment of sustainable and low-emission transport solutions, and the use of environmentally friendly and recyclable packaging materials [2,3]. Such integration enables data-driven decision-making, real-time monitoring of logistics processes, and enhanced transparency across postal supply chains, which collectively contribute to improved resource utilization and reduced environmental footprint.

This synergistic approach establishes a robust foundation for the development of postal logistics systems capable of responding to increasing market complexity, evolving customer expectations, and regulatory requirements related to sustainability. Moreover, it supports the strengthening of competitive advantage and long-term system resilience. Within this section, key technologies and sustainable practices facilitating this transformation are systematically examined, with a focus on their specific contributions to sustainability performance, operational efficiency, and the overall quality of postal services.

2.1 Role of Web 4.0 Technologies in Sustainable Postal Logistics Supply Chains

Web 4.0 technologies constitute a fundamental pillar for the transformation of postal logistics toward intelligent, flexible, and sustainable systems. AI enables predictive planning, delivery route optimization, and dynamic real-time adjustment of transport schedules, directly contributing to the reduction of transport costs, fuel consumption, and CO2 emissions [4]. In addition, AI and blockchain technologies support the analysis of large-scale datasets related to demand patterns, seasonal fluctuations, and traffic conditions, thereby reducing delivery delays and improving service reliability. Companies such as DHL and FedEx already employ AI-based systems for vehicle load balancing and predictive route planning, achieving significant energy savings, emission reductions, and more efficient utilization of transport capacities [1].

The IoT enables continuous shipment monitoring, as well as the control of temperature, humidity, and other parameters that are critical for maintaining product integrity, particularly in the transport of food, pharmaceuticals, and other sensitive goods. Through the use of IoT sensors, postal operators are able to respond to potential disruptions in real time, thereby minimizing losses and improving overall service quality.

Blockchain technology provides a high level of data transparency and security within postal supply chains [5]. Its application enables the verification of material authenticity and sustainability, tracking of the shipment life cycle, and the creation of digital green certificates for postal items. By reducing the risk of errors and increasing data integrity, blockchain enhances customer trust and facilitates regulatory compliance, especially with respect to environmental standards and sustainability certifications.

Advanced analytics, including predictive and descriptive data analysis techniques, support the optimization of warehouse capacity utilization, accurate resource planning, and waste reduction [6]. Analytical tools enable the identification of inefficiencies and inconsistencies across packaging, storage, and transport processes, contributing to improved resource management and lower operational costs. The integrated application of these Web 4.0 technologies allows postal operators to develop intelligent, flexible, and sustainable supply chains, enhance efficiency and reliability, reduce environmental impact, and deliver added value to customers through improved transparency and service quality. Despite the considerable benefits proposed by these technologies, their implementation is associated with several challenges. High investment costs related to digital infrastructure, the need for skilled personnel, cybersecurity risks, and regulatory constraints can slow down the digital transformation process [7]. Furthermore, the integration of heterogeneous systems and standards requires strong coordination among supply chain stakeholders, while organizational resistance to change and the need for continuous employee training further complicate the transition toward intelligent logistics models [1].

2.2 Sustainable Transport and Warehousing Systems

Electric and hybrid vehicles are increasingly becoming a standard component of modern postal logistics, representing one of the most effective solutions for reducing carbon dioxide emissions and fuel-related operating costs. Their application is particularly prominent in urban environments, where high delivery density enables the achievement of maximum economic savings and environmental benefits. For instance, Singapore Post and Deutsche Post DHL are actively testing and deploying electric vehicle fleets for last-mile delivery in urban areas, thereby reducing their environmental footprint while simultaneously strengthening their image as socially and environmentally responsible companies [8]. The significance of these technologies in postal logistics lies primarily in their ability to support the development of sustainable and reliable delivery systems

that comply with regulatory requirements and respond to growing customer expectations for environmentally friendly solutions.

Despite these advantages, several challenges limit the widespread adoption of electric and hybrid vehicles. These include high initial investment costs, limited availability of charging infrastructure, and a relatively shorter driving range compared to conventional diesel-based vehicles [9]. Addressing these limitations requires coordinated investments, supportive regulatory frameworks, and the integration of intelligent route planning and energy management systems, which can further enhance the operational viability of electric vehicle fleets within postal logistics networks.

In addition to transport systems, smart warehousing solutions play a critical role in the transformation of postal logistics. Automated material handling systems, energy-efficient lighting, climate control mechanisms, and intelligent space management enable optimal resource utilization and significant reductions in operational costs [1,9]. The use of sensors and digital monitoring systems allows for precise tracking of energy consumption, temperature, and humidity levels, which is particularly important for handling sensitive shipments and minimizing waste. These innovations contribute to lower greenhouse gas emissions while enhancing service reliability, processing speed, and delivery accuracy. Nevertheless, the implementation of smart warehouses is associated with several challenges, including substantial upfront investments, increased system complexity, and the need for continuous workforce training to ensure effective operation and maintenance of digital infrastructures [8]. Consequently, the successful deployment of sustainable transport and warehousing systems in postal logistics requires a holistic approach that integrates technological innovation, organizational adaptation, and long-term strategic planning.

2.3 Sustainable Packaging and Biodegradable Materials

Recycled and biodegradable packaging materials are becoming an indispensable component in the development of sustainable postal logistics, as they directly contribute to reducing environmental impact and supporting circular economy principles. Their adoption represents one of the most visible and tangible changes for end users, given that packaging often constitutes the largest share of waste generated after delivery [10]. Innovative solutions, such as paper-based and biodegradable materials, as well as compostable boxes and mailing bags, facilitate recycling processes, reduce the volume of non-recyclable waste, and relieve the burden on landfills.

Within postal logistics systems, the importance of sustainable packaging solutions lies in their ability to support regulatory compliance, enhance the public image of postal operators, and meet the growing expectations of environmentally conscious customers, which has increasingly become a key factor of competitiveness in global markets [7]. In addition, the integration of packaging systems with blockchain-based solutions introduces an additional dimension of sustainability by enabling transparent verification of material origin and environmental compliance throughout the entire supply chain. Through this approach, postal operators can certify green shipments, strengthen customer trust, and monitor sustainability performance in real time [6,9]. Leading global postal service providers have already begun combining innovative packaging materials with digital technologies to achieve higher levels of transparency, traceability, and corporate accountability.

Despite these advantages, the large-scale adoption of recycled and biodegradable packaging materials faces several challenges. These include higher costs compared to conventional packaging solutions, limited availability of certain materials, and the need for standardization and clearly defined regulatory frameworks. Furthermore, technical limitations related to durability, protective performance, and suitability for sensitive or high-value goods remain significant, indicating the need

for continued research and innovation in the development and application of sustainable packaging materials within postal logistics systems.

2.4 Digital Platforms and Customer Experience

Digital platforms represent a key driver of modernization in postal logistics, as they enable a high level of interaction between customers and postal operators. Through mobile applications and Web-based services, users can track shipments in real time, schedule deliveries according to their individual preferences, and communicate directly with operators in the event of delivery issues or additional service requests. Such solutions significantly enhance customer experience by reducing uncertainty, waiting times, and the frequency of failed deliveries. For example, postal service applications increasingly provide precise delivery time windows and automated customer notifications, which optimize service time management, reduce repeated delivery attempts, and improve overall operational efficiency [4].

The primary value of digital platforms in postal logistics lies in their ability to integrate data from multiple sources, including vehicles, warehouses, and customer demand information, and transform this data into actionable insights for intelligent decision-making. This integration supports more efficient resource utilization, cost reduction, and measurable environmental benefits, as a lower number of failed deliveries directly contributes to reduced fuel consumption and lower carbon dioxide emissions. From the customer perspective, digital platforms provide greater control and transparency over delivery processes, while for postal operators, they represent a strategic channel for building long-term trust, service reliability, and customer loyalty [8].

Despite their advantages, the implementation of digital platforms is associated with several challenges. The development and maintenance of advanced information technology infrastructure require substantial financial investments and specialized expertise. In addition, data security and privacy protection have become critical concerns, as large volumes of personal and logistics-related data must be safeguarded against potential misuse and cyber threats. Furthermore, differences in user digital literacy may limit the full utilization of platform functionalities, highlighting the importance of user-friendly interface design and targeted customer education as key priorities for postal operators.

3. Synergy of Technologies and Sustainable Practices

The combination of advanced technologies and sustainable practices in postal logistics has emerged as a key driver of transformation in contemporary parcel delivery systems. This synergy enhances operational performance while simultaneously reducing costs and environmental impact. The integration of Web 4.0 technologies, including AI, blockchain, IoT sensors, and advanced analytics, with sustainable solutions such as electric and hybrid vehicles, energy-efficient warehousing systems, and environmentally friendly packaging, establishes the foundation for adaptive, resilient, and sustainable postal logistics supply chains [9,10].

By enabling data-driven decision making, real-time monitoring, and predictive optimization, this integrated approach supports improved resource utilization, lower greenhouse gas emissions, and increased service reliability. Table 1 and Figure 1 summarize the key benefits, challenges, and limitations associated with the implementation of these technologies, as well as the specific advantages of selected Web 4.0 solutions within the postal sector.

Table 1
Impacts of advanced technologies and sustainable practices in postal logistics

Domain	Key advantages	Challenges and limitations	Overall impact
Web 4.0 technologies	Route optimization, predictive planning, shipment tracking, and error reduction	High initial investment costs, need for workforce training, integration with legacy systems	Reduced transport and warehousing costs, improved delivery reliability
Transport systems and vehicles	Reduced CO_2 emissions and improved energy efficiency	Limited charging infrastructure, regulatory constraints	Lower environmental footprint, energy savings
Warehousing systems	Efficient space utilization and optimized resource management	Need for infrastructure and software upgrades	Reduced energy consumption, higher operational efficiency
Packaging solutions	Waste reduction and support for the circular economy	Higher material costs, need for monitoring, and certification	Lower environmental impact, compliance with sustainability standards
Digital platforms and customer experience	Transparency, flexible delivery options, and efficient shipment tracking	Integration with existing service channels, data security concerns	Higher customer satisfaction, faster complaint resolution, and increased customer trust

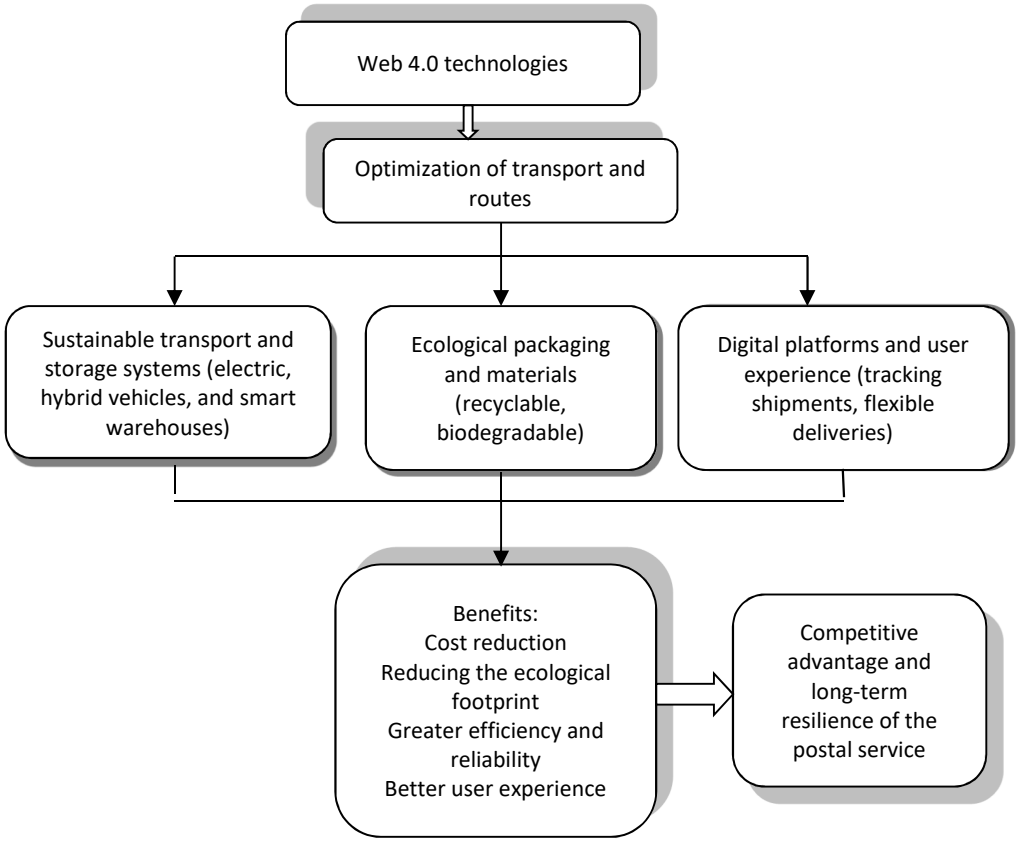

Fig. 1. Key advantages of implementing Web 4.0 technologies in postal logistics

The integration of contemporary Web 4.0 technologies with existing operational practices is shaping a new paradigm of postal logistics, in which technological advancement and sustainability function as interdependent drivers of development. Rather than evaluating efficiency solely through the lenses of speed and cost reduction, this modern approach incorporates broader criteria, including economic viability, environmental responsibility, social value creation, and the long-term resilience of postal logistics supply chains [2,6]. Such an orientation enables the development of more durable

and flexible supply chains, contributing to societal value creation through resource conservation and the mitigation of negative environmental impacts.

4. Discussion

The findings discussed in this study indicate that the implementation of Web 4.0 technologies in postal logistics supply chains offers substantial potential for improving operational efficiency while simultaneously supporting environmental, economic, and social sustainability objectives. However, the results also confirm that the implementation of these technologies represents a complex and multidimensional process that extends beyond purely technological considerations and requires coordinated organizational, economic, and regulatory alignment.

From an operational perspective, predictive logistics and route optimization emerge as key drivers of performance improvement. The results suggest that the use of AI and advanced analytics enables stable reductions in fuel consumption, maintenance costs, and carbon dioxide emissions, typically on the order of 20 %, primarily through improved routing efficiency, vehicle utilization, and demand anticipation [11]. These findings support earlier research indicating that digital optimization in postal logistics generates incremental but reliable gains rather than radical efficiency breakthroughs, reflecting the structural constraints of large-scale postal networks.

Customer-related performance indicators show more pronounced improvements. Digital platforms that support real-time shipment tracking, flexible delivery scheduling, and proactive customer communication are associated with reductions in failed delivery attempts of approximately 20 to 30 %, alongside measurable increases in on-time delivery performance and overall customer satisfaction [12]. This suggests that the primary strategic value of digitalization in postal logistics may lie not only in cost efficiency, but also in enhanced service transparency, reliability, and user trust, which are increasingly critical determinants of long-term competitiveness. From an environmental perspective, the discussion highlights that technological solutions alone are insufficient to achieve sustainability targets. While the deployment of electric delivery vehicles and energy-efficient warehouse systems can result in emission and energy reductions exceeding 30 % in urban delivery contexts, the magnitude of these benefits is highly dependent on the availability of supporting infrastructure, system integration, and operational coordination [13]. Similarly, sustainable packaging solutions deliver tangible environmental benefits through reductions in packaging waste and material consumption [14], yet their broader adoption remains constrained by cost considerations, material performance limitations, and the lack of harmonized standards.

Despite the observed benefits, several limiting factors may constrain the adoption of Web 4.0 technologies in the postal sector. Technical barriers include high initial investment requirements, interoperability challenges between legacy and new systems, and the need for continuous workforce training. Legal and regulatory uncertainties, particularly those related to autonomous vehicles, drone deliveries, and data protection, further complicate implementation efforts. In addition, organizational resistance to digital transformation and the need for structured change management highlight the importance of addressing human and cultural dimensions alongside technological innovation. Overall, the discussion underscores that the most significant and sustainable performance improvements are achieved when Web 4.0 technologies are implemented as part of an integrated transformation strategy, combining technological innovation with organizational adaptation and sustainable operational practices. This reinforces the argument that digitalization and sustainability in postal logistics need to be treated as mutually reinforcing processes [15] rather than isolated initiatives, providing a clear direction for both managerial decision-making and future academic research.

The development of sustainable supply chains in postal logistics represents a critical factor for improving operational efficiency, competitiveness, and system resilience under conditions of accelerated digital transformation and increasing customer expectations [16]. The adoption of Web 4.0 technologies enables a transition from traditional, rigid logistics systems toward intelligent, flexible, and adaptive processes that integrate environmental and social responsibility with economic sustainability [17]. Technological tools associated with Web 4.0, including AI, blockchain, the IoT, and advanced data analytics, support real-time shipment tracking, delivery route optimization, predictive maintenance of transport assets, and efficient management of warehouse capacities. These approaches enhance transparency and predictability, reduce delays and operational costs, and simultaneously contribute to lower carbon dioxide emissions and reduced resource consumption.

The deployment of electric and hybrid vehicles, smart warehouse systems with automated energy and temperature control [18], and the use of recycled and biodegradable packaging materials represent concrete measures toward reducing the environmental footprint of postal logistics. In parallel, digital platforms that facilitate coordination with partners and end users enable improved communication, faster complaint resolution, and greater service flexibility in response to diverse market requirements. Practical examples include automated warehousing solutions that optimize space utilization and energy consumption, customer-oriented digital applications that enable precise shipment tracking, and the use of blockchain technologies to ensure transparent tracking of parcels and materials across the entire supply chain.

The mitigation of negative effects and the maximization of the benefits associated with sustainable practices can only be achieved through an integrated and holistic implementation strategy [19]. Such an approach requires close cooperation with regulatory authorities, suppliers, and end users, supported by continuous performance monitoring and process improvement. The results suggest that synergy between technological innovation and sustainability principles maintains resilience and flexibility in postal logistics supply chains, while simultaneously creating a sustainable competitive advantage in a highly dynamic and uncertain global environment. Accordingly, future research should focus on several key areas that further bridge theory and practice and address emerging trends in sustainable and digitally enabled postal logistics, as summarized in Table 2.

Table 2
Practical examples, benefits, and future research directions in sustainable postal logistics

Category	Practical examples	Key benefits	Future research directions
Web 4.0 technologies	AI, IoT, blockchain, advanced analytics	Route optimization, real-time shipment tracking, and efficient warehouse management	Development of AI-based predictive decision support systems, and advanced route optimization models
Transport and vehicles	Electric and hybrid delivery vehicles	Reduction of CO_2 emissions and improved energy efficiency	Assessment of economic feasibility, scalability, and lifecycle impacts of sustainable vehicle fleets
Warehouse systems	Smart warehouses, automated sorting, and storage systems	Reduced energy consumption and improved space utilization	Energy-efficient automation, application of AI for adaptive warehouse management
Packaging	Recycled and biodegradable packaging materials	Reduced environmental footprint and support for the circular economy	Development of new sustainable materials and blockchain-based traceability of packaging throughout the supply chain
Digital platforms and customer experience	Shipment tracking applications, digital customer communication channels	Higher customer satisfaction, faster complaint handling, and increased service flexibility	Analysis of the impact of digitalization on customer experience and social sustainability

Contemporary postal logistics increasingly relies on the implementation of concrete technological and organizational solutions that simultaneously enhance operational efficiency and sustainability performance. The integration of Web 4.0 technologies represents a strategic pathway for transforming traditional postal supply chains into intelligent, flexible, and environmentally responsible systems [20]. The adoption of AI-based route planning, real-time shipment monitoring supported by the IoT, and blockchain-enabled data transparency enables postal operators to improve delivery reliability, optimize resource utilization, and reduce operational costs and carbon emissions.

5. Conclusion

The findings of this study indicate that the combined application of predictive logistics, automated and autonomous transport solutions, and digital platforms significantly strengthens transparency, trust, and coordination across postal logistics supply chains. In parallel, the deployment of electric and hybrid vehicles, energy-efficient warehouse systems, sustainable packaging materials, and digital documentation contributes to reducing environmental impact and supports compliance with increasingly stringent sustainability requirements. Beyond environmental benefits, these technologies facilitate greater flexibility and agility, allowing postal operators to adapt to fluctuating demand and evolving customer expectations rapidly.

The widespread implementation of Web 4.0 technologies in postal logistics should be viewed not merely as a technological upgrade but as a comprehensive transformation strategy that integrates operational optimization, sustainability principles, and customer-oriented innovation. By leveraging data-driven decision-making and digital connectivity, postal operators can develop renewed interaction models, enhance service quality, and strengthen their competitive position in a highly dynamic global logistics environment. The results highlight that long-term resilience and sustainable growth in the postal sector depend on the successful alignment of technological innovation with organizational capabilities and sustainability objectives.

Conflict of Interest

The authors declare no conflict of interest.

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