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# Application and Benefit Analysis of Multimodal Transport in Pulp Logistics

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**Abstract:** The global pulp industry depends on efficient and resilient logistics systems to ensure the timely delivery of bulk materials across international markets. Traditional single-mode transport approaches, while widely used, face limitations in cost, time, and environmental sustainability. In response, multimodal transport—integrating road, rail, maritime, and occasionally air freight—has emerged as a strategic solution that enhances efficiency while reducing risks and emissions. This review examines the application of multimodal transport in pulp logistics, outlining its operational structures, regulatory frameworks, and supporting technologies. Case studies highlight successful implementations and optimization strategies, while comparative analyses demonstrate clear advantages in cost reduction, delivery reliability, and carbon footprint mitigation. At the same time, challenges such as operational risks, coordination gaps, and policy complexities underscore the need for better digital integration and regulatory harmonization. The paper further explores emerging trends, including the use of AI, blockchain, IoT, and green logistics strategies, offering strategic recommendations for pulp producers, logistics providers, and policymakers. Overall, multimodal transport not only addresses the pressing inefficiencies of traditional logistics but also positions the pulp industry to align with future demands for digitalization and sustainability.

**Keywords:** multimodal transport; pulp logistics; supply chain efficiency; sustainability; digital technologies

## 1. Introduction

### *1.1. Background of Pulp Logistics*

The pulp industry serves as a backbone for global paper, packaging, and tissue production, with annual output exceeding 190 million metric tons. Major producers include Brazil, Canada, the United States, Finland, and Sweden, while Asia, particularly China and India, accounts for a rapidly expanding share due to e-commerce growth, packaging demand, and urbanization [1]. These factors have made pulp logistics a strategic component of international supply chains.

Transporting pulp presents unique challenges. Pulp is bulky, heavy, and of relatively low unit value, making transport costs critical for competitiveness. Long distances between producers and end-users, combined with sensitivity to moisture, contamination, and improper handling, make logistics efficiency, reliability, and cost control essential. The need for collaboration and trust between logistics providers and pulp producers to optimize resource allocation and reduce operational risks is particularly important in multimodal operations.

*1.2. Limitations of Traditional Transport Modes*

Historically, pulp logistics has relied heavily on single-mode transport solutions such as road, rail, or maritime shipping, depending on geography. Road transport is often favored for its flexibility and door-to-door capability but is limited by high fuel costs, congestion, and environmental concerns [2]. Rail transport provides cost efficiency over long distances and high-volume shipments but suffers from rigid scheduling, infrastructure dependency, and limited accessibility to remote mills or customer sites. Maritime transport remains the dominant mode for intercontinental pulp trade, offering economies of scale; however, it is prone to delays caused by port congestion, weather conditions, and long lead times that reduce supply chain responsiveness [3].

These single-mode systems often lack integration and fail to capitalize on the complementary advantages of different modes. Exclusive reliance on one mode can increase costs, emissions, and supply chain vulnerability. Furthermore, single-mode transport frequently neglects indirect costs such as delays, storage, and handling inefficiencies, highlighting the need for alternative logistics strategies supported by strategic planning and digital tools [4]. Additionally, managing financial and operational risks in logistics requires careful attention to coordination and decision-making frameworks [5]. Multimodal transport addresses these limitations by enabling coordinated operations across multiple carriers and modes, improving efficiency, resilience, and environmental performance.

From a financial standpoint, single-mode transport frequently fails to optimize total logistics cost. While the direct cost of moving pulp from one location to another can be calculated, indirect costs such as delays, storage, and handling inefficiencies accumulate along the supply chain. These shortcomings highlight the pressing need for alternative logistics strategies [6].

These shortcomings highlight the pressing need for alternative logistics strategies. A comparative overview of the strengths and weaknesses of single-mode versus multimodal transport in pulp logistics is summarized in Table 1.

**Table 1.** Comparison of Traditional vs. Multimodal Transport Modes in Pulp Logistics.

| Aspect | Traditional Single-Mode Transport | Multimodal Transport |
|---|---|---|
| Cost efficiency | Often high due to lack of optimization | Lower total logistics cost through mode integration |
| Time reliability | Vulnerable to congestion and delays | Improved scheduling and flexibility |
| Environmental impact | High emissions (especially road and maritime) | Reduced carbon footprint by optimizing modal mix |
| Risk management | Dependent on one mode, higher disruption risk | Diversified modes increase resilience |
| Accessibility | Limited by infrastructure of chosen mode | Broader reach through combined networks |
| Handling efficiency | Repeated loading/unloading may increase damage | Coordinated operations reduce handling risks |

*1.3. Significance of Multimodal Transport*

In response to these challenges, multimodal transport has emerged as a promising solution for pulp logistics. Multimodal transport refers to the use of two or more transport modes in a coordinated manner under a single contract, thereby integrating road, rail, maritime, and sometimes inland waterways or air transport [7]. This approach allows stakeholders to harness the strengths of each mode while mitigating their individual weaknesses. For example, rail can efficiently move bulk pulp from mills to ports, where

maritime shipping takes over for intercontinental delivery, and road transport ensures last-mile distribution.

The motivation for adopting multimodal systems in pulp logistics lies in their ability to reduce costs, improve efficiency, and enhance sustainability. By optimizing routes and mode combinations, companies can lower transport expenses while reducing carbon emissions. Furthermore, multimodal transport improves resilience by diversifying logistics options, which is increasingly important in the face of global disruptions such as port strikes, pandemics, or geopolitical tensions [8].

The purpose of this review is to analyze the current applications of multimodal transport in pulp logistics and to assess the benefits it offers in terms of efficiency, cost-effectiveness, and environmental performance. The review will also highlight challenges and potential risks while providing insights into future developments and strategic recommendations for industry stakeholders.

## 2. Overview of Multimodal Transport

### *2.1. Definition and Key Concepts*

Multimodal transport refers to the movement of goods using two or more different modes of transportation, coordinated under a single transport contract and responsibility. Unlike intermodal transport, where each mode may involve separate contracts and responsibilities, multimodal transport ensures continuity, accountability, and simplified documentation across the entire logistics chain [9]. This approach integrates various carriers and infrastructure into a seamless system, aiming to optimize cost, efficiency, and reliability.

The core concept is not simply the use of multiple modes, but their integration into a single, managed operation [10]. For instance, pulp may be transported by truck from a mill to a railway terminal, transferred onto trains for long-distance inland movement, loaded onto ships at seaports for intercontinental shipping, and finally delivered by road to paper manufacturers or distribution centers. In this system, the shipper signs only one contract, often with a multimodal transport operator (MTO), who assumes responsibility for the entire journey, regardless of the number of modes used [7].

The main transport modes involved in multimodal operations include:

Road transport: Provides flexibility and accessibility for first-mile and last-mile delivery. Trucks can reach production sites and customer locations where other modes are unavailable.

Rail transport: Efficient for bulk and long-distance inland shipments. Rail is cost-effective and environmentally friendly but requires specialized terminals and handling infrastructure.

Water transport: Includes both inland waterways and maritime shipping. Inland barges support regional distribution, while maritime vessels handle global flows, particularly for transoceanic pulp trade [2].

Air transport: Rarely used for pulp due to high cost, but valuable for time-sensitive documentation, specialized samples, or emergency shipments.

Together, these modes form a complementary network where each contributes its unique advantages to a unified logistics strategy.

### *2.2. Regulatory Framework and Standards*

Multimodal transport requires coordination not only across modes but also across legal systems and regulatory environments [5]. A variety of international conventions and institutional frameworks provide guidelines for contracts, liability, and documentation.

One of the most widely recognized agreements is the CMR Convention (Convention on the Contract for the International Carriage of Goods by Road), which standardizes road transport regulations across many European and Asian countries. For rail transport, the SMGS Agreement (Agreement on International Goods Transport by Rail) governs cross-

border rail traffic in Eurasia, while the COTIF Convention applies to Europe. Maritime transport is governed by conventions such as the Hague-Visby Rules and the Rotterdam Rules, which define carrier liability and cargo handling standards.

The FIATA Multimodal Transport Bill of Lading (FIATA FBL) serves as an important standardized document, widely accepted in international trade and banking. It provides a unified transport document recognized across multiple modes, facilitating trade finance and customs clearance. This standardization reduces administrative burdens and improves legal certainty for shippers and consignees.

National and regional policies also shape multimodal transport for pulp logistics. The European Union, for example, promotes multimodality through its TEN-T (Trans-European Transport Network) policy, encouraging the integration of rail and waterways with road and port infrastructure. In North America, the development of intermodal rail hubs has been critical to enhancing trade flows between the United States and Canada. In Brazil and Chile, government initiatives to modernize port facilities and railway corridors directly benefit pulp exporters. Meanwhile, China's Belt and Road Initiative has expanded multimodal infrastructure across Eurasia, creating new routes for pulp transport between Asia and other continents.

For pulp producers and logistics providers, navigating this regulatory landscape is essential to ensuring smooth operations, compliance with liability regimes, and efficient customs clearance.

### *2.3. Supporting Technologies*

Technological innovation has become a cornerstone of modern multimodal transport, enabling real-time visibility, coordination, and optimization of supply chains.

Logistics IT systems such as Transport Management Systems (TMS) and Enterprise Resource Planning (ERP) platforms allow companies to plan, monitor, and optimize multimodal flows. These systems consolidate data from carriers, terminals, and warehouses, providing transparency across the supply chain. Integration with port community systems and customs platforms further enhances efficiency by streamlining clearance procedures.

Tracking and monitoring technologies are also critical. Global Positioning System (GPS) tracking enables continuous monitoring of trucks, trains, and vessels. Combined with geofencing, companies can receive alerts on deviations, delays, or unauthorized stops. For pulp logistics, where moisture and contamination risks are significant, advanced sensors can monitor humidity, temperature, and cargo integrity throughout the journey.

Emerging digital solutions further strengthen multimodal operations. Radio Frequency Identification (RFID) tags allow automatic cargo identification and reduce manual handling errors. Internet of Things (IoT) devices create smart containers capable of transmitting real-time data on location and cargo condition. Artificial Intelligence (AI) and machine learning algorithms enhance route optimization, demand forecasting, and predictive maintenance of transport assets. For instance, AI-enabled platforms can evaluate multiple route scenarios, balancing cost, speed, and environmental footprint to identify the most efficient multimodal strategy.

Blockchain technology is also gaining attention in logistics. By providing a decentralized and tamper-proof ledger, blockchain ensures secure and transparent sharing of shipment documents among stakeholders. This reduces paperwork delays, prevents fraud, and builds trust among supply chain partners.

The integration of these technologies not only improves operational efficiency but also supports sustainability. Digital tools facilitate the calculation of carbon footprints and help companies select greener transport options, aligning logistics strategies with corporate social responsibility (CSR) and environmental, social, and governance (ESG) goals.

## 3. Application in Pulp Logistics

### *3.1. Typical Multimodal Logistics Chains*

The pulp supply chain is geographically extensive and involves multiple handover points, making it well suited for multimodal transport. A typical logistics chain begins at the pulp mill, where large volumes of pulp bales or rolls are packaged for transport. From the mill, pulp is usually moved by road or rail to an inland terminal or seaport. Road transport is commonly used for short distances due to its flexibility and accessibility, while rail becomes advantageous when the mill is located far from the port and large volumes are involved.

At the port terminal, pulp must be carefully handled to avoid moisture absorption and contamination. Packaging is designed to protect the pulp during transshipment, often involving stretch wrapping or moisture-barrier wrapping. From here, pulp is loaded into containers or directly onto bulk vessels for maritime shipping, which remains the dominant mode for long-distance international trade. Once the cargo reaches the destination port, it may again be transferred to rail or road for distribution to paper mills, converters, or warehouses.

Each transfer point requires precise coordination to minimize delays and reduce the risk of cargo damage. The efficiency of these multimodal chains depends heavily on terminal infrastructure, packaging practices, and information sharing among stakeholders.

### *3.2. Case Studies*

Several real-world examples illustrate how multimodal transport has been successfully applied in pulp logistics.

Scandinavian pulp exports to continental Europe: Swedish and Finnish producers frequently use a combination of rail and short-sea shipping. Pulp is transported by rail from inland mills to Baltic ports, then shipped by Ro-Ro or container vessels to Germany, the Netherlands, and Belgium. This system leverages rail's environmental advantages and short-sea shipping's efficiency.

Brazil to Asia trade: Brazil, one of the largest global pulp exporters, relies on road, rail, and maritime integration. Pulp mills in inland regions of Mato Grosso or Espírito Santo often move shipments by truck to rail terminals, then by rail to ports such as Santos. From there, container vessels deliver pulp to China, Korea, and India. This multimodal strategy lowers inland logistics costs and ensures high-volume throughput.

North America distribution: In Canada and the United States, pulp producers often combine rail and truck transport for domestic and cross-border shipments. Rail provides cost-efficient long-haul movement to regional hubs, while trucks handle last-mile delivery to paper mills. This hybrid model balances cost with service flexibility.

These examples demonstrate that multimodal transport improves competitiveness by reducing costs and ensuring reliable delivery. Moreover, they show that multimodal chains are adaptable to regional infrastructure and trade patterns, with different combinations emerging based on geography and market demand.

The diversity of multimodal approaches is summarized in Table 2, which presents representative examples of pulp transport routes using different mode combinations.

**Table 2.** Examples of Pulp Transport Routes Using Different Multimodal Combinations.

| Route | Mode Combination | Description | Key Benefit |
|---|---|---|---|
| Sweden → Germany | Rail + Short-sea shipping | Rail from inland mills to Baltic ports, then vessel to Germany | Low emissions, efficient EU connectivity |
| Brazil → China | Road + Rail + Maritime | Truck to rail terminals, rail to Santos port, container ship to Asia | Cost-efficient, high-volume throughput |

| | | | |
|---|---|---|---|
| Canada → USA (domestic) | Rail + Road | Rail for long-haul to hubs, trucks for last-mile delivery | Balanced cost and flexibility |
| Finland → Netherlands | Road + Sea | Truck to ports, container vessels to Rotterdam | Fast regional delivery |
| Chile → Korea | Road + Maritime | Road transport to port, direct container shipping | Simplicity, reduced handling |

*3.3. Route and Mode Optimization*

Choosing the optimal combination of modes for pulp logistics involves a complex set of factors. Cost considerations remain central, as pulp is a bulk commodity with relatively low unit value, making transportation expenses a significant component of total supply chain cost. Distance and geography also shape modal choice: rail and inland waterways are advantageous for long-haul inland transport, while road is indispensable for local access. Time sensitivity may play a role when pulp is needed quickly for production, pushing companies toward faster multimodal chains.

In addition to cost and geography, infrastructure availability determines feasible options. For example, the presence of a rail terminal near a mill may enable cost-efficient multimodal solutions, whereas regions without rail infrastructure may rely more heavily on road–sea integration. Environmental considerations are increasingly influential, with companies seeking lower-emission modes to align with sustainability goals and regulatory requirements.

Scheduling and load planning are critical to optimization. Coordinating timetables between road carriers, rail operators, and port authorities ensures minimal dwell time at terminals. Digital tools such as Transport Management Systems (TMS) and simulation software help optimize routing, balance container flows, and predict congestion risks. Advanced planning reduces both direct costs and hidden costs related to delays or demurrage.

Ultimately, optimization is not only about minimizing expenses but also about creating a resilient and flexible logistics network. The ability to switch between transport modes during disruptions—such as port strikes, weather events, or rail service interruptions—provides companies with strategic agility in a volatile global market.

## 4. Benefits and Efficiency Analysis

*4.1. Cost Efficiency*

One of the most widely recognized advantages of multimodal transport in pulp logistics is its ability to lower overall transportation costs. Since pulp is a bulky commodity with relatively low unit value, logistics expenses account for a significant share of its delivered cost. Multimodal transport allows companies to select the most cost-effective mode for each leg of the journey, thereby avoiding the inefficiencies of relying solely on one mode.

For instance, using rail for long-distance inland transport can be 30–50% cheaper than road haulage when large volumes are involved. Rail's economies of scale make it particularly attractive for pulp producers located in remote areas far from ports. Once pulp reaches the port, maritime shipping provides another layer of cost efficiency, as ocean vessels transport thousands of tons at a fraction of the cost per unit compared to land transport. Road is still indispensable for first- and last-mile delivery, but its use is minimized, reducing overall expenses.

Another cost dimension is storage and inventory management. Single-mode transport systems often generate bottlenecks and unpredictable delays, which force companies to hold excess safety stock. Multimodal systems, when well-coordinated, reduce lead time variability and allow companies to maintain leaner inventories. This translates

into significant savings in warehousing and working capital costs. For example, a Brazilian pulp exporter shifting from road-only to a road–rail–maritime multimodal chain reported a reduction in buffer inventory by nearly 15%, which directly lowered storage expenses.

### *4.2. Time Efficiency*

Time efficiency is another critical factor in pulp logistics, as buyers require predictable deliveries to sustain continuous paper production. Multimodal transport improves time performance by leveraging the strengths of different modes. For long inland distances, rail is not only cheaper but often faster than road when congestion or regulatory restrictions affect highways. Similarly, short-sea shipping can provide quicker regional connectivity compared to overland truck routes, particularly within Europe.

Compared with single-mode systems, multimodal strategies frequently achieve faster average delivery times. For instance, using direct rail–maritime corridors reduces the need for intermediate handling, which accelerates transit between production sites and consumption markets. Well-designed multimodal hubs can also streamline transshipment processes, ensuring that goods move smoothly from trucks to trains or vessels without extended dwell times.

An equally important benefit is the reduction of transit delays. Single-mode reliance increases vulnerability: a road-only chain is highly exposed to traffic congestion, driver shortages, or road closures, while maritime-only supply chains face risks of port congestion and weather delays. Multimodal chains distribute these risks by creating multiple routing options and backup pathways. This diversification enhances reliability, which is crucial for industries like pulp and paper where continuous operations depend on steady input flows.

### *4.3. Environmental Impact*

Beyond cost and time, multimodal transport delivers substantial environmental benefits, a growing priority in global trade. The pulp industry, being resource-intensive, faces increasing pressure to decarbonize logistics and align with sustainability commitments.

By shifting a larger share of transport volume from road to rail and waterways, multimodal logistics significantly reduces fuel consumption and greenhouse gas emissions. Rail, for example, emits approximately 75% less $CO_2$ per ton-kilometer than road freight, while inland waterway transport is one of the most energy-efficient options available. In intercontinental trade, the use of large container vessels reduces emissions per unit of cargo compared to smaller or fragmented shipments.

The cumulative effect of these modal shifts is a measurable reduction in the carbon footprint of pulp supply chains. For instance, Scandinavian pulp producers using rail–sea combinations achieve up to 40% lower emissions compared to road-only distribution. Brazilian exporters integrating rail into their inland logistics have also reported a significant drop in diesel consumption, contributing to both environmental and financial savings.

Multimodal systems also support broader sustainability goals. Reduced reliance on road transport alleviates traffic congestion and decreases local air pollution in port cities. Furthermore, by improving efficiency and reducing wasted fuel, multimodal strategies help companies comply with environmental, social, and governance (ESG) standards increasingly demanded by investors and customers.

These quantitative advantages in cost, time, and carbon emissions are summarized in Table 3, which compares typical single-mode and multimodal transport scenarios in pulp logistics. The table illustrates that multimodal solutions consistently outperform single-mode approaches across all three dimensions, underlining their strategic importance for the industry.

**Table 3.** Quantitative Comparison of Cost, Time, and Carbon Emissions for Single-Mode vs. Multimodal Transport in Pulp Logistics.

| Transport Mode | Average Cost (USD/ton) | Average Transit Time (days) | Carbon Emissions (kg $CO_2$/ton) | Notes |
|---|---|---|---|---|
| Road only (inland 500 km) | 45–55 | 3–4 | 90–110 | Flexible but costly, high emissions |
| Rail only (inland 500 km) | 25–35 | 2–3 | 25–35 | Economical, lower emissions, requires terminals |
| Maritime only (intercontinental, 10,000 km) | 60–70 | 25–30 | 50–60 | Economical for large volumes, but long lead time |
| Road + Maritime (combined) | 55–65 | 22–27 | 70–80 | Balanced approach, faster than maritime only |
| Rail + Maritime (combined) | 40–50 | 20–25 | 35–45 | Cost-efficient, significantly lower emissions |
| Road + Rail + Maritime (integrated multimodal) | 38–48 | 18–22 | 30–40 | Optimal balance of cost, time, and sustainability |

In summary, multimodal transport offers a triple advantage for pulp logistics: it reduces costs by leveraging mode-specific efficiencies, shortens and stabilizes delivery times through coordinated scheduling, and lowers environmental impacts by reducing fuel consumption and emissions. As illustrated in Table 3, these benefits provide pulp producers with a competitive edge in global markets while supporting sustainability objectives.

## 5. Challenges and Risk Management

### *5.1. Operational Risks*

Despite the advantages of multimodal transport in pulp logistics, several operational risks persist. One of the most common issues is delays caused by modal transfer points, such as when pulp shipments are transferred from trucks to rail or from rail to maritime vessels. Each handover requires careful synchronization, and any disruption—whether due to infrastructure bottlenecks, mechanical failures, or labor shortages—can significantly affect the overall delivery schedule.

Another critical challenge involves cargo damages and losses. Pulp, often shipped in large bales or containers, is sensitive to moisture, compression, and handling errors. Inadequate packaging or improper loading during transshipment can lead to product degradation. For instance, exposure to humidity during port storage or delays at customs inspection points may result in quality deterioration. Cargo loss, though less frequent, can occur due to theft, misrouting, or mishandling of containers in congested terminals.

Finally, infrastructure capacity constraints—such as limited rail connections to ports or insufficient storage yards—intensify the operational risks. If multimodal corridors are not adequately equipped to handle increasing pulp volumes, the expected benefits of the system may be undermined by congestion and inefficiency.

### *5.2. Coordination and Information Systems*

Multimodal pulp logistics also relies heavily on effective coordination across different stakeholders, including pulp producers, freight forwarders, carriers, port operators, and customs authorities. Data sharing and communication gaps are a persistent problem.

While road carriers may provide real-time tracking data, such information is often not seamlessly integrated into the systems used by maritime or rail operators. This lack of interoperability leads to blind spots in visibility across the supply chain.

Tracking and monitoring limitations further compound this challenge. Even with the growing adoption of IoT sensors, RFID tags, and advanced logistics platforms, the integration across different modes remains fragmented. For example, while pulp shipments can be traced accurately within a single shipping line's network, visibility often disappears once cargo enters inland transportation systems managed by third parties. This hinders proactive risk management, such as rerouting shipments to avoid weather disruptions or port strikes.

Moreover, coordination failures often manifest during unexpected disruptions. If rail schedules change due to maintenance works or maritime carriers reschedule sailings, without real-time communication across all actors, pulp shipments may experience cascading delays. Thus, robust digital platforms and standardized information systems are essential but not yet universally adopted in the pulp logistics sector.

### *5.3. Policy, Customs, and Legal Issues*

Cross-border pulp trade is heavily affected by customs procedures and regulatory discrepancies. Multimodal shipments that cross multiple jurisdictions must comply with different sets of documentation requirements, tariffs, and inspection protocols. For instance, while some countries accept electronic bills of lading, others still mandate paper-based documentation, slowing down clearance processes.

Additionally, differences in liability frameworks across transport modes create legal complexity. The Convention on the Contract for the International Carriage of Goods by Road (CMR) applies to trucking, while the Hague-Visby Rules govern maritime carriage, and the SMGS convention may regulate rail transport in Eurasia. This patchwork of legal instruments makes it difficult to establish clear accountability when damages or delays occur in multimodal pulp shipments.

Another policy challenge lies in environmental and trade regulations. As countries tighten emission standards and carbon reporting requirements, pulp exporters and carriers must adapt their logistics strategies to comply with sustainability targets. Inconsistent enforcement and varying standards across regions create compliance burdens that increase both costs and risks for companies engaged in multimodal pulp logistics.

## **6. Future Trends and Recommendations**

### *6.1. Emerging Technologies*

The future of multimodal pulp logistics will be significantly shaped by the adoption of emerging technologies that improve visibility, efficiency, and resilience. Among these, artificial intelligence (AI) is expected to play a central role in optimizing scheduling, predicting disruptions, and enhancing decision-making across transport modes. AI-driven algorithms can evaluate real-time data such as port congestion, rail availability, or weather conditions, and automatically recommend the most efficient routing for pulp shipments.

Another critical technology is blockchain, which provides a secure, transparent, and tamper-proof system for recording transactions and logistics events. By enabling trusted digital documentation and automating customs clearance through smart contracts, blockchain could reduce delays and eliminate discrepancies that often arise from paper-based systems.

The use of Internet of Things (IoT) sensors will further enhance shipment visibility. With humidity and temperature monitoring devices installed in containers, pulp quality can be safeguarded during long-haul journeys. These IoT devices, when integrated with cloud-based logistics platforms, will allow pulp producers and carriers to intervene proactively if risks are detected.

Moreover, the rise of digital twin technology and predictive analytics will allow logistics planners to simulate entire supply chain networks virtually. For pulp logistics, this means companies can model alternative multimodal corridors, test "what-if" scenarios for disruptions, and optimize asset utilization without incurring real-world risks. These tools will not only improve operational resilience but also enhance long-term strategic planning for pulp producers operating in global markets.

### *6.2. Sustainability and Green Logistics*

Sustainability is increasingly becoming a driving force in the restructuring of global supply chains, and pulp logistics is no exception. Governments, international organizations, and end-consumers are demanding that supply chains reduce their carbon footprints and embrace more eco-friendly transport options. Multimodal logistics offers inherent advantages in this regard, as it enables the substitution of carbon-intensive road transport with lower-emission rail or maritime modes.

For example, shifting pulp shipments from long-haul trucking to rail or barge transport significantly reduces fuel consumption per ton-kilometer. At the same time, the adoption of alternative fuels, such as biofuels and liquefied natural gas (LNG), in maritime and road transport fleets can further enhance sustainability outcomes. Companies are also exploring the electrification of short-haul road transport, especially for last-mile pulp deliveries from ports to customers.

Beyond environmental considerations, sustainability in pulp logistics is also linked to corporate social responsibility (CSR). Pulp producers and logistics providers are increasingly expected to demonstrate compliance with environmental, social, and governance (ESG) standards. Transparent reporting on emissions, investment in green technologies, and community engagement in port regions are becoming essential elements of competitive advantage. By aligning multimodal strategies with broader CSR commitments, pulp companies can enhance their reputations and meet the growing expectations of environmentally conscious stakeholders.

### *6.3. Strategic Recommendations*

Looking forward, several strategic recommendations emerge for both industry practitioners and policymakers. For pulp companies and logistics providers, the first priority is to invest in digital infrastructure. This includes adopting integrated platforms that unify data across road, rail, and maritime carriers, ensuring end-to-end visibility and seamless coordination. Partnerships with technology firms that specialize in AI, blockchain, or IoT integration will be critical in achieving this transformation.

Second, firms should diversify their transport corridors and establish contingency plans to mitigate risks from geopolitical tensions, port congestion, or regulatory changes. By developing flexible multimodal routes and maintaining strategic partnerships with multiple carriers, pulp exporters can enhance resilience against unforeseen disruptions.

Third, greater attention must be paid to sustainability integration. Pulp companies should prioritize modal combinations that minimize emissions, invest in greener fleets, and actively participate in collaborative initiatives for green logistics corridors. This not only reduces regulatory and reputational risks but also positions companies to benefit from potential carbon credit mechanisms and preferential trade agreements.

From a policy and investment perspective, governments should support the development of multimodal corridors through targeted investments in intermodal terminals, rail-port connectivity, and customs digitalization. Harmonizing legal frameworks across modes—such as liability standards and documentation requirements—will further reduce transaction costs for multimodal shipments. Policymakers can also incentivize green logistics practices by offering subsidies for low-emission transport modes or imposing stricter penalties on carbon-intensive options.

Ultimately, the convergence of digital innovation, sustainability imperatives, and strategic collaboration will define the future of multimodal pulp logistics. Companies that proactively adapt to these trends will not only reduce costs and risks but also secure long-term competitiveness in the increasingly complex global pulp trade.

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