BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Circular Logistics Engineering: Minimizing Waste and Carbon Footprint

Qing Wang

Zhejiang Technical Institute of Economics, Hangzhou 310018, China

ABSTRACT

The shift from linear to circular economic systems has created new needs for the design of logistics systems, especially for minimising waste and reducing the carbon footprint. This review discusses how logistics engineering can incorporate the principles of a circular economy to support the realisation of more resource-efficient, low-carbon, and recovery-oriented supply systems. The article begins by elucidating the theoretical principles of circular logistics by contrasting it with traditional, green, reverse, and closed-loop logistics, and by emphasising the necessity of considering logistics as a multi-directional system to retain value rather than distributing products in a one-way manner. It subsequently develops key engineering advances, including sustainable transport, smart warehousing, reverse logistics infrastructure, reusable packaging, and digital technologies such as IoT, AI, and digital twins. The review also examines the optimisation models and decision-support strategies applied to balance cost, service, and waste reduction and carbon mitigation under uncertainty. Moreover, it assesses the barriers to implementation in terms of infrastructure, economics, organisational capacity, regulation and sector-specific conditions of operation. The article posits that the originality of logistics driven by the circular economy lies in its comprehensive approach to waste and carbon goals through engineering design, rather than distinct green interventions. The review concludes that the idea of circular logistics can become a vital facilitator of sustainable industrial change, but it will require the assistance of lifecycle-based assessment, integrated infrastructure, and context-specific implementation strategies.

Keywords: Circular Economy; Logistics System Design; Waste Minimisation; Carbon Footprint; Engineering Innovation

*CORRESPONDING AUTHOR:
Qing Wang, Zhejiang Technical Institute of Economics, Hangzhou 310018, China; Email: wangqing4207@163.com

ARTICLE INFO
Received: 19 May 2026 | Revised: 28 July 2026 | Accepted: 3 August 2026 | Published Online: 14 August 2026
DOI: https://doi.org/10.30564/jees.v8i8.13531

CITATION
Wang, Q., 2026. Circular Logistics Engineering: Minimizing Waste and Carbon Footprint. Journal of Environmental & Earth Sciences. 8(8): 847–875. DOI: https://doi.org/10.30564/jees.v8i8.13531

1. Introduction

The logistics industry faces dual challenges of environmental damage and carbon reduction. Logistics systems, encompassing transportation, warehousing, packaging, inventory management, and product recovery, are both central to economic activity and major contributors to resource depletion, waste production, and greenhouse gases [1]. Traditional logistics design follows linear economic logic: extract, produce, distribute, consume, discard. Efficiency has been narrowly defined as transportation cost reduction, lead time shortening, or inventory turnover. While still important, these objectives are insufficient given climate goals, environmental regulations, and societal demands for sustainable production [2–6].

The circular economy offers a powerful alternative to linear constraints. Focusing on reduction, reuse, repair, remanufacturing, recycling, and recovery, it aims to maintain material value while minimizing waste and environmental load. Logistics is determinant here—without effective forward distribution, reverse collection, sorting, refurbishment, and reintegration of secondary materials, circularity is impossible. Logistics thus becomes enabling infrastructure rather than passive support [7,8].

Despite growing interest in green supply chains, sustainable transport, and reverse logistics, the literature remains disjointed. Transportation decarbonization (electric vehicles, alternative fuels, route optimization) is studied separately from reverse logistics and closed-loop supply chains. Digital technologies (IoT, blockchain, digital twins, AI) are proposed for visibility and efficiency, but these streams rarely integrate. Many researchers optimize isolated logistics components without examining their interaction under circular economy goals. Others discuss circular economy conceptually without guiding how engineering innovations translate into integrated logistics system design. This gap between circular economy theory and real-world logistics engineering remains significant [9,10].

This gap matters because logistics environmental impact is multidimensional. Waste arises not only from packaging and damaged products but also from inefficient asset use, excess inventory, redundant transportation, and inability to recycle end-of-life products. Carbon emissions come from transport fuels, warehouse electricity, handling equipment, cold chains, and construction materials. Critically, measures to reduce one burden may unintentionally increase another, more frequent delivery reduces spoilage but increases transport emissions; reusable packaging reduces solid waste but requires collection, cleaning, and reverse transport [11–13].

Engineering innovations now make it possible to redesign physical flows, information flows, and decision-making to synchronize operational performance with circular economy objectives. IoT tracking enhances asset visibility and minimizes product loss. Digital twins model logistics networks and test circular strategies before implementation. AI-based forecasting optimizes capacity use and minimizes emissions. Warehouse automation and energy-efficient facilities reduce operational waste and power consumption. Modular unit loads, reusable packaging, and product-service-based logistics extend material life and reduce disposable resource use. At the network level, integrating collection centers, disassembly hubs, recycling facilities, and remanufacturing nodes transforms traditional logistics into circular value-retention systems [14].

Against this background, this review discusses how circular economy principles can be incorporated into logistics system design to reduce waste and carbon footprint through engineering innovations. We offer four novel contributions. First, we develop a comprehensive framework linking circularity principles (reduce, reuse, recycle, remanufacture) to tangible logistics design choices, network structure, facility layout, transport systems, handling technologies, and information infrastructure. Second, we simultaneously address waste reduction and carbon footprint reduction, identifying synergies, tensions, and trade-offs necessary for effective circular logistics. Third, we position engineering innovations as the operational interface between circular economy ambition and implementable solutions, synthesizing new technologies, information-based solutions, and optimization methods. Fourth, we identify unaddressed methodological and practical issues—performance measurement, uncertainty management, infrastructure compatibility, cross-actor coordination, defining a future research agenda [15–17].

Figure 1 shows the big-picture conceptual relationships among the principles of the circular economy, the design of the logistics system, engineering innovation, and environmental outcomes. With this, the review attempts to go beyond incremental sustainability interventions and a more structural re-conceptualisation of logistics architecture [18–22].

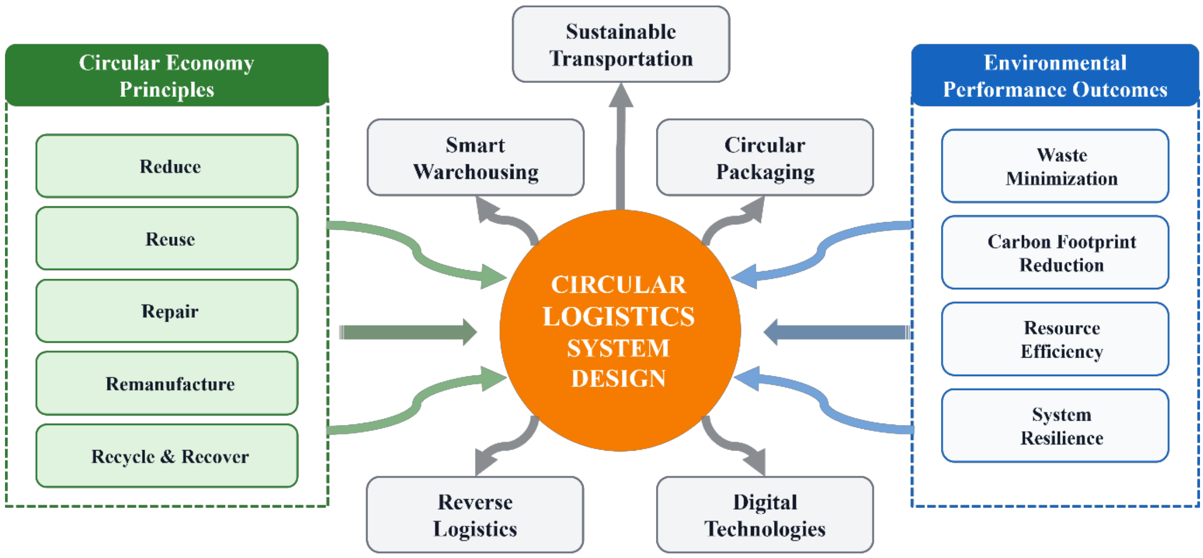

Figure 1. Conceptual framework linking circular economy principles, logistics system design, and environmental performance outcomes.

This review is also opportune. The world is targeting ambitious net-zero and waste-reduction goals set by governments and industries, and requires more transparent and sustainable models of product delivery in consumer markets. Meanwhile, negative impacts of global supply chains have highlighted the significance of resilience, localization, and resource security. The logistics powered by the circular economy present an avenue to deal with these interrelated issues and decrease reliance on virgin materials, decrease environmental impacts, and develop supply networks relying on recovery. However, unless a strict synthesis of existing knowledge is undertaken, the field runs the risk of being conceptually interesting and operationally disjointed. Synthesising engineering-oriented understandings is therefore required to guide researchers, practitioners, and policymakers toward more consistent approaches.

2. Theoretical Foundations of Circular Economy-Driven Logistics Systems

2.1. Circular Economy as a Design Logic for Logistics Systems

The circular economy has been developed as an extension of a wide sustainability concept to a viable systems approach to reorganise industrial production and consumption. In its purest form, it aims to decouple the processes of creating economic value from the extraction of virgin resources and the generation of uncontrollable waste by slowing, tightening, and closing material and energy flows. In the context of logistics research, this shift is all the more important, as logistics is not merely a supporting practice that connects production and markets but a central process that facilitates or constrains the circulation of materials. The decisions made in transportation, warehousing, packaging, handling, collection, and redistribution directly influence the lives of products and materials, their recoverability, and their environmental impact [23,24].

In traditional linear systems, logistics is designed to maximise one-way forward flows that are fast, reliable, and cost-effective. The materials are transferred from suppliers and manufacturers to distributors, and ultimately to end users, with little regard for post-consumption recovery or long-term asset use. This orientation is redefined by logistics driven by the circular economy. It considers logistics systems as multi-directional systems that cannot merely deliver products but must also accommodate product returns, the secondary market for resources, harvesting products, and recycling into production systems. This change means that logistics design can no longer be considered solely through classic metrics. Minimisation of costs and service performance remains critical, yet it needs to be understood in the context of waste reduction and material reuse, carbon emissions reduction, and regenerative possibilities.

One important lesson is that the principles of the circular economy must not be reduced to end-of-pipe recycling approaches. This very limited understanding will tend to maintain the essence of fundamentally linear logistics structures and merely introduce recovery routes along the periphery. An ideally circular solution entails designing logistics systems in a manner that enables them to be used in the long run, reused, modularly recovered, and have low-emission circulation. This implies that the circular economy is not merely a design logic but also an environmental goal which restructures system boundaries, decision priorities, and performance trade-offs [25,26].

2.2. From Traditional Logistics to Green, Reverse, Closed-Loop, and Circular Logistics

Circular logistics is intellectually underpinned by a number of established research streams, such as green logistics, reverse logistics, and closed-loop supply chain management. Though these ideas are connected, they are different in volumes and analytical direction. Traditional logistics is concerned with the effective planning, implementation and regulation of product movements between origin and consumption. Its prevailing assumptions include demand fulfillment, cost efficiency and time responsiveness. Externalities in the environment are generally considered as secondary constraints and not as central drivers of design [27].

Green logistics expanded this view to include environmental issues like the use of fuel, emissions, noise and the packaging waste in the planning of logistics. This area brought on some critical arguments on clean transportation, energy conservation warehousing, modal changes and environmentally favorable packaging systems. Nevertheless, green logistics usually is improvement-based but not transformation-based. It would rather streamline the existing linear flows by minimizing their environmental impact, instead of reconsidering the very concept of the flow of products and materials. Reverse logistics represented a more significant change by considering the flow of used, defective, or end-of-life products in their movement between the consumer and the producer or recovery centers. It brought up critical questions like designing the collection network, inspection, sorting, remanufacturing, recycling and disposal choices. Reverse logistics also understood that there is a value to be recaptured once consumed, and in most of the literature the reverse flows are still treated as reactive add-ons driven by returns or regulatory pressures [28–30].

Closed loop supply chain studies also incorporated both forward and reverse flows into one system. It focused on integration of production, distribution, collection, and recovery decisions thus giving a more analytical foundation to circularity. However, it is still evident that even closed-loop models can be characterized by an orientation to the recovery of economic value instead of a more systematic regeneration of a system. The circular logistics approach builds on these previous strategies by explicitly introducing logistics into the broader circle economy agenda. **Table 1** summarizes the conceptual development of traditional logistics to logistics driven by the circular economy as well as the distinction of the flow orientation, environmental focus, and the scope of analysis. It also deals not only with the issue of product recalls, but also with how logistic systems can be programmed to reduce the amount of waste generated to start with, the product usefulness across more than one cycle, the reliance on virgin materials, and the carbon intensity at every stage of movement and storage [24,31].

This difference matters because circular logistics cannot be viewed as merely environmentally branded reverse logistics. It is unique in integrating the restorative loop of materials with preventive design and low-carbon operating techniques. Consequently, circular logistics demands broader systems thinking than previous models, particularly when engineering innovations change the physical architecture and decision-making intelligence of logistics networks.

Table 1. Conceptual evolution of logistics paradigms toward circular economy-driven logistics.

Logistics Paradigm	Core Objective	Flow Orientation	Main Environmental Focus	Limitation	Relevance to Circular Economy-Driven Logistics
Traditional logistics	Cost efficiency, speed, service reliability	Primarily forward flow	Limited or implicit	Neglects waste generation, end-of-life recovery, and carbon externalities	Serves as the baseline model from which circular logistics departs
Green logistics	Reduce environmental burden of logistics activities	Mostly forward flow, with some environmental adjustments	Emissions, fuel use, packaging, energy efficiency	Often improves linear systems without changing their structural logic	Provides environmental improvement logic but not full circularity
Reverse logistics	Manage product returns and end-of-life flows	Reverse flow added to forward chain	Collection, returns, recycling, disposal reduction	Frequently reactive and focused on downstream recovery	Introduces return channels essential for circular systems
Closed-loop logistics/supply chain	Integrate forward and reverse flows in one system	Bidirectional	Recovery, remanufacturing, recycling, economic value recovery	May prioritize economic recovery over broader resource regeneration	Strong analytical precursor to circular logistics
Circular economy-driven logistics	Preserve value, minimize waste, reduce carbon footprint, enable resource circulation	Multi-directional and lifecycle-oriented	Waste prevention, reuse, repair, remanufacturing, recycling, low-carbon operation	Complex to implement due to coordination, infrastructure, and data requirements	Represents the most integrated and systems-based sustainability paradigm

2.3. System Boundaries and Structural Components of Circular Logistics

The strong theoretical basis lies in the clear definition of logistics system boundaries within the circular economy. The transport, warehouse, and inventory functions related to forward distribution are usually treated as the transport boundary in linear models. The boundary of circular systems needs to be further extended to include product take-back, waste segregation, repair, refurbishment, remanufacturing, recycling, and, in other instances, biological or energy recovery pathways. This larger boundary is critical since the results of circularity are the effectiveness of the coordination of these stages, and are not the effectiveness of a certain logistics function [29].

Circular logistics systems can be interpreted as a network of interacting nodes, flows, and decision layers that constitute the system's structural components. Examples of nodes are suppliers, manufacturers, warehouses, distribution centres, retail outlets, consumers, collection points, repair centres, remanufacturing plants, recycling facilities, and disposal sites. Flows refer to the movement of products, components, packaging, materials, information and energy in both forward and reverse directions. Decision layers include strategic decisions like facility location and network topology, tactical decisions like choice of transportation mode and inventory decision and operational decisions like routing, sorting and handling schedules [32].

One of the major theoretical issues is that circular systems are not merely the larger analogues of linear systems. Their structure is more intricate because the return flows are not predictable in terms of timing, quality or quantity. End-of-life products are in varying conditions, with residual and recoverable values. The reliability of collection systems is influenced by consumer behaviour. The markets for secondary materials can be unstable. The conditions render circular logistics more dynamic and stochastic than the traditional forward one. System design, therefore, has to take the variability, imperfect information and cross-stage dependence into consideration.

A second critical boundary problem is the incorporation of packaging, infrastructure, and digital systems into logistics theory. Packaging is regarded as a peripheral design variable, but in circular systems, it is central as it determines the rate of damage, transport density, reuse cycles, and ability to recover. Likewise, warehouses and transport assets cannot be regarded as mere passive infrastructure; their energy consumption, flexibility, and compatibility with return flows significantly impact circular outcomes. Digital platforms, traceability tools, and real-time monitoring systems also become structural components rather than auxiliary technologies, as they enable the identification of the product, evaluation of its condition, and organisation of its lifecycle [33–35].

2.4. Interactions between Waste Generation, Carbon Emissions, and Resource Efficiency

The key theoretical postulation in the logistics of the circular economy is that waste generation and carbon emissions are closely intertwined yet not necessarily in tandem. This observation should be given careful consideration, since most sustainability plans presuppose that when waste is less, emissions are lower, or the other way round. In reality, the correlation is more subtle.

Logistics waste occurs in a variety of ways, such as disposable packaging, inefficiencies in transportation, spoilage, product damage, underutilized resources, unneeded inventory, and inabilities to reclaim end-of-use materials. The sources of carbon emission are fuel burning, electricity use, refrigeration, material movement, facility operation and the embodied effects of logistics infrastructure. There is some intervention which produces explicit co-benefits. For example, fuel consumption, package intensity, and handling losses can be reduced by enhancing load consolidation. Reusable packaging can reduce waste at disposal and be more protective, with less frequent replacement over time [36].

Nevertheless, conflicts can occur. Return flows that are poorly consolidated or dispersed can result in higher emissions, as reverse logistics activities can greatly increase transport activity. A very protective package can reduce product loss at the cost of increased materials and complexity in recovery. The fast delivery models can meet market expectations while producing low asset utilisation and high carbon intensity. These tensions show that single-objective optimisation and simple environmental assumptions are insufficient for circular logistics.

A third dimension is resource efficiency, which can help explain these interactions. The logistics system can be operationally efficient in terms of carbon efficiency, yet materially inefficient in supporting disposable product-service models. On the other hand, a material circular system might not benefit the climate when recovery activities are energy-intensive and reliant on carbon-intensive energy. The implication is that the concept of circular logistics performance should be viewed as a multidimensional balance among material retention, carbon reduction, and operational feasibility. This justifies the use of combined measures and lifecycle-based evaluation rather than individualised performance measures [37].

2.5. Performance Dimensions and Evaluation Criteria

Circular logistics systems must be evaluated across a broader range of performance dimensions than conventional logistics studies. The conventional measures of system value, such as transportation cost, lead time, fill rate, and inventory turnover, remain applicable, though they capture only a portion of the system value. The logistics of a circular economy should also be assessed based on material circularity, waste divestment, energy conservation, carbon footprint, recovery yield, durability support, and resilience to uncertainty.

Material circularity is a measure of how much the products, components, and materials are still productive in a series of cycles. Waste diversion is a measure of the extent to which materials are avoided from being converted to landfill or incineration products without recovery of their value. Carbon performance should encompass both direct operational emissions and indirect emissions associated with packaging, infrastructure, and recovery processes. Recovery yield is a measure of how well collection and processing systems extract usable value from returned products. The reason resilience is growing in significance is that the circular system is sensitive to disruptions to consumer participation, infrastructure capacity, and secondary markets, due to heterogeneous actors and uncertain reverse flows [38,39].

The problem in the literature that has been highlighted as being critical is the fragmentation of these metrics. Most research focuses on costs and emissions without paying attention to material retention quality. Others are concerned with the recycling rates, with no focus on the intensification of transport or rebound effects. Such a piecemeal analysis may yield false outcomes, particularly when there is a local efficiency improvement at the expense of overall system environmental performance. Thus, the multi-criteria and lifecycle-based evaluation frameworks that reflect trade-offs at the economic, environmental, and operational levels should be grounded in the theoretical foundation of circular logistics.

2.6. Toward an Integrated Conceptual Framework for Circular Economy-Driven Logistics

A coherent conceptual framework for circular logistics makes logistics a dynamic interface between the principles of the circular economy and their sustainability outcomes. Circular concepts, which include minimising material throughput, maximising product life, recovering hidden value, and reusing resources, are used in this framework to inform decisions in logistics design at the network, facility, asset, and information levels. These design choices determine how forward and reverse flows are organised and coordinated, and, in the process, affect waste production, carbon emissions, and resource productivity [23].

The framework should also consider enabling and constraining conditions. Circular coordination can be facilitated through technological capabilities, including sensor networks, automation, electric mobility, and digital twins, but these capabilities rely on supportive policies, data interoperability, infrastructure investment, and organisational alignment. Similarly, the rapid service demanded by the market may limit the adoption of circular design unless supported by new business models and consumer engagement mechanisms. Circular logistics can therefore be viewed as a socio-technical system and not a strictly technical issue.

Theoretically, the most significant implication is that the design of logistics systems should shift toward adaptive, lifecycle-oriented, and multi-objective engineering rather than traditional efficiency optimisation. Circularity introduces new decision interdependencies that traditional logistics theory only partially describes. An optimal system under linear assumptions could be an inferior system in the real world after accounting for recovery potential, material loops, and carbon constraints. This is why future studies will need to consider circular economy-driven logistics as a separate design field with its own system logic, modelling assumptions, and evaluation criteria [40].

3. Engineering Innovations for Waste and Carbon Footprint Reduction in Logistics Systems

3.1. Engineering Innovation as the Operational Foundation of Circular Logistics

It is impossible to move towards linear logistics to circular economy-based logistics solely via managerial intention. It demands engineering breakthroughs that transform the physical and digital configuration and operational control of logistics systems. Traditional logistics has tended to equate engineering enhancements with efficiency gains, such as faster handling, reduced transport costs, and improved inventory precision. With circular logistics, engineering plays a more strategic role. It becomes a way to integrate waste avoidance, material reuse, carbon reduction, and service sustainability into a pragmatic system design [41].

This change is significant as circularity requires more than recovery functions to be added to the current supply chains. To accommodate the multi-directional flows, variable product conditions, repetitive use of assets, and higher level of informational complexity, a truly circular logistics system should be designed. These demands change the technical logic of the design of logistics. The transportation facilities should be able to meet both delivery and take-back. Warehouses are forced to handle more returns, repairable, and reusable goods in addition to virgin goods. Packaging needs to safeguard goods and aid recovery and reuse processes. The information systems have to monitor not just the position of the shipment but also the identity of the materials, the status of the product, and its remaining value. This interdependence of needs justifies treating engineering innovation as central to circular logistics rather than peripheral [42].

One prominent analysis of the issue is that engineering innovations are not necessarily sustainable. Their input varies according to the context in which they are used and the effects they have at the system level. The use of technology to speed up operations can lead to waste if it promotes overproduction or one-time consumption. Digital optimisation solutions can reduce empty miles but also create pressure on delivery and increase transport frequency. In this regard, the applicability of engineering innovation needs to be considered not only in terms of novelty but also in terms of its ability to support circular value and achieve absolute environmental enhancement. This should involve a critical evaluation of the areas where innovations create synergies between waste-reduction and carbon-mitigation efforts, and those in which they create hidden trade-offs [43].

3.2. Sustainable Transportation Engineering and Low-Carbon Circulation Networks

The most apparent environmental impact of logistics systems is transportation, which is why much of the sustainability research has focused on this system. Transport engineering in circular economy-driven logistics should not merely focus on fuel efficiency but on the larger issue of facilitating circulation with less material loss and lower carbon intensity. This necessitates a re-examination of vehicle technology, route design, network design, and modal integration in a coordinated manner [44].

One of the most effective engineering tools to minimise logistics emissions is route optimisation. Distance and vehicle idling can be minimised, and underutilised capacity can be reduced, using advanced routing models with real-time traffic data, geospatial analytics, and machine learning. In circular systems, route engineering is also more complicated, as it must account for reverse flows such as packaging returns, defective product collection, and end-of-life retrieval. It is not only necessary to minimise the time taken by the routes but also to coordinate forward and reverse movements in a manner that reduces empty runs and maximises the recovery value of transported goods. This transforms the conventional delivery-efficiency optimisation goal into the integrated-circulation efficiency.

Another engineering direction is vehicle electrification. Direct emissions can be greatly minimised with battery-electric vehicles, particularly in urban logistics, short-haul delivery, and scheduled collection routes. They are most applicable to circular logistics in urban systems with reusable packaging, returns, and decentralised recovery hubs, thereby creating more frequent, shorter transport routes. But the circular value of electrification must not be overrated. When there is a lack of charging infrastructure, battery production is production-intensive, and electricity supply is carbon-intensive, environmental benefits will not be evenly distributed. In addition, electric fleets can resolve the tailpipe emissions without packaging waste, delivery fragmentation or low load factor. This reflects the wider argument that cleaner propulsion is needed, though not enough, unless incorporated in redesigned circulation systems [45].

Hydrogen, biomethane, and advanced biofuels are also viable alternative fuels for long-haul and heavy-duty logistics when battery electrification is limited by range, payload, or charging time. There are more aligned fuels than others in the view of a circular economy. Waste biomass or industrial by-products can be converted into fuels, which can contribute to a broader resource valorisation approach, and first-generation biofuels can trigger land-use and resource trade-offs that subvert the sustainability agenda. Thus, the decision on fuel should be evaluated not solely by emissions but also by material circularity and general system externalities.

Multimodal transport engineering offers another way of minimising logistics carbon footprints. By moving some of their flows off the road onto rail, inland waterways or sea, firms will be able to lower unit transport emissions and enhance network resilience. The concept of multimodal design is particularly applicable in circular systems where the secondary materials, returned products or remanufactured products are transferred between geographically distributed processing nodes. Nonetheless, multimodal integration is not necessarily good. Subsequent handling steps can add product abuse, packaging needs, and unpredictability to lead times. The solutions to the problems of engineering should therefore be in terms of transhipment efficiency, unit loads that are standard and traceability across modes so that modal shifts do not simply push the burdens around [46–49].

The key understanding is that propulsion innovation, routing intelligence, and network redesign are most effective when combined in sustainable transportation engineering within circular logistics. The reduction in emissions comes not merely from cleaner vehicles but from a wholesale decrease in unwarranted motion, greater capacity utilisation, and more effective coordination of delivery and recovery processes.

3.3. Smart Warehousing, Material Handling, and Facility Engineering

Warehouses are central to circular logistics, as they are becoming not only storage points but also sorting, consolidation, inspection, refurbishment, and redistribution hubs. This increased functionality implies that facility engineering has considerable consequences for waste reduction and carbon performance. Conventional warehousing has emphasised the speed of throughput, storage density, and labour productivity. Warehousing supported by the circular economy should also facilitate material segregation, condition-based handling, packaging recovery, and flexible handling of returned items.

Robotic picking systems, automated guided vehicles, autonomous mobile robots, and intelligent conveyor systems are automation technologies that could be used to improve operational efficiency in warehouses, minimise handling errors, and reduce product damage. This is especially useful in circular systems, since product damage is directly wasted and may also impair the ability to recover goods or parts. The use of automated systems may also enhance the sorting and separation of reusable, repairable, recyclable, and non-recoverable materials, thereby further increasing the recovery yield and minimising contamination. But the viability of automation is not assured. Embodied energy in equipment, high capital intensity, and the demands of high electricity use can offset some environmental benefits, except when systems are designed to last long, be highly utilised, and be integrated with renewable power sources [50,51].

Another significant area of innovation is energy-efficient facility engineering. The use of smart lights, adaptive HVAC, energy management, insulated construction materials, solar rooftops, and thermal optimisation of cold storage can significantly minimise warehouse emissions. These interventions are particularly critical in circular logistics since returned goods and reusable packaging can be subject to further cleaning, conditioning, or temporary storage, which adds to the energy footprint of the facilities. The problem is to ensure that the environmental advantage of recovery activities is not lost to carbon-intensive warehousing. This supports the facility-level lifecycle thinking [52].

The design of warehouse layout varies under circular goals as well. Traditional designs are optimised for quick outbound order fulfilment, but circular warehouses might require dedicated areas for returns inspection, cleaning, repacking, repair staging, and material disassembly. These functions may be integrated to minimise duplication in transport between the different facilities and enhance the speed of reintegrating into the value chain. But too much multifunctionality can cause congestion and operational complexity. The design of engineering should thus strike a balance between specialisation and flexibility, particularly in areas where the amount and the state of returns are unpredictable.

The handling of materials is also important. Electrified forklifts, regenerative braking systems, automated lifts, and smart dock scheduling minimise direct emissions and idle energy consumption. More to the point, precision handling solutions can reduce breakage and contamination, which are often ignored as sources of logistics waste. By considering operational productivity not just on its own but also in conjunction with material retention and recovery effectiveness, a circular perspective makes these engineering choices all the more meaningful [53].

On the whole, smart warehousing and facility engineering indicate that circular logistics relies equally on the layout of the fixed infrastructure as on transport networks. A circular network warehouse is not just a passive storage asset; it is a processing environment that preserves value, whose technical structure may facilitate or inhibit circularity.

3.4. Reverse Logistics and Recovery-Oriented System Engineering

One of the most apparent forms of circular economy practice is reverse logistics, yet it requires meticulous engineering design to be implemented successfully. The way collected, the inspection process, sorting technology, disassembly operations, and the layouts of recovery facilities all affect the value of collected products as inputs or as expensive waste streams. Reverse logistics engineering, in this sense, is not some form of downstream correction to the linear systems, but rather one of the fundamental design domains in circular logistics.

One major concern is the design of the collection network. Good take-back systems must have available return points, transport synchronisation, and cost-effective consolidation systems. There are engineering options such as centralised return centres, decentralised drop-off lockers, retail-based take-back, mobile collection services, and hub-and-spoke recovery networks. The right design will be based on product features, return volume, customer usage, and residual value. The high-value durability of goods can warrant special collection and inspection processes, while low-value packaging or consumables may require a high level of local aggregation to be viable. This implies that the reverse network architecture should be product-specific rather than generic [54].

The importance of sorting and inspection technologies cannot be overstated, as recovery decisions require accurate assessment of product condition and recovery pathways. The uncertainty can be managed through vision systems, sensor-based inspection, RFID tracking, and AI-assisted classification, providing faster triage decisions. This is particularly useful in cases of high product heterogeneity, such as electronics, e-commerce returns, and industrial spare parts. Condition-based better assessment minimises unnecessary disposal and enhances the distribution of the items into reuse, repair, remanufacturing, or recycling. Nevertheless, these systems also need a solid data structure and product information standard, which is yet to be developed in most industries.

Remanufacturing engineering and disassembly move the frontiers of logistics to product recovery processes. In the case of interconnecting logistics systems with modular product architecture and standardised component interfaces, disassembly will become more economical, less harmful, and faster. On the other hand, inefficient products may overstrain reverse logistics networks with excessive labour and energy, and circular strategies may be impossible to realise in practice, even when recovery is theoretically favourable. This exemplifies a vital systems understanding: logistics circularity is not solely reliant on logistics infrastructure but also on product engineering compatibility. The optimal recovery-oriented logistics cannot be achieved when the products themselves are not designed for recovery, inspection, and part replacement [55].

Logistics based on recycling is not easy. Recovery of materials is mostly contaminated, with poor density, and unpredictable commodity prices. Transport efficiency and material quality can be enhanced through engineering solutions such as pre-processing stations, compaction systems, smart bins, and source-separation technologies. But recycling must not be regarded as the fall-back circular practice. In terms of a circular economy hierarchy, reuse, repair, and remanufacturing, as opposed to material recycling, tend to retain more value and use fewer resources overall. Hence, reverse logistics engineering needs to focus on value-retention channels rather than solely on the volume of collections.

The bigger picture is that reverse logistics can truly be a circular process only when the recovery networks are structured such that quality preservation, reduction of unnecessary transport, and matching product returns flows to the most resource-efficient recovery route is achieved. This alignment cannot take place without engineering innovation.

3.5. Digital Technologies Enabling Circular Visibility and Decision Intelligence

Digitalisation has proven to be among the most disruptive enablers of circular logistics, as circular systems demand far more information than linear systems. A one-way delivery model could operate with low visibility once a shipment has been received by the customer. A circular system, in contrast, will need to be aware of product location, their state, the time they are expected to be returned, the number of reuse cycles, and which reuse pathway has the greatest environmental and economic value. These needs render digital technologies the focus of logistics engineering [56].

The Internet of Things enables real-time tracking of assets, containers, pallets, vehicles, and products. Sensors can be used to reduce waste, enhance utilisation, and enable predictive maintenance of logistics assets. In reusable packaging systems, IoT can identify circulation frequency, dwell time, and points of loss, thus minimising invisible waste from asset loss and underutilization. Condition monitoring can prevent spoilage and recover the value of high-value products or temperature-sensitive products. IoT is important in circular logistics not just for visibility but also for enabling repeated use and lifecycle management.

Another significant innovation is digital twins. Digital twins enable operators to simulate a circular strategy by creating virtual representations of logistics networks, facilities, or assets prior to implementation. They can experiment with warehouse redesigns, assess changes to transport routes, approximate the effects of take-back programs, and compare different recovery configurations under uncertainty. They are particularly valuable in circular systems, as the interactions between forward and reverse flows are often nonlinear and hard to predict. But digital twins demand high-quality data, interoperability, and the organisational ability to produce significant outputs. In the absence of these, they risk becoming mere visualisation tools with little operational value [57].

Demand forecasting, return prediction, load planning, and dynamic routing can be enhanced by artificial intelligence and advanced analytics. The capabilities are especially applicable in the case of e-commerce and service-based product systems where returns are hard to predict and the patterns of assets circulation. The matching of the returned products to the secondary market or remanufacturing opportunities can also be assisted by AI, and thus, value retention can be enhanced. However, with AI usage, it also brings forth its own issues, such as model transparency, data bias, and high computational complexity. In circular terms, digital intelligence is to be rated based on whether it contributes to absolute waste and emissions reduction, rather than incremental efficiency in consumption systems of high throughput.

Blockchain and distributed ledger systems are frequently talked about as a means of traceability and trust. They can help enhance material provenance, recycled-content certification, and responsibility across multi-actor recovery chains in circular logistics. It may be useful in cases where ownership, compliance or the product's material authenticity affects the feasibility of recovery. However, the practical advantages of blockchain depend on the quality of governance and system integration. The simplified digital traceability solutions can, in most instances, be more efficient and resource-friendly. In this way, the digitalisation of circular logistics ought to be problem-driven rather than technology-driven [58,59].

The decisive role of digital technologies is that they transform circular logistics from a predominantly reactive activity into an anticipatory and adaptive one. They offer the informational infrastructure that is required to deal with uncertainty, coordinate distributed actors, and maintain value across multiple use cycles.

3.6. Packaging, Unit-Load, and Logistics Asset Design for Circularity

Packaging has been seen as a limited operational issue but it is one of the most critical engineering interfaces involving product protection, transport efficiency, generation of waste, and recovery of material. The design of packaging in logistics driven by the circular economy has to fulfill a number of goals at the same time: the reduction of material utilization, the minimization of damages, the possibility of reuse or recyclability, the facilitation of efficient handling and reverse collection.

One of the most promising innovations in this field is reusable packaging systems. Reusable crates, pallets, totes, insulated containers, and modular transport containers can help a lot in eliminating the single-use waste when recycled in several circulation processes. They have been particularly advantageous in the closed or semi-closed logistical loops like in retail distribution, automotive supply chains, food delivery, and industrial component transportation. Reusability is not, however, necessarily better. Reusable packaging environmental performance is determined by the return rates, cleaning needs, distance of transportation and frequency of breakages. Unmanaged reusable systems can result in reverse logistics burden (carbon-intensive) that can negate waste reduction outcomes. That is why the packaging design has to be incorporated with the design of the collection network and digital tracking [60].

Circular logistics can also be supported by modular unit-load systems, which enhance cross-compatibility of transport modes, warehouse systems, and return channels. Standardization minimizes the handling inefficiencies, damage and repackaging, which leads to reduction in wastes. It also enables multimodal transfer and automation. Circularly, the standardized and repairable logistics assets themselves can be considered long-life infrastructure and not disposable support materials [61].

The other critical issue is the selection of the material. Lightweight materials have the potential to enhance efficiency in transport, but might not be efficient in repeated reuse cycles or they are hard to recycle. The biobased or compostable may look appealing but the true circular value of the material is what the recovery infrastructure and use of the products can provide. The packaging material is technically recyclable but unrecovered in practice; this type of packaging will add minimal value to circularity. The engineering choices should thus be based on particular realities of recovery of a system instead of material claims of abstraction. This is also the case with logistics resources including pallets, containers, shelving systems, and rolling equipment. **Table 2** summarizes the key areas of engineering innovation, their impact on waste and carbon mitigation, and their trade-offs. They are durable, repairable, interoperable and traceable, not only in terms of efficiency in logistics, but also long-term material demand. A circular logistics system relies on assets designed to last longer and circulate many times, as opposed to low initial price [62,63].

Table 2. Major engineering innovations for waste and carbon reduction in logistics systems.

Engineering Innovation Area	Representative Technologies/Approaches	Contribution to Waste Reduction	Contribution to Carbon Reduction	Trade-Offs/Challenges
Sustainable transportation engineering	Route optimization, multimodal transport, electric vehicles, hydrogen/fuel alternatives	Reduces redundant transport, empty runs, and product damage	Lowers fuel consumption and transport emissions	Infrastructure gaps, battery/fuel constraints, rebound from faster delivery expectations
Smart warehousing and facility engineering	Warehouse automation, energy management systems, adaptive HVAC, robotic handling	Reduces handling damage, spoilage, and sorting errors	Cuts electricity use and improves facility energy efficiency	High capital cost, embodied energy of equipment, integration complexity
Reverse logistics and recovery systems	Collection hubs, sorting centers, inspection technologies, remanufacturing networks	Diverts products and materials from disposal; supports reuse and repair	Can reduce virgin production-related emissions through value recovery	Reverse transport may increase emissions if poorly consolidated
Digital technologies	IoT, AI, blockchain, digital twins, predictive analytics	Improves traceability, reduces loss, optimizes reuse cycles	Enhances load planning, reduces unnecessary movement and inefficiency	Data fragmentation, high implementation cost, interoperability issues
Circular packaging and logistics asset design	Reusable packaging, modular containers, repairable pallets, standardized unit loads	Cuts single-use packaging waste and asset loss	Improves transport efficiency and reduces replacement demand	Cleaning, collection, return rates, and reverse logistics burden
Recovery-compatible product-logistics integration	Design for disassembly, modular product architecture, digital product passports	Improves recoverability and extends product/component life	Avoids carbon-intensive virgin material extraction and manufacturing	Requires coordination between product design and logistics functions

3.7. Trade-Offs, System Integration, and the Limits of Technological Optimism

Even though engineering innovations have significant opportunities, they do not imply circular results. Most innovations have both positive and negative impacts, which can only be seen at the system level. The automation could decrease errors but increase energy consumption. Electrification can only reduce direct emissions; network inefficiency remains unchanged. Reusable packaging can reduce solid waste and raise the cleaning and reverse transportation costs. Digital optimisation can enhance vehicle use and drive faster, more segmented delivery expectations. These cases demonstrate that circular logistics cannot be developed based on separate technological replacements.

System integration is the most significant need, therefore. Innovations should be coordinated across product design, transport engineering, warehousing, packaging, recovery infrastructure, and digital control systems. When these elements are interdependent, circular performance occurs. To give an example, a reusable packaging program is optimised by supporting track-and-trace systems, by optimising the return route, by compatible warehouse handling, and by standardised asset design. On the same note, reverse logistics networks can be enhanced by product architectures that facilitate modular disassembly and recovery information through a digital product passport [64,65].

This is also an indication of the boundaries of technological optimism. Innovation in the engineering process is needed, but it is not a substitute for governance, business model transformation, or consumer involvement. Unless the recovery system is technologically advanced, a lack of strong return incentives or product design aimed at rapid obsolescence will result in its failure. A logistics system made circular by a low-carbon warehouse will not support a high rate of disposable throughput. The true value of engineering is not in its single-handed efficiency but in making possible structural changes that reduce material extraction, increase product life, and decrease environmental intensity.

4. Optimization Models and Decision-Support Approaches for Circular Logistics System Design

4.1. Optimization as the Analytical Core of Circular Logistics Design

Circular economy-based logistic systems design is an optimisation problem, per se, but a much more complicated one than in traditional logistics. Conventional logistics optimisation has largely centred on cost reduction, shorter lead times, or better service provision in a mainly forward-oriented supply chain. In contrast, circular logistics has to synchronise forward distribution, reverse recovery, material recirculation, and carbon reduction simultaneously under uncertain and technologically heterogeneous conditions, with contradictory stakeholders' priorities. Consequently, optimisation of circular logistics cannot be reduced to just a continuation of classical logistics modelling. It needs a wider analytical framework which includes lifecycle thinking, multi-objective trade-offs and dynamic system interactions [29].

This increased functionality of optimisation represents the structural facts of circular systems. The location of the facility, routing of transport, setting of the return channel, inventory holding, remanufacturing capacity and reuse of packaging are closely intertwined. An option that benefits a section of the machine may strain other aspects. As an example, a very centralised recovery network can enhance economies of scale in remanufacturing but can also extend transport distances and increase emissions. A decentralised collection structure can enhance accessibility and recovery rates of returns, but also increase the fixed infrastructure costs and operational complexity. Since no intuition can overcome such trade-offs, optimisation models are indispensable decision-support systems to help convert the principles of the circular economy into technically and economically feasible logistics architectures [66].

Meanwhile, the application of optimisation to circular logistics also poses some conceptual questions. Models are touted as having analytical rigour, but they are never free of assumptions about objective functions, system boundaries, and performance priorities. In most analyses, these assumptions are either too economic in nature or too simplistic in their operation to capture the full logic of circularity. Transformative logistics redesign can thus be facilitated, or linear biases can be creatively labelled as sustainability. The question is not whether it is optimised, but how it is optimised, what variables it has, and whether it supports the more general environmental/resource-retention objectives of circular systems.

4.2. Network Design Models for Circular and Closed-Loop Logistics Systems

One of the most well-established areas of optimisation in circular logistics is network design, since recovery, reuse, remanufacturing, and recycling are feasible mainly depending on the network structure. Network design models usually determine the optimal number, type, location, and capacity of facilities, as well as the allocation of flows among them. These facilities can be suppliers, manufacturing facilities, warehouses, distribution facilities, customer areas, collection facilities, inspection facilities, repair facilities, remanufacturing facilities, recycling facilities, and disposal facilities in circular systems. It is more difficult than in linear systems, since networks must support both forward and reverse flows and maintain value across various product life stages [67].

This area has been given an analytical basis by closed-loop network design models, which combine outbound and return logistics into a single framework. These models usually dictate how products are to be collected, where returned products are to be checked, and which plants should carry out refurbishment, remanufacturing, recycling or final disposal. Their primary contribution is that recovery channels cannot be viewed outside of the context of forward logistics. The location of manufacturing plants affects remanufacturing prices; the concentration of client demand determines the feasibility of collection; and warehouse design determines whether reusable packaging systems can be maintained economically.

Nevertheless, many network models are constrained by overly simplistic assumptions. They usually assume that return rates, product quality, and recovery demand are known or deterministic, although these variables are highly uncertain in real circular systems. They can also take homogeneous recovery routes, although the returned products may differ greatly in condition and remaining value. Consequently, there are model outputs which are analytically beautiful but operationally weak. A network that seems optimal under average assumptions can perform poorly when return flows vary or when products need to be treated differently. This brings to light one of the main contradictions in the literature: network optimisation is required in the design of circular logistics, yet its applicability is strongly dependent on its ability to capture the idea of uncertainty, heterogeneity, and adaptive response [68].

The other significant problem is the hierarchical arrangement of the recovery choices. The concept of a circular economy often places greater value on reuse, repair, and remanufacturing than on recycling and disposal, since it conserves more of the inherent value. However, some models place all recovery activities within a generic reverse-flow structure, which masks the qualitative distinctions among value-retention pathways. The volume of recovered materials should not be maximised alone; the returned products should also be distributed to the most viable retention alternative via a circular logistics network. Models of optimisation that do not embody this hierarchy may promote materially poorer outcomes despite improving formal recovery rates [69].

Hence, the development of network design models in circular logistics is increasingly inclined towards hybridised formulations that integrate spatial choices and lifecycle priorities, product condition states, and differentiated recovery pathways. These models are more realistic, as they show how circular systems should operate to reduce both waste and carbon load.

4.3. Multi-Objective Optimization of Cost, Emissions, Waste, and Service Performance

One of the main peculiarities of circular logistics is that it cannot be meaningfully optimised in terms of a single goal. Minimization of costs is still significant, however when done independently, usually tends to support linear, high throughput systems that have limited recovery infrastructure and externalized environmental costs. Designing with a circular economy demands the economic, environmental and operational goals be considered in tandem and this has contributed to the growing popularity of multi-objective optimization methods [70].

The common aim of these models is to strike a balance between the total logistics cost and carbon emissions, waste generation, recovery yield or service quality. Their value is in that they are not hidden trade-offs but are made overt. They tend to produce a family of Pareto-efficient options, describing a variety of tradeoffs among competing goals, rather than just one optimal solution. This is particularly handy in circular logistics, where the decision-maker must weigh lower emissions against higher infrastructure investment, or whether more product can be recovered without excessive transport intensity, or whether responsiveness of the service can be ensured and slower, less impactful recovery channels used.

Multi-objective modeling is strong in that it aligns with the reality of the complexity of logistics sustainability. But it too entails methodological problems. The choice and weighting of objectives is one of the issues. Cost and carbon emissions are a common feature in many studies with comparatively few studies having equal focus on material circularity or waste prevention. This causes the imbalance whereby carbon can be readily measured as opposed to value retention quality. The logistics network can seem more environmentally friendly when considered solely based on emissions, even though it might deliver high volumes of goods to less valuable recycling rather than to more valuable reuse or remanufacturing. The decision of objectives, therefore, has a significant effect on the form of the best possible circularity that a model will manifest [71].

The other issue is related to the comparability of metrics. Cost is normally quantified in terms of monetary value, emission, in terms of kilograms of CO_2-equivalent, and service in terms of delivery time or fill rate. The indicators of waste and circularity can be expressed in terms of tons diverted, percentage recovered, or qualitative scores in lifecycle. To bring these various indicators into a single optimization structure, some normalization, weighting, or constraint-based formulations are required, which all involve methodological assumptions. Such assumptions are not insignificant. They are good at encoding value judgments on what is and is not sustainability and acceptable trade offs.

Though these are the limitations, multi-objective optimization is one of the most suitable tools of the circular logistics as it recognizes the reality that environmental and operational objectives are dependent yet not necessarily coincidental. It might not be the best design that it produces, but rather the establishment of an open decision space within which trade-offs can be evaluated critically [72].

4.4. Life Cycle Assessment and Carbon Accounting in Logistics Decision-Making

Life cycle assessment has also gained significance in the area of circular logistics due to the fact that most of the interventions that seem to be environmentally friendly at the operational level can have unseen burdens in the other parts of the system. Another example of a logistics design that is designed circular and minimizes packaging waste is that it might need additional transport and cleaning. A remanufacturing system can save on the use of virgin materials but will boost inspection and re-processing energy requirements. These relations cannot be measured by the direct logistics indicators only. They need a lifecycle viewpoint that takes into account the upstream, operational and downstream environmental impacts [38].

Use of life cycle assessment to integrate into optimization and decision-support model can resolve this issue by broadening the scope of analysis beyond operational emissions in the short-run. It allows the incorporation of embodied emissions in packaging materials, warehousing infrastructure, vehicle manufacturing, use of energy, and recovery. This would be especially useful in circular systems since the environmental benefit of maintaining materials in circulation is not just determined by the amount of material recovered but also includes the impacts of each recovery pathway. Reuse can be better than recycling not just because it does not require disposal, but also because it does not require as much reprocessing to maintain product functionality. On the other hand, a very diffused reusable packaging system can prove to be worse to the environment when the burden of collection and cleaning is too high [73].

Carbon accounting systems act as a complementary measure since they offer standardized mechanisms of measuring the greenhouse gas emissions in logistics in terms of transport, storage, handling, and recovery processes. Their significance has increased alongside the increase in net-zero goals and disclosure of supply chains. Carbon accounting is also of particular importance in circular logistics since reverse flows and secondary processing are frequently not covered by standard reporting practices. In the absence of detailed accounting, companies can exaggerate the environmental benefit of circular programs and ignore indirect emissions related to logistics of returns or low-efficiency systems of recovery.

Nevertheless, the lifecycle and carbon approach to logistics design is not an easy task. Availability of data is one of the greatest limitations. Credible emission factors of remanufacturing, repair, reusable packaging loops or decentralized recovery operations are frequently incomplete or context-specific. A methodological problem of defining functional units is also present. Is the system to be measured on a per-shipment, per-product life cycle, per-service delivered or unit of retained material value basis? The various options may have varying conclusions about comparative performance of circular strategies [74].

The important point to note is that lifecycle-based decision-making enhances the optimization of circular logistics by ensuring that operational enhancements that are achieved in narrow ways are not confused with the systemic sustainability. It moves the focus of analysis on individual process efficiency to environmental impact on the entire system, which is crucial in an area where trade-offs are usual and rebound effects are a possibility.

4.5. Simulation, Stochastic Modeling, and Uncertainty Analysis

Circular logistic systems are characterized by uncertainty. The volumes of returns are not constant, quality of products changes, customer involvement is not predictable, recovery yields are unknown and secondary material markets may be volatile. Such characteristics render deterministic optimization inadequate in most real-life applications. To mitigate this, researchers are turning to simulation, stochastic programming, robust optimization and scenario-based analysis to assist in the design of a circular logistics in case of uncertainty.

Simulation models are especially helpful when the interactions between the systems are nonlinear or the time behavior of the logistics processes is as important as the structural configuration. Warehouse operations, return processing times, congestion effects and queuing behavior of recovery centers can be simulated with discrete-event simulation. Feedback loops between the product use and the rate of returns, remanufacturing capacity and the demand of reused products in the market are often represented by system dynamics models. Heterogeneous actors including consumers, logistics providers, repair operators and recyclers can be included in an agent-based model and their behavior affects the outcomes of the system. These methods are useful since circular logistics can rely on decentralized decision-making and behavioral responses which are abstracted in classical optimization [75].

Stochastic programming puts uncertainty right in optimization models by modelling uncertain parameters as probability distributions or discrete scenarios. This is very applicable in terms of quantity of returns, quality of returns, disruption on transport and uncertainty in the demand. Circular systems may require decisions to be made ahead of these uncertainties being resolved, e.g., where to place collection facilities or what size remanufacturing capacity to allocate. Stochastic models are thus able to give solutions which are more robust than deterministic ones even though in many cases at a higher computational cost.

Robust optimization aims to solve a similar problem by finding solutions that are reasonably good in a set of possible future scenarios instead of optimizing a solution to one of the expected scenarios. This is desirable in circular logistics since reverse flows tend to be hard to characterize with confidence using probabilities. A network architecture that is well designed can lead to reduced nominal efficiency in favor of a better stability to uncertain returns, changes in policy, or even carbon pricing regimes. These trade-offs are of great importance to real-world applications where decision-makers might favor robust designs to theoretically efficient but weak designs [76].

Scenario analysis provides a strategic perspective to uncertainty modeling. It enables logistics planners to simulate how circular systems would work with various futures that include regulation change, consumer return behavior, fuel prices, electricity carbon intensity or digital infrastructure maturity. This is especially helpful in an industry that is impacted by the blistering technological change and policy development. Scenario approaches do not eliminate uncertainty, but make preparations and strategy space more effective.

The key weakness of these approaches is that they might turn out to be analytically complicated, data-intensive. Additionally, uncertainty analysis can only be as significant as the assumptions that are incorporated in it. When scenarios are too limited or behavioral processes are simplified, the resultant insights could give a false sense of confidence. However, uncertainty-conscious modelling is needed since it is impossible to design circular logistics believably on the premise of predictable, stable reverse flows [77].

4.6. Data-Driven and AI-Enabled Decision-Support Systems

The growing digitalization of logistics has resulted in the development of data-driven decision-support systems that can enhance planning, coordination, and responsiveness in circular networks. Formal optimization models are not supplanted by these systems, but rather complemented by giving real time data, prediction and control adaptability.

Demand forecasting, route planning, failure anticipation and return prediction can be enhanced with the help of machine learning and predictive analytics. Return forecasting is particularly significant in the context of circular logistics since the recovery activities rely on predicting the time when products, packaging, or components will re-enter the system and in what state. Enhanced forecasting aids capacity planning in collection centers, inspection plants and remanufacturing processes. It also minimizes waste levels of overcapacity, emergency transportation and inefficient allocation of recovery [78].

Dynamic routing, decision-support tools based on AI can also be used to match the returned goods with the appropriate recovery channels and to optimize the use of inventory in the case of reusable assets. In returns of e-commerce, such as returned goods, intelligent systems can categorize the returned products on whether they can be resold, repaired, remanufactured or recycled, and save time on manual decision-making and increase the value maintenance. The digital platform can track the movement of containers in reusable packaging systems and suggest rebalancing to reduce loss and underutilisation. These tools enhance responsiveness of circular logistics which is critical when conditions in a system vary quickly [79].

Digital twins also expand decision support through the integration of optimization, simulation and real time information into a virtual model of the logistical system. This facilitates ad-hoc testing of scenarios, monitoring, and control. Digital twins prove particularly useful in a circular system due to the interaction of forward and reverse flows that cannot be easily handled using traditional planning methods. A digital twin may show the developing congestion in return channels, predict bottlenecks in remanufacturing, or predict the carbon consequences of different routing changes. In this respect, it transforms to not only a monitoring device but a dynamic platform of circular decision intelligence.

Nevertheless, there are drawbacks and risks associated with data-driven tools, as well. Circular systems have many issues related to incomplete or fragmented information as products move through a number of actors with differing traceability levels. Artificial intelligence systems can fail to work well when past data indicates linear logistics, but not circular behavior. It is also a risk that digital decision support will take the form of speed and usage without giving adequate consideration to lifecycle sustainability requirements. A digital system needs not be sophisticated to optimise on circular value. The usefulness of decision-support tools is solely dependent on what goals and signals they are trained or programmed to follow [80].

The overarching suggestion is that data-driven techniques are best applied that are integrated into circular design reasoning and not as individual efficiency technologies. They are supposed to augment visibility, anticipation and coordination in the service of waste reduction and carbon mitigation, not just to hasten throughput.

4.7. Toward Integrated Decision-Support Frameworks for Circular Logistics

It is becoming clear in the literature that there is no single modeling/decision support methodology that is adequate in the design of a circular logistics system. Optimization of networks offers structural information, multi-objective models elucidate trade-offs, lifecycle analysis expands environmental horizons, stochastic models help in managing uncertainty and AI-enabled tools enhance real-time responsiveness. The further advance of isolated models is not the next step in the field, but the creation of integrated decision-support frameworks, integrating these analytical strengths. **Table 3** compares the key optimization and decision-support strategies along with their decision levels, their strengths and weaknesses [81].

This kind of integration is needed as circular logistics is at the same time a strategic, operational, environmental as well as a socio-technical problem. A network model can determine an effective recovery structure but without lifecycle information it can be wrong on environmental benefit. A simulation will show congestion with reverse flows, but unless optimization is done, will not tell us how the infrastructure should be redesigned. The AI platform can enhance the responsiveness of routing but without multiple-objective criteria it can disregard the waste prevention or the quality of the material retention. To design a successful circular logistics, analytical architectures are needed where such approaches are mutually-informed at decision levels.

Table 3. Optimization and decision-support approaches in circular logistics research.

Approach	Main Purpose in Circular Logistics	Typical Decision Level	Strengths	Limitations	Suitable Application Examples
Network design optimization	Determine facility locations, capacities, and forward-reverse flow structures	Strategic	Clarifies system architecture and recovery network configuration	Often relies on simplified or static assumptions	Collection center location, remanufacturing network design
Multi-objective optimization	Balance cost, emissions, waste reduction, and service performance	Strategic/tactical	Makes trade-offs explicit; generates Pareto-efficient solutions	Requires weighting or normalization across unlike metrics	Low-carbon closed-loop distribution network planning
Life cycle assessment-integrated modeling	Evaluate full environmental impacts across logistics and recovery stages	Strategic/tactical	Captures hidden upstream and downstream burdens	Data-intensive and sensitive to system boundaries	Reusable packaging evaluation, remanufacturing vs. recycling comparison
Simulation modeling	Analyze dynamic operations, bottlenecks, and process interactions	Tactical/operational	Handles nonlinear behavior and temporal dynamics	May not directly provide optimal solutions	Warehouse returns processing, urban circular logistics operations
Stochastic/robust optimization	Address uncertainty in return rates, demand, and recovery quality	Strategic/tactical	Produces more resilient solutions under uncertainty	Computationally demanding; may require strong assumptions	Uncertain take-back networks, spare-parts recovery systems
AI and data-driven decision support	Improve forecasting, routing, classification, and real-time control	Tactical/operational	Adaptive, responsive, useful for real-time management	Dependent on data quality and transparency	Return prediction, dynamic route planning, automated recovery triage
Digital twin-based support	Combine monitoring, simulation, and system testing	Tactical/operational/strategic	Enables scenario analysis and adaptive system management	Requires strong digital infrastructure and interoperable data	Circular warehouse redesign, reuse asset monitoring

The lifecycle assessment combined with the multi-objective optimization and real-time digital control is a promising direction. Within this framework, the cost, carbon and circularity of strategic network design might be optimized, the uncertainty-based simulation of tactical planning might be simulated and operational execution might be facilitated by digital twins and AI-based adjustment tools. This would shift the concept of circular logistics decisions towards non-adaptive, single-time planning and instead to evidence-based system governance [82,83].

However, integration does have a caution to the wind. Not all more complex models make better models. This should not be achieved at the cost of interpretability, transparency of data or practicality. The most logistics decisions have to be made under time, budget and information constraints, and practitioners might be opposed to those models, which are opaque or hard to run. Thus, the future of circular logistics decision support lies not only in methodological development but also in the development of tools that are resilient, clear, and in tune with the realities of industrial practice.

5. Implementation Challenges, Industrial Practices, and Future Research Directions

5.1. From Conceptual Promise to Implementation Reality

The conceptual and analytical background of the expanding literature on circular economy-based logistics has a solid foundation, but practice is still unbalanced and incomplete. Isolated sustainability projects, such as electric delivery fleets or recyclable packaging, or even take-back systems, have been implemented in many organisations, but comparatively few have managed to restructure logistics in a fully circular, low-carbon way. This gap in implementation is not merely due to a lack of awareness. Instead, it indicates that circular logistics necessitates the coordination of technological, infrastructural, organisational, market-relations, and policy-related changes. That is, it is not that it is hard to see the value of the concept of circularity, but rather that it has to be integrated into operational systems that have long been optimised for linear throughput [84].

One of the key issues is that circular logistics creates new types of complexity for firms and supply networks. Conventional logistics infrastructure is based on comparatively predictable forward flows, uniform service metrics, and constant cost frameworks. Circular systems bring reverse flows that are uncertain in volume, timing, and quality. They need to track their products beyond the point of sale, cross-organisational recovery alliances, and more discriminating processing of returned products, reusable assets, or secondary materials. These requirements may be incompatible with current performance practices that favour speed, simplicity and cost-cutting in the short term. Consequently, circular logistics usually face structural opposition rooted in the design logic of traditional operations [85].

It is a critical section of the barriers that restrict implementation, the industrial practices in which circular logistics is beginning to take shape, and the research directions to move the field beyond fragmented application. The main point is that circular logistics should be viewed as a systemic shift rather than a separate technical improvement. This can be implemented as long as the organisations can match engineering innovation with organisational capability, institutional support and market incentives.

5.2. Technological and Infrastructural Barriers to Circular Logistics Adoption

Despite the critical opportunities that engineering innovations can generate, their implementation is limited by the level of technological maturity, interoperability, and preparedness of the infrastructure. Circular logistics is highly dependent on the ability to track products and materials, handle non-homogeneous returns, and run recovery channels effectively. The technologies required in most industries are either too expensive, not standardised enough, or not well-integrated with the existing logistics systems [86].

Among the key obstacles is the incongruency between the product design and the logistics recovery ability. This phenomenon persists, with many products designed for low-cost manufacturing and high market turnover, rather than repair, modular replacement or disassembly. This reduces the efficacy of reverse logistics when there are collection channels. In cases where the components are hard to disassemble, repair is labour-intensive, or materials are strongly bonded, recovery operations are economically marginal and environmentally inefficient. This imposes complexity on logistics systems, which have been engineered into the product. This is an example of a long-run issue: circular logistics cannot entirely compensate for non-circular product engineering.

Infrastructure constraints also curtail implementation. Reusable packaging systems need redistribution, repair, inspection, and washing facilities. Repair and remanufacturing require special processing facilities and access to spares. Recycling networks rely on material sorting facilities and local or regional reprocessing facilities. The implementation of electrified logistics fleets necessitates charging infrastructure, grid capacity, and energy systems compatible with the routes. These infrastructures are either incomplete or disjointed in most areas, which makes them bottlenecks and prevents circular strategies from scaling. The consequence is that otherwise viable projects will be limited to certain products, geographies or pilot projects [87].

Another problem is digital infrastructure. Circular logistics requires knowing the identity, condition, location, and recovery route of products, yet most supply chains continue to use fragmented data structures. Old systems might not enable inter-firm communication, and traceability may be compromised after products leave the forward supply chain. No advanced tools, including digital twins, predictive return analytics, and asset circulation tracking, can be effective without high-quality data exchange. This leads to an implementation paradox: companies can invest in advanced digital tools, yet the data ecosystem is too fragmented to enable significant circular decisions.

The bigger picture is that technological barriers are not merely about a lack of innovation. Frequently, they result from the partial congruence among product design, logistics engineering, infrastructure investment, and data governance. Effective implementation will not be based on individual adoption of technology but on the development of integrated technical systems.

5.3. Economic and Organisational Constraints

One of the most often mentioned obstacles to circular logistics is economic viability. Although circular strategies can generate long-term value by reducing waste, recovering materials, and reducing environmental exposure, they can be expensive to implement and have unpredictable payback timeframes. Capital is also required to invest in new facilities, reverse transport networks, digital tracking, automated sorting equipment, reusable packaging pools, and remanufacturing operations. These costs are hard to justify in many companies, particularly with short budgeting cycles, as traditional logistics models can still provide a visible low cost in the short term [88].

Incompatible cost structures exacerbate this. Externalities in the environment, such as emissions, disposal burdens, and resource depletion, are not usually fully internalised in linear systems. Circular logistics is therefore economically competitive with systems that are not considered to have their actual societal cost. As an example, single-use packaging is often less expensive than reusable options because waste management and carbon impacts are externalised. In like manner, landfilling or low-value recycling can be economically viable compared to higher-value recovery options when disposal costs are low and secondary markets are weak. In such circumstances, companies have minimal direct motivation to restructure logistics to be circular unless regulations, carbon prices, or customer demand change the business case.

Organisational impediments are also important. The concept of circular logistics requires cross-functional collaboration among procurement, logistics, product design, operations, sustainability, and after-sales service. These functions, in most companies, operate in silos, and there is little incentive to optimise across them. Logistics units can be concerned with transport and delivery costs and performance; sustainability units with emissions goals; and product teams with market features or cost competitiveness. Devoid of an integrated governance, circular initiatives can be disjointed, redundant, or marginal [89].

Managerial skill is also an issue. Circular logistics presents new decision-making challenges of uncertain reverse flows, multi-objective trade-offs, and coordination of partnerships over the long product lifecycle. Companies used to linear distribution might lack the analytical tools, performance measures, and operational know-how to handle such systems. This capability gap may lead to risk aversion, particularly when recovery markets are volatile or when implementation will disrupt settled service patterns.

There is even a more fundamental concern about organisation time horizons. Circular logistics is closely associated with lifecycle thinking, in which many logistics decisions are based on quarterly or annual efficiency indices. The systems of recovery infrastructure, systems of reusing assets, and transitions to low-carbon usually generate value over time and among many actors. Unless companies consider these investments using the short-term internal cost provisions, circular implementation will continue to look unappealing. This implies that the organisational transformation needs new technology, as well as new accounting logic and strategic orientation [90].

5.4. Policy, Regulatory, and Standardisation Issues

The institutional environment of firms operating in circular logistics greatly influences the implementation of the latter. Policies, regulations and standards can facilitate circular transitions or strengthen these linear practices. This is because most of the advantages of circular logistics, such as reduced emissions, waste, and material consumption, are system-level or societal benefits that markets may not necessarily value. One of the most impactful policies has been the extended producer responsibility policies, which have triggered reverse logistics and product recovery. Through their financial or physical accountability for end-of-life products or packaging, these regulations will provide incentives to develop more recoverable systems and to invest in the infrastructure for returns. The policies of carbon disclosure, waste reduction, and green procurement also play a role in building the business case of circular logistics. Regulatory pressure has emerged as a significant force driving system redesign in areas such as electronics, packaging, automotive, and batteries [91].

Regulatory environments, however, are not even in all regions and sectors. In other environments, policies encourage recycling and little to no support for reuse, repair, or remanufacturing, even though these tend to have greater circular value. In others, transport control, waste classification regulations, or cross-border shipment controls complicate the recovery logistics to be coordinated. This leads to a scenario where policy espouses circularity in theory but frustrates it in practice by implementing it in disjointed or inconsistent ways.

Another significant problem is standardisation. Circular logistics rely on product, packaging, data systems, and recovery compatibility. Regularised containers, modular-format packing, product identification, labelling of materials, and virtual product passports can greatly enhance logistics efficiency and recovery quality. However, over-standardisation can also limit innovation or fail to reflect sector-specific requirements. The problem is then to come up with standards that would facilitate interoperability without built-in functional diversity [92].

This is particularly problematic with the absence of shared metrics. Companies usually report carbon emissions, recycling rates, and waste diversion alone, whereas there is less consistency in quantifying material circularity, recycling quality, reuse intensity, or value retention. This complicates benchmarking and may promote the superficial reporting of high-visibility, low-value recovery activity. A more consistent set of standards for measuring the performance of circular logistics would enhance comparability and enable more informed decisions regarding investments and policies [93].

The key learning is that institutional design is significant, as circular logistics is a cross-organisational, long-term operation. In the absence of favourable regulation and common standards, companies incur substantial coordination costs and are continually uncertain about the value of circular investment.

5.5. Sectoral Practices and Emerging Industrial Applications

Despite the uneven implementation of circular logistics, several industries have begun to show how engineering innovation and the redesign of systems can facilitate practical implementation. These instances indicate the extent of advancement already achieved and the circumstances under which circular models are more likely to succeed.

Circular logistics is more developed in the manufacturing sector, especially in automotive and industrial equipment, since the residual value of products is high, the standardisation of components is often higher, and reverse channels can be integrated with existing service networks. These environments feature returnable transport packaging, remanufacturing of spare parts, component recovery, and core return systems. Since industrial products are not perishable and are intensive of assets, companies are better motivated to maintain material value in the long run. Nevertheless, in these areas, broader carbon integration has been lopsided, and reverse systems are frequently tailored more towards recouping economic value than comprehensive environmental performance across the lifecycle [94].

This is a different scenario with e-commerce. It could be circular logistics as it is digitally visible and has well-established home delivery networks, yet also poses significant sustainability issues due to high return rates, fragmented deliveries, and single-use packaging. Several companies have adopted consolidated return points, reusable pilot shipping containers, AI-based return disposition, and route optimisation for collection flows. However, the e-commerce business model based on convenience may compromise these benefits by promoting behaviours such as over-ordering and fast returns. This indicates that logistics innovation is insufficient to address circularity issues as long as demand-side practices remain inherently linear.

The food industry is a valuable setting for circular logistics experimentation due to packaging waste, spoilage, and cold-chain emissions. There is an increase in the use of reusable crates and reusable insulated containers, the redistribution of unsold products, and the valorisation of food residue into secondary products or energy streams. The Urban Food Delivery Network has also considered container reuse and micro-hub consolidation. Nevertheless, food systems face a challenging trade-off among hygienic needs, transportation efficiency, and the possibility of reuse. The environmental superiority of circular packaging or reverse collection, in most instances, is contingent on local infrastructure and return behaviour [95].

Another new application is in healthcare and pharmaceutical logistics. In this case, circularity is fueled by the desire to reuse transport containers and medical equipment, and to optimise the recovery of packaging and temperature-controlling assets. Nonetheless, the strictness of regulations, contamination issues, and traceability requirements make it particularly challenging. The industry demonstrates that high-value logistics systems can facilitate circular investment, but only if quality assurance and compliance are ensured.

The broader use of urban logistics has emerged as a critical testing ground for circular innovation. Cities have the benefits of concentrated delivery density, packaging waste, and return flows, and are the target locations for reusable packaging pools, electric last-mile fleets, urban consolidation centres, and localized repair or redistribution hubs. Circular practices are especially promising in high-density urban areas where the distance to transport assets is short, and recirculation can occur within a short time. However, land, congestion, and lack of coordination among stakeholders are also problems in urban systems that inhibit scale-up [96,97].

Otherwise, in industries, there is a general trend: circular logistics is most adaptable in situations where product value is high enough, reverse flows can be concentrated, infrastructure is geographically concentrated, and digital coordination is feasible. In cases where the products are low-value, highly dispersed or have a short lifespan, implementation is that much harder. This implies that sector-specific strategy is vital, and there is no single circular logistics model that is likely to succeed across all industries.

5.6. Emerging Trends Shaping the Next Generation of Circular Logistics

There are several new trends that will likely transform the future of circular logistics. **Figure 2** provides a prospective implementation pathway linking barriers, facilitating levers, industry usage, and future research directions. One is the increasing overlap of circularity and decarbonization. Previous sustainability efforts tended to treat waste minimisation and carbon reduction as two similar yet distinct sets of objectives. More and more companies and policymakers are recognising that both should be considered in logistics systems. This is driving the sphere towards complete network design, which integrates the return logistics, electrification, the usage of renewable energy, redesigned packaging and lifecycle carbon accounting [98,99].

The other trend has been the emergence of product-service systems and access-based business models. When companies do not give up products, packaging or transportation equipment, they are better placed to recover, preserve and repurpose the equipment effectively. This changes logistics from a one-time distribution to lifecycle circulation management. In this respect, leasing, refill systems, and delivery of industrial equipment as a subscription and service-based model are especially pertinent. These models are not circular, but they establish organisational circumstances that enable recovery-oriented logistics to become economically viable.

Circular hubs that are localized and regionalised are also receiving some attention. Instead of large centralised recovery systems, future circular logistics might entail distributed systems of urban micro-hubs, regional remanufacturing systems, local repair ecosystems, and local-scale collection systems. This movement has been motivated by the issue of resilience and, in part, by the need to reduce recovery loops. However, decentralisation also introduces coordination complexity and can result in a loss of economies of scale, so it should not be presumed to be a positive factor [100].

Digital product passports, sophisticated traceability systems, and interoperable material data systems are bound to become increasingly powerful. These tools can enhance the visibility required for recovery decisions, the formation of a secondary market, and compliance reporting. They are important not only for technical efficiency but also for limiting information asymmetry among actors, which is a significant obstacle to circular coordination [27].

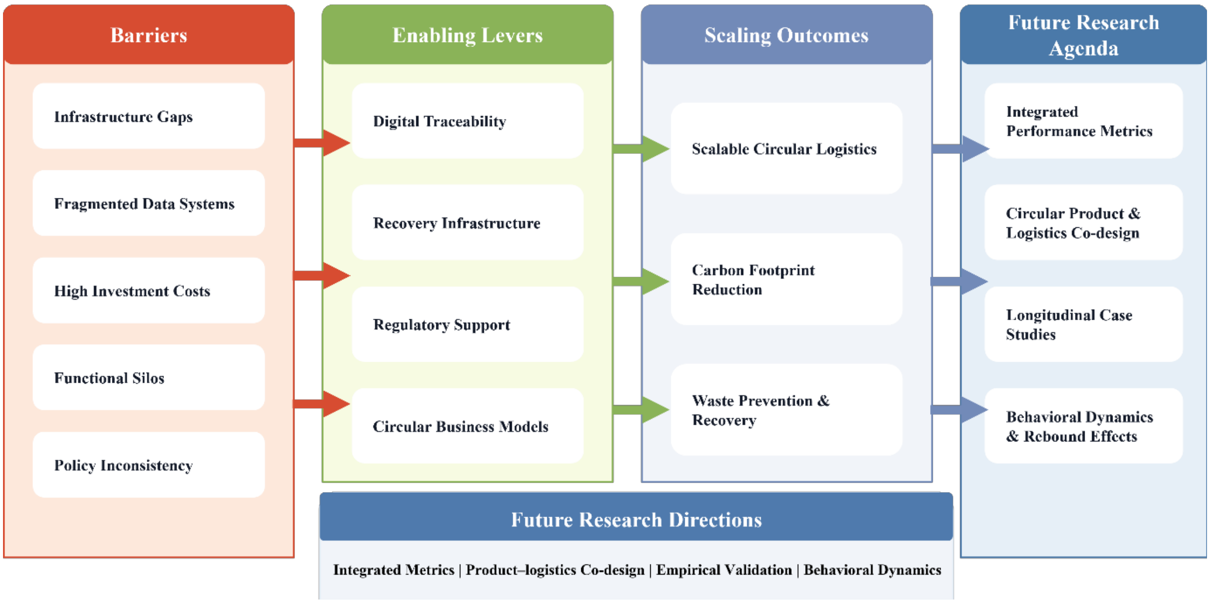

Figure 2. Implementation pathway, enabling conditions, and future research directions for circular economy-driven logistics systems.

The field will continue to be influenced by automation and AI, specifically in return triage, inventory balancing, warehouse target sorting, and predictive maintenance of reusable resources. But the way these technologies are headed is important. Their role in circularity will be to deploy them to foster value retention and reduce throughput intensity or to speed up the already high-volume logistics models.

5.7. Future Research Directions

Even though significant development is underway, there are still significant gaps in research. Among the key priorities, one must mention the evolution of integrated performance frameworks that will effectively embrace not only cost and carbon but also material retention quality, recovery hierarchy, and system resilience over the long term. The current research may tend to quantify what is measurable rather than what is most important in circularity. More sophisticated indicators are required to differentiate between shallowly circular systems and those that truly hold value and reduce the environmental load at the system scale. The second priority deals with the connection between product design and logistics design. A significant portion of the literature continues to address logistics optimisation without considering product architecture, although disassembly, repairability, standardisation, and modularity directly impact recoverability. Future studies are encouraged to better integrate design-for-circularity with logistics system engineering, particularly in industries where product complexity limits the reversibility of logistics [98].

Third, additional empirical and longitudinal research is required. Much of the literature remains model-based or conceptual, with little evidence on the long-term performance of circular logistics systems in practice under actual operating conditions. Pilot projects are useful; however, they tend to be run in controlled settings and might not reveal the challenges of scale-up, coordination with partners, or user behaviour. Longitudinal case studies would help clarify which circular practices are truly strong and which are based on exceptional circumstances.

Fourth, the behavioural and organisational dynamics should be considered in future studies. Consumer involvement in returns, reuse, and refill systems is not sufficiently explored compared with the technical design. On the same note, organisational capability, inter-firm trust, and governance mechanisms are often considered secondary issues, yet they have a serious impact on implementation outcomes. Circular logistics is not only a matter of network structure but also of coordinated action among a variety of actors.

Fifth, more emphasis should be placed on the geographic and regional diversity. The majority of the evidence available today comes from highly industrialised environments where infrastructure and policy support are relatively high. In growing economies, circular logistics, disjointed urban areas or informal recovery systems can take extremely different routes. Studies that do not consider these contexts are likely to make strategies that are technically beautiful but limited to global applicability [101].

Lastly, the area could benefit from additional research into rebound effects and systemic unintended consequences. **Table 4** summarises the relationships among implementation barriers, current industrial practices, and future research priorities. Circular initiatives can enhance recovery rates and increase consumption, product turnover, or logistics activity. The environmental promise of circular logistics can be exaggerated without consideration of such rebound mechanisms. Future studies should thus not only challenge efficiency narratives but also investigate the role of circular logistics in achieving absolute decreases in material extraction and carbon emissions [102].

Table 4. Implementation barriers, industrial practices, and future research priorities in circular logistics.

Dimension	Major Implementation Barriers	Current Industrial Practices	Future Research Priorities
Technology and infrastructure	Inadequate recovery facilities, lack of charging/washing/sorting infrastructure, poor interoperability	Pilot remanufacturing hubs, reusable packaging pools, and electric urban fleets	Scalable infrastructure models, interoperable circular logistics platforms
Economics and finance	High upfront investment, uncertain payback, weak internalisation of environmental externalities	Selective adoption in high-value sectors such as automotive and industrial equipment	Better business-case models, lifecycle costing, and financing mechanisms for circular logistics
Organisation and management	Functional silos, limited circular capability, and short-term performance metrics	Cross-functional sustainability teams, return-management units, and digital logistics integration initiatives	Governance models for cross-functional and inter-firm collaboration
Data and digitalisation	Fragmented information systems, weak traceability beyond the point of sale, and poor data quality	IoT-enabled asset tracking, AI-assisted returns management, and early digital passport initiatives	Data-sharing standards, explainable AI for circular logistics, and digital twin implementation frameworks
Policy and regulation	Inconsistent waste rules, uneven carbon regulation, and a lack of circular standards	Compliance-driven take-back systems, packaging responsibility schemes	Comparative policy studies, harmonised circular and carbon performance metrics
Sector-specific operations	Low-value products, dispersed return flows, hygiene or quality constraints.	Stronger adoption in automotive, electronics, food crates, healthcare assets, and urban logistics pilots	Sector-adapted circular logistics design frameworks
Environmental assessment	Narrow focus on recycling or direct emissions only	Carbon disclosure and selected waste reporting practices	Integrated metrics combining material circularity, waste prevention, and lifecycle carbon impacts

6. Conclusion

This review has discussed how the principles of the circular economy can transform the design of logistics systems, with the dual goal of reducing waste generation and carbon footprint through engineering innovation. The main point of the article is that logistics can no longer be perceived as a neutral facilitating role in a linear supply chain, but rather as a strategic and technical system that makes the difference between materials, products, packaging, and assets moving in a circle and wasting away. Circular economy-driven logistics, in this sense, is not merely green or reverse logistics, but an extension of both. It is a broader shift in systems, in which forward distribution, return flows, recovery infrastructure, digital intelligence, and low-carbon operations should be developed as a single entity.

The review has demonstrated that the theoretical background of circular logistics extends the limits of logistics design beyond cost, speed, and reliability. Circularity involves the addition of recovery loops, material retention levels, lifecycle emissions and multi-directional flows. This radically changes the rationale of logistics engineering. Transportation systems should not only be configured to deliver efficiently but also be synchronised to maintain take-back and low-emissions mobility. Warehousing should be transformed into a versatile processing system capable of sorting, repairing, redistributing, and maintaining asset value. The packaging and logistics resources should be designed to be recyclable, compatible, and traceable. Reverse logistics needs to shift towards reactive waste management to proactive value retention. IoT, AI, and digital twin technologies should help improve visibility, prediction, and adaptive control of complex and uncertain circular networks.

One of the lessons that the review has taught is that waste reduction and carbon footprint are two similar yet not necessarily aligned concepts. Decreases in packaging waste can lead to increases in transport or cleaning loads. Recovery networks have the potential to enhance material circularity, but generate new emissions when poorly designed. Direct logistics emissions can be reduced through electrification without altering the throughput logic of disposable systems. These strains demonstrate that circular logistics cannot be based on isolated technological interventions or single-objective optimisation. Rather, the performance of the systems needs to be evaluated using combined systems that eliminate trade-offs among cost, emissions, waste prevention, quality of recovery, and service results. All of these models (optimisation models, lifecycle assessment, uncertainty analysis, and data-driven decision support systems) can play a significant role. Still, their utility hinges on whether they are grounded in true circular design reasoning rather than traditional linear efficiency assumptions.

One of the biggest challenges, as pointed out in the article, has also been implementation. There is a rapid pace of technological innovation, yet adoption is limited by inadequate infrastructure, disjointed data ecosystems, short-term cost pressures, organisational silos, and heterogeneous regulatory environments. Circular logistics is not only a technical challenge but also an institutional, managerial and behavioural one. Circular logistics are most feasible in sectors where product value is high, reverse flows are consolidated, infrastructure is in place, and digital coordination is well developed. However, these positive conditions are not universal, which implies that circular strategies need to be refined for sectoral, geographic, and policy settings and not implemented as a set of one-size-fits-all strategies.

Academically, this review is valuable in that it synthesises the circular economy theory, logistics engineering, optimisation-based decision support, and implementation realities into a single construct. It outlines that the next wave of research should go beyond disjointed studies of decarbonising transport, recycling or reverse logistics. More focus should be on integrated performance measures, co-designing of products and logistics, empirical validation of real-life systems, uncertainty on recovery behaviour, and the risk of rebound effects. Research would need to more frequently pose not whether a logistics system is more efficient, but whether it leads to absolute decreases in the material extraction, waste leakage, and carbon emissions over the entire lifecycle. In practical terms, the results imply that companies and policymakers need to adopt the view that circular logistics is a long-term design transformation, not a set of isolated sustainability projects. Significant improvement will require the collective creation of engineering infrastructure, digital traceability, product designs that support recovery, supportive regulation, and new business models that deliver better value retention than one-way throughput. The future of sustainable logistics will thus be based on the ability of circular economy principles to be implemented at scale through coherent system design.

To sum up, the logistics of the circular economy are a promising avenue to more resource-efficient, low-carbon, and resilient industrial systems. Its success, though, lies in the capacity to combine engineering innovation and lifecycle thinking, institutional assistance and system-wide coordination. Making logistics a whole enables it to become a driver of circular and climate-friendly development, rather than a source of waste and emissions.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Halldórsson, Á., Kovács, G., 2010. The sustainable agenda and energy efficiency: Logistics solutions and supply chains in times of climate change. International Journal of Physical Distribution & Logistics Management. 40(1–2), 5–13.

[2] Abeyratne, D., 2024. Circular economy integration in soft robotic design: biodegradable actuators for sustainable packaging and reduced plastic waste in food logistics. Northern Reviews on Smart Cities, Sustainable Engineering, and Emerging Technologies. 9(11), 39–48.

[3] Haashni, S., Meera, K.L., Ranjitha, P.K., et al., 2026. Technology-Enabled Circular Economy. In Prioritizing Environmental Sustainability in Local Industrial Systems. IGI Global Scientific Publishing: Hershey, PA, USA. pp. 99–126.

[4] Dimitriou, D., Karagkouni, A., 2022. Due diligence of transport infrastructure operators sustainability: a circular economy driven approach. Frontiers in Sustainability. 3, 916038.

[5] Herold, D.M., Lee, K.-H., 2017. Carbon management in the logistics and transportation sector: An overview and new research directions. Carbon Management. 8(1), 79–97.

[6] Semrau, J., 2025. Logistics in the era of climate change: a review of challenges and development opportunities. Scientific Papers of Silesian University of Technology Organization and Management Series. 2025(217), 485–498.

[7] Naveen Kumar, R., Janani, M., John William, A., et al., 2025. Assessing performance metrics for e-commerce reverse logistics and circular economy initiatives in supply chains: the five R's model approach. IIMBG Journal of Sustainable Business and Innovation. 3(2), 154–172.

[8] Dwek, M., 2017. Integration of Material Circularity in Product Design [PhD Thesis]. Université Grenoble Alpes: Grenoble, France.

[9] Brad, E., Brad, S., 2021. Algorithm for designing reconfigurable equipment to enable industry 4.0 and circular economy-driven manufacturing systems. Applied Sciences. 11(10), 4446.

[10] Radu, I.-C., Vadureanu, A.-M., Cozorici, D.-E., et al., 2025. Advancing sustainability in modern polymer processing: strategies for waste resource recovery and circular economy integration. Polymers. 17(4), 522.

[11] Wu, H.J., Dunn, S.C., 1995. Environmentally responsible logistics systems. International Journal of Physical Distribution & Logistics Management. 25(2), 20–38.

[12] Ikpe, V., Shamsuddoha, M., 2024. Functional model of supply chain waste reduction and control strategies for retailers—The USA retail industry. Logistics. 8(1), 22.

[13] Abbas, H., Gang, T., Faiz, N., et al., 2026. Strategies and framework for achieving environmental sustainability in the retail food supply chain: food loss and waste management. Frontiers in Sustainable Food Systems. 9, 1701772.

[14] Vasamsetty, C., Alavilli, S.K., Kadiyala, B., et al., 2025. AI-Powered Supply Chain Management: Combining ASRS, Slotting Optimization, Economic Simulations, and Energy-Efficient Warehousing Solutions. In Proceedings of the 2025 6th International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV), Tirunelveli, India, 17–19 June 2025; pp. 1818–1824.

[15] Hazen, B.T., Russo, I., Confente, I., et al., 2021. Supply chain management for circular economy: conceptual framework and research agenda. The International Journal of Logistics Management. 32(2), 510–537.

[16] Lewandowski, M., 2016. Designing the business models for circular economy—Towards the conceptual framework. Sustainability. 8(1), 43.

[17] Marrucci, L., Daddi, T., Iraldo, F., 2022. The circular economy, environmental performance and environmental management systems: the role of absorptive capacity. Journal of Knowledge Management. 26(8), 2107–2132.

[18] Mc Loughlin, K., Lewis, K., Lascelles, D., et al., 2023. Sustainability in supply chains: reappraising business process management. Production

Planning & Control. 34(1), 19–52.
[19] Pratitajati, E., Lestari, Y.D., Okdinawati, L., 2026. Reframing innovation adoption in high compliance sectors: a multi-level perspective on digital twins for circular economy in pharmaceuticals. International Journal of Innovation Science. 1–26.
[20] Singh, P., Yaseen, I., Siddiqui, A.A., et al., 2026. Logistics digitalisation and trade flows: evidence from the logistics performance index using a gravity model. International Journal of Logistics Research and Applications. 1–20.
[21] Wilson, D.C., Parker, D., Cox, J., et al., 2012. Business waste prevention: A review of the evidence. Waste Management & Research. 30(9_ suppl), 17–28.
[22] Ali, K.Q., Nimarta, W., Bano, R., 2025. Students as Partners in Designing Educational Games for Sustainability: A Case Study from a Higher Education Institution in Pakistan. In Engineering Educational Games for a Sustainable Society: Play, Learn and Transform. Springer Nature: Singapore. pp. 125–152.
[23] Hassan, A., 2025. Theoretical Foundation for a Framework to Support Business Transition to a Circular Economy [Master's Thesis]. Åbo Akademi University: Turku, Finland.
[24] Urbinati, A., Chiaroni, D., Chiesa, V., 2017. Towards a new taxonomy of circular economy business models. Journal of Cleaner Production. 168, 487–498.
[25] Zahran, S., 2024. Investigating the nexus between green supply chain practices and sustainable waste management in advancing circular economy. Sustainability. 16(9), 3566.
[26] Hernandez, J.C.R., Villa-Enciso, E., Cardona-Acevedo, S., et al., 2025. Smart innovation for a circular economy: a systematic review of emerging trends and the future of AI in the sustainable economy. Sustainability. 17(13), 5793.
[27] Mishra, A., Dutta, P., Jayasankar, S., et al., 2023. A review of reverse logistics and closed-loop supply chains in the perspective of circular economy. Benchmarking: An International Journal. 30(3), 975–1020.
[28] Nikseresht, A., Golmohammadi, D., Zandieh, M., 2024. Sustainable green logistics and remanufacturing: a bibliometric analysis and future research directions. The International Journal of Logistics Management. 35(3), 755–803.
[29] Fatorachian, H., Kazemi, H., 2025. From linear to circular: transitioning supply chains using advanced logistics and closed-loop supply chain theory. Cogent Business & Management. 12(1), 2575259.
[30] Ferreira, J.J., Candeias Fernandes, A.J., Nguyen, T.H.D., et al., 2026. Green logistics and supply chain knowledge management: an extended framework-based systematic literature review. Journal of Knowledge Management. 30(11), 168–188.
[31] Trushkina, N., Dzwigol, H., Serhieieva, O., 2020. Development of the logistics 4.0 concept in the digital economy. Economic Herald of the Donbas. 4(62), 85–96.
[32] Makarova, I., Shubenkova, K., Mavrin, V., et al., 2019. Features of logistic terminal complexes functioning in the transition to the circular economy and digitalization. In Modelling of the Interaction of the Different Vehicles and Various Transport Modes. Springer: Cham, Switzerland. pp. 415–527.
[33] Beames, A., Claassen, G., Akkerman, R., 2021. Logistics in the circular economy: challenges and opportunities. In Strategic Decision Making for Sustainable Management of Industrial Networks. Springer: Cham, Switzerland. pp. 1–14.
[34] Ripanti, E.F., Tjahjono, B., 2019. Unveiling the potentials of circular economy values in logistics and supply chain management. The International Journal of Logistics Management. 30(3), 723–742.
[35] Ripanti, E.F., 2016. A Framework to Design Reverse Logistics Operations Based on Circular Economy Values [PhD Thesis]. Cranfield University: Cranfield, UK.
[36] Sun, J., Wang, T., Lu, S., et al., 2023. Leverage of resource efficiency over environmental emissions: Case of a megacity in China. Science of The Total Environment. 858, 159514.
[37] Lee, R.P., Keller, F., Meyer, B., 2017. A concept to support the transformation from a linear to circular carbon economy: net zero emissions, resource efficiency and conservation through a coupling of the energy, chemical and waste management sectors. Clean Energy. 1(1), 102–113.
[38] De Souza, E., Kerber, J.C., Bouzon, M., et al., 2022. Performance evaluation of green logistics: Paving the way towards circular economy. Cleaner Logistics and Supply Chain. 3, 100019.
[39] González-Sánchez, R., Settembre-Blundo, D., Ferrari, A.M., et al., 2020. Main dimensions in the building of the circular supply chain: A literature

review. Sustainability. 12(6), 2459.

[40] Roy, M., Sarker, J., 2025. Integration of circular economy principles within information logistics: case study of Australia. In Organizational Readiness and Research: Security, Management, and Decision Making. IGI Global Scientific Publishing: Hershey, PA, USA. pp. 449–490.

[41] Nasr, N., 2024. Technology Innovation for the Circular Economy: Recycling, Remanufacturing, Design, System Analysis and Logistics. John Wiley & Sons: Hoboken, NJ, USA.

[42] Nicoletti, B., Appolloni, A., 2024. Green Logistics 5.0: a review of sustainability-oriented innovation with foundation models in logistics. European Journal of Innovation Management. 27(9), 542–561.

[43] He, B., Yuan, X., Qian, S., et al., 2023. Product low-carbon design, manufacturing, logistics, and recycling: An overview. Wiley Interdisciplinary Reviews: Energy and Environment. 12(5), e479.

[44] Hu, S., 2016. Evaluation of the regional green circulation low-carbon transportation development. International Journal of Earth Sciences and Engineering. 9(5), 2249–2255.

[45] Lee, C.T., Hashim, H., Ho, C.S., et al., 2017. Sustaining the low-carbon emission development in Asia and beyond: Sustainable energy, water, transportation and low-carbon emission technology. Journal of Cleaner Production. 146, 1–13.

[46] Pardhi, S., Chakraborty, S., Tran, D.-D., et al., 2022. A review of fuel cell powertrains for long-haul heavy-duty vehicles: technology, hydrogen, energy and thermal management solutions. Energies. 15(24), 9557.

[47] Larson, P.D., Parsons, R.V., Kalluri, D., 2024. Zero-emission heavy-duty, long-haul trucking: obstacles and opportunities for logistics in North America. Logistics. 8(3), 64.

[48] Aslam, M.A., Abbas, M.S., Irfan, R.M., et al., 2025. From ammonia to hydrogen: Evolution of ruthenium-based catalysts. ACS Catalysis. 15(21), 18631–18662.

[49] Aslam, M.A., Mustaqeem, M., Abbas, M.S., et al., 2025. Hydrogen Revolution: Advances in Catalytic Ammonia Decomposition. Clean Energy Technologies. 1(1), 49–69.

[50] Suha, K.F., 2024. The Knowledge Management Transition to Smart Circular Economy: A Study on Logistics Industry [Master's Thesis]. Åbo Akademi University: Turku, Finland.

[51] Tadić, S., Krstić, M., Dabić-Miletić, S., et al., 2023. Smart material handling solutions for city logistics systems. Sustainability. 15(8), 6693.

[52] Felez, R., Felez, J., 2025. Advanced energy management for residential buildings optimizing costs and efficiency through thermal energy storage and predictive control. Applied Sciences. 15(2), 880.

[53] Odufuwa, O.Y., 2024. Optimal Energy Management of the Ice Thermal Storage-Based Air Conditioning System for Commercial Buildings with a Solar Photovoltaic System [PhD Thesis]. Central University of Technology, Free State: Bloemfontein, South Africa.

[54] Jayant, A., Gupta, P., Garg, S., 2012. Perspectives in reverse supply chain management (R-SCM): a state of the art literature review. Journal of Manufacturing and Industrial Engineering. 6(1), 87–102.

[55] Gry, S., Niederlaender, M., Lodi, A.N., et al., 2023. A conceptual approach for an AI-based recommendation system for handling returns in fashion e-commerce. In Proceedings of the International Conference on Smart Business Technologies, Rome, Italy, 11–13 July 2023.

[56] Bekrar, A., Ait El Cadi, A., Todosijevic, R., et al., 2021. Digitalizing the closing-of-the-loop for supply chains: A transportation and blockchain perspective. Sustainability. 13(5), 2895.

[57] Romagnoli, S., Tarabu', C., Maleki Vishkaei, B., et al., 2023. The impact of digital technologies and sustainable practices on circular supply chain management. Logistics. 7(1), 1.

[58] Grigoriadis, L., 2026. Strategic Repositioning in the E-Commerce Value Chain: A Case Study of a Traditional Distribution and Logistics Company Reevaluating the Nordic Market and New Business Models for Parcel Delivery [Master's Thesis]. KTH Royal Institute of Technology: Stockholm, Sweden.

[59] Ezeudu, O., Kennedy, C., 2024. Insights and dynamics of circular business model in developing countries' context: The empirical analysis of the returnable glass bottles process. Business Strategy & Development. 7(1), e349.

[60] Lee, S.-G., Xu, X., 2005. Design for the environment: life cycle assessment and sustainable packaging issues. International Journal of Environmental Technology and Management. 5(1), 14–41.

[61] Cabot, M.I., Luque, A., de las Heras, A., et al., 2019. Aspects of sustainability and design engineering for the production of interconnected smart

food packaging. PLoS One. 14(5), e0216555.

[62] Olaleye, I.A., Mokogwu, C., Olufemi-Phillips, A.Q., et al., 2024. Innovative frameworks for sustainable transportation coordination to reduce carbon footprints in logistics. International Journal of Science and Technology Research Archive. 7(2), 68–75.

[63] Li, Y., Cao, Z., 2024. Research and practice of energy saving and emission reduction technology in green logistics engineering. Smart Systems and Green Energy. 6(1), 20–25.

[64] Chen, W.-H., Yang, Y.-M., Chen, H.-N., 2024. Determinants of Carbon Inventory and Systematic Innovation Methods to Analyze the Strategies of Carbon Reduction: An Empirical Study of Green Lean Management in Electroplating an Factory. Sustainability. 16(19), 8301.

[65] Constable, G., Somerville, B., 2003. A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives. Joseph Henry Press: Washington, DC, USA.

[66] Beskorovainyi, V., Draz, O., 2021. Mathematical models of decision support in the problems of logistics networks optimization. Innovative Technologies and Scientific Solutions for Industries. 4(18), 5–14.

[67] Cao, S., Liao, W., Huang, Y., 2021. Heterogeneous fleet recyclables collection routing optimization in a two-echelon collaborative reverse logistics network from circular economic and environmental perspective. Science of The Total Environment. 758, 144062.

[68] Daramola, O.M., Apeh, C.E., Basiru, J.O., et al., 2023. Optimizing reverse logistics for circular economy: Strategies for efficient material recovery and resource circularity. International Journal of Social Science Exceptional Research. 2(1), 16–31.

[69] Bressanelli, G., Perona, M., Saccani, N., 2019. Challenges in supply chain redesign for the Circular Economy: a literature review and a multiple case study. International Journal of Production Research. 57(23), 7395–7422.

[70] Akkad, M.Z., Bányai, T., 2020. Multi-objective approach for optimization of city logistics considering energy efficiency. Sustainability. 12(18), 7366.

[71] Zarbakhshnia, N., Govindan, K., Kannan, D., et al., 2023. Outsourcing logistics operations in circular economy towards to sustainable development goals. Business Strategy and the Environment. 32(1), 134–162.

[72] Mattsson, J., Sterneus, C., 2024. Understanding CO_2 Emission Measurements in Global Logistics: Insights and Recommendations for CO_2 Emission Measurement Strategies [Bachelor's Thesis]. Jönköping University: Jönköping, Sweden.

[73] Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. The International Journal of Life Cycle Assessment. 22(5), 832–837.

[74] Peña, C., Civit, B., Gallego-Schmid, A., et al., 2021. Using life cycle assessment to achieve a circular economy. The International Journal of Life Cycle Assessment. 26(2), 215–220.

[75] Zeballos, L.J., Gomes, M.I., Barbosa-Povoa, A.P., et al., 2012. Addressing the uncertain quality and quantity of returns in closed-loop supply chains. Computers & Chemical Engineering. 47, 237–247.

[76] Inderfurth, K., 2005. Impact of uncertainties on recovery behavior in a remanufacturing environment: a numerical analysis. International Journal of Physical Distribution & Logistics Management. 35(5), 318–336.

[77] Mehrbakhsh, S., Ghezavati, V., 2020. Mathematical modeling for green supply chain considering product recovery capacity and uncertainty for demand. Environmental Science and Pollution Research. 27(35), 44378–44395.

[78] Mahmud, D., 2025. An IOT-Enabled Decision Support System for Circular Economy Business Models: A Review Of Economic Efficiency and Sustainability Outcomes. American Journal of Scholarly Research and Innovation. 4(1), 250–286.

[79] Moazzeni, S., Sgarbossa, F., 2025. Collaborative logistics and digital technologies in rural contexts: a systematic review and a decision aid model for logistics decision-makers. NHH Dept. of Business and Management Science Discussion Paper No. 2015/12. 1–27.

[80] Guo, Y., Mao, H., Ding, H., et al., 2022. Data-driven coordinated development of the digital economy and logistics industry. Sustainability. 14(14), 8963.

[81] Li, Y.-F., Ng, S.H., Xie, M., et al., 2010. A systematic comparison of metamodeling techniques for simulation optimization in decision support systems. Applied Soft Computing. 10(4), 1257–1273.

[82] Volk, M., Lautenbach, S., van Delden, H., et al., 2010. How can we make progress with decision support systems in landscape and river basin management? Lessons learned from a comparative analysis of four different decision support systems. Environmental Management. 46(6), 834–849.
[83] Jiang, H., 2025. Digital Twin-Enhanced MCDM framework for circular construction dynamic lifecycle optimization of hybrid concrete mix design. Decision Making: Applications in Management and Engineering. 8(2), 53–70.
[84] Müller, J.M., Kiel, D., Voigt, K.-I., 2018. What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. Sustainability. 10(1), 247.
[85] Sony, M., Naik, S., 2020. Critical factors for the successful implementation of Industry 4.0: a review and future research direction. Production Planning & Control. 31(10), 799–815.
[86] Sharma, R., Panigrahi, P.K., 2015. Developing a roadmap for planning and implementation of interoperability capability in e-government. Transforming Government: People, Process and Policy. 9(4), 426–447.
[87] Pardo, T.A., Nam, T., Burke, G.B., 2012. E-government interoperability: Interaction of policy, management, and technology dimensions. Social Science Computer Review. 30(1), 7–23.
[88] Libecap, G.D., 2014. Addressing global environmental externalities: Transaction costs considerations. Journal of Economic Literature. 52(2), 424–479.
[89] Ekins, P., Zenghelis, D., 2021. The costs and benefits of environmental sustainability. Sustainability Science. 16(3), 949–965.
[90] Bithas, K., 2011. Sustainability and externalities: Is the internalization of externalities a sufficient condition for sustainability? Ecological Economics. 70(10), 1703–1706.
[91] Kazancoglu, I., Sagnak, M., Kumar Mangla, S., et al., 2021. Circular economy and the policy: A framework for improving the corporate environmental management in supply chains. Business Strategy and the Environment. 30(1), 590–608.
[92] Vu, T.N.Q., Nguyen, N.A., Nguyen, K.H., et al., 2025. Navigating the Green Transition: Drivers, Barriers, and Policy Implications for Circular Economy Adoption Among Logistics SMEs in an Emerging Economy. Sustainability. 18(1), 55.
[93] Yuan, L., 2026. Environmental Regulation at the Crossroads: A Review of Catalysts and Barriers in Circular Economy Transitions. Business Strategy and the Environment.
[94] Nwamekwe, C.O., Chikwendu, O.C., 2025. Circular economy strategies in industrial engineering: From theory to practice. International Journal of Multidisciplinary Research and Growth Evaluation. 6(01), 1773–1782.
[95] Van Buren, N., Demmers, M., Van der Heijden, R., et al., 2016. Towards a circular economy: The role of Dutch logistics industries and governments. Sustainability. 8(7), 647.
[96] Heyes, G., Sharmina, M., Mendoza, J.M.F., et al., 2018. Developing and implementing circular economy business models in service-oriented technology companies. Journal of Cleaner Production. 177, 621–632.
[97] Kazancoglu, Y., Ozkan-Ozen, Y.D., Sagnak, M., et al., 2023. Framework for a sustainable supply chain to overcome risks in transition to a circular economy through Industry 4.0. Production Planning & Control. 34(10), 902–917.
[98] Govindan, K., Hasanagic, M., 2018. A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. International Journal of Production Research. 56(1–2), 278–311.
[99] Agrawal, R., Wankhede, V. A., Kumar, A., et al., 2022. Progress and trends in integrating Industry 4.0 within Circular Economy: A comprehensive literature review and future research propositions. Business Strategy and the Environment. 31(1), 559–579.
[100] Handoyo, S., Sueb, M., 2026. Integrating Digital Technologies Into the Circular Economy: a Systematic Literature Review of Trends, Challenges, and Opportunities. Circular Economy and Sustainability. 6(2), 111.
[101] Upadhyay, A., Laing, T., Kumar, V., et al., 2021. Exploring barriers and drivers to the implementation of circular economy practices in the mining industry. Resources Policy. 72, 102037.
[102] Bianchini, A., Rossi, J., Pellegrini, M., 2019. Overcoming the main barriers of circular economy implementation through a new visualization tool for circular business models. Sustainability. 11(23), 6614.