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Big Data Analytics and AI for Optimizing Supply Chain Sustainability and Reducing Greenhouse Gas Emissions in Logistics and Transportation

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Abstract
Big Data Analytics (BDA) and Artificial Intelligence (AI) are transforming supply chain sustainability by enhancing efficiency and minimizing environmental impact. The integration of these technologies in logistics and transportation enables real-time monitoring, predictive modeling, and optimized decision-making, thereby reducing greenhouse gas (GHG) emissions. BDA facilitates data-driven insights by aggregating information from diverse sources such as IoT sensors, GPS tracking, and enterprise resource planning (ERP) systems. These insights support route optimization, demand forecasting, and dynamic inventory management, minimizing fuel consumption and waste. AI-powered solutions, including machine learning algorithms and reinforcement learning models, improve fleet management and predictive maintenance, reducing energy usage and emissions. Moreover, AI-driven automation enhances warehouse operations through smart robotics and efficient resource allocation, leading to lower carbon footprints. Advanced AI applications, such as digital twins and blockchain-based transparency, further improve sustainability by enabling end-to-end visibility and accountability in supply chains. Furthermore, BDA and AI facilitate compliance with environmental regulations and corporate sustainability goals by providing accurate carbon footprint assessments and scenario analysis for emission reduction strategies. Challenges such as data privacy, infrastructure costs, and integration complexities remain, but advancements in cloud computing and AI-driven analytics continue to mitigate these barriers. This explores the role of BDA and AI in optimizing supply chain sustainability and reducing GHG emissions in logistics and transportation. It examines case studies and emerging trends, highlighting the potential for these technologies to drive sustainability in global supply chains. By leveraging AI and big data, businesses can achieve operational efficiency while contributing to global climate change mitigation efforts.

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Keywords: Big data analytics, Supply chain, Greenhouse gas emissions, Logistics and transportation

1. Introduction

Sustainability challenges in logistics and transportation have become a critical concern due to the sector's significant contribution to global greenhouse gas (GHG) emissions (Folorunso *et al*., 2024). The rapid expansion of e-commerce, global supply chains, and increasing consumer demand for fast deliveries have exacerbated the environmental impact of transportation networks (Ishola *et al*., 2024; Afolabi *et al*., 2024). According to the International Energy Agency (IEA), the transport sector accounts for nearly 25% of global CO_2 emissions, with road freight, shipping, and aviation being major contributors. These emissions contribute to climate change, air pollution, and resource depletion, necessitating urgent action to implement sustainable logistics solutions (Ewim *et al*., 2024; Alozie, 2024). Companies and policymakers are increasingly looking toward innovative technologies to mitigate these environmental challenges while maintaining operational efficiency.

Big data analytics and artificial intelligence (AI) play a transformative role in optimizing supply chain operations and reducing carbon footprints (Sam-Bulya *et al*., 2024). The integration of AI-powered predictive analytics, machine learning algorithms, and real-time monitoring systems enables organizations to enhance route optimization, reduce fuel consumption, and improve overall efficiency in logistics. Additionally, AI is instrumental in automating warehouse management, improving fleet efficiency, and facilitating demand forecasting, all of which contribute to minimizing waste and emissions (Joel *et al*., 2024; Odunaiya *et al*., 2024). When combined with big data analytics, AI can process vast amounts of real-time logistics data, providing actionable insights to enhance sustainability initiatives.

Reducing GHG emissions in logistics and transportation is essential for achieving long-term environmental and economic sustainability (Alozie *et al*., 2024). The primary objectives of AI-driven supply chain optimization include lowering fuel consumption, minimizing carbon-intensive activities, and improving the overall environmental performance of transportation networks. This not only aligns with global climate action goals, such as the Paris Agreement, but also enhances corporate sustainability efforts, regulatory compliance, and cost savings. By leveraging AI and big data analytics, companies can transition toward greener supply chain models, adopt alternative energy sources, and implement low-emission transportation strategies (Collins *et al*., 2024; Ewim *et al*., 2024).

The significance of these advancements extends beyond environmental benefits. AI-driven logistics solutions enhance operational resilience, reduce costs, and improve service reliability. Sustainable supply chain practices also contribute to a positive corporate image, attracting environmentally conscious consumers and investors (Ajayi *et al*., 2024). Furthermore, governments worldwide are enforcing stricter emission regulations, making AI-powered solutions a strategic necessity for businesses seeking to maintain compliance and competitive advantage. As the logistics and transportation sector evolves, the integration of AI and big data analytics will continue to drive innovations in sustainable supply chain management. However, challenges such as data availability, infrastructure limitations, and policy constraints must be addressed to maximize the potential of these technologies (Elete *et al*., 2024). Future research should focus on refining AI algorithms, improving data-sharing frameworks, and developing standardized regulations to facilitate the widespread adoption of AI-driven emission reduction strategies. By combining technological advancements with policy support, the logistics industry can achieve significant reductions in GHG emissions, paving the way for a more sustainable and environmentally responsible future (Abiola *et al*., 2024; Oluokun *et al*., 2024).

2. Methodology

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was applied to conduct a systematic review on the role of Big Data Analytics (BDA) and Artificial Intelligence (AI) in optimizing supply chain sustainability and reducing greenhouse gas (GHG) emissions in logistics and transportation. The study followed a structured approach, starting with the identification of relevant literature through comprehensive searches in databases such as Scopus, Web of Science, IEEE Xplore, and Google Scholar. Keywords including “Big Data Analytics,” “Artificial Intelligence,” “Supply Chain Sustainability,” “GHG Emissions,” “Logistics,” and “Transportation” were used to refine search results. Articles published between 2015 and 2024 were considered, focusing on peer-reviewed journals, conference proceedings, and industry reports.

The eligibility criteria included studies that provided empirical evidence, case studies, or theoretical models on the integration of BDA and AI in sustainable supply chain practices. Exclusion criteria were non-English articles, studies lacking clear methodology, and research unrelated to supply chain emissions reduction. The selection process involved title and abstract screening, followed by full-text review, ensuring relevance to the research objectives. Duplicates were removed using citation management software.

Data extraction focused on key themes, including AI-driven optimization techniques, predictive analytics for emissions reduction, and real-time decision-making in logistics. A qualitative synthesis was conducted to identify patterns, challenges, and emerging trends in BDA and AI applications for sustainable supply chain management. Risk of bias was assessed using the Cochrane Risk of Bias Tool and the Critical Appraisal Skills Programme (CASP) checklist to ensure the reliability of included studies.

Findings indicate that AI and BDA significantly contribute to carbon footprint reduction through improved route optimization, fleet management, and demand forecasting. However, challenges such as data privacy, infrastructure costs, and integration complexities persist. This systematic review provides a foundation for future research on technology-driven sustainability in logistics and transportation.

2.1 Understanding sustainability in supply chains

A sustainable supply chain is one that integrates environmental, economic, and social considerations into logistics and operational processes to minimize negative impacts while ensuring long-term efficiency and resilience (Onukwulu *et al*., 2024; Odunaiya *et al*., 2024). Sustainable supply chains aim to balance business profitability with environmental responsibility and social well-being. This approach involves adopting greener logistics practices, optimizing resource consumption, and promoting ethical labor standards. Key components of a sustainable supply chain include eco-friendly sourcing, energy-efficient transportation, waste reduction strategies, and adherence to regulatory sustainability standards (Elete *et al*., 2024; Ewim *et al*., 2024). With increasing regulatory pressures and stakeholder expectations, businesses are now prioritizing sustainability as a fundamental aspect of supply chain management.

The sustainability of supply chains is built on three interrelated dimensions: environmental, economic, and social sustainability (Joel *et al*., 2024). Environmental sustainability focuses on reducing carbon footprints, minimizing resource depletion, and preventing pollution. This includes initiatives such as fuel-efficient transportation, renewable energy integration, circular economy practices, and emissions reduction strategies (Alozie, 2024; Nwulu *et al*., 2024). By implementing environmentally friendly policies, businesses can mitigate their contributions to climate change and align with global sustainability goals. Economic sustainability ensures that companies maintain profitability while integrating sustainable practices. This involves cost-effective logistics strategies, optimization of transportation routes, and waste reduction measures that enhance operational efficiency. Sustainable supply chains not only reduce expenses but also create long-term value by improving resilience against supply disruptions and regulatory changes. Social sustainability emphasizes fair labor practices, community engagement, and ethical sourcing. It includes ensuring worker safety, promoting diversity in the workforce, and fostering equitable supplier relationships (Okolie *et al*., 2024; Alozie, 2024). A socially responsible supply chain strengthens corporate reputation, enhances employee satisfaction, and contributes to positive social change.

Logistics and transportation are among the largest contributors to greenhouse gas (GHG) emissions, significantly impacting climate change. The major sources of GHG emissions in logistics and transportation stem from fossil fuel consumption in freight operations, inefficient supply chain networks, and energy-intensive warehousing (Sam-Bulya *et al*., 2024). Road transportation, including trucks and delivery vehicles, is responsible for a substantial portion of global CO_2 emissions due to reliance on diesel and gasoline-powered engines. The inefficiency of last-mile delivery further exacerbates emissions, as multiple trips are often required to complete deliveries in urban and remote areas. Maritime shipping, while more fuel-efficient per ton-mile compared to road freight, still produces large amounts of CO_2 and sulfur emissions, particularly from container ships operating on heavy fuel oil. Air cargo is another major contributor, as jet fuel combustion releases high levels of CO_2 and nitrogen oxides into the atmosphere, making air freight one of the most carbon-intensive modes of transportation. Rail transport, though more environmentally friendly than road and air freight, still contributes to emissions if powered by diesel locomotives instead of electrified rail systems (Jessa, 2024; Onukwulu *et al*., 2024).

Beyond transportation, warehousing and distribution centers also play a significant role in emissions generation (Jessa and Ajidahun, 2024). Warehouses require large amounts of energy for lighting, heating, cooling, and automated logistics systems. Inefficient warehouse management, excessive inventory storage, and poor facility design contribute to increased carbon footprints (Oluokun *et al*., 2024). Additionally, emissions from packaging waste add to environmental degradation, particularly when non-recyclable materials such as plastic and Styrofoam are used in supply chains (Onukwulu *et al*., 2024).

To address these sustainability challenges, businesses are increasingly adopting green logistics strategies, such as alternative fuel vehicles, electric trucks, and AI-driven route optimization to reduce fuel consumption. The integration of renewable energy sources in supply chain operations, such as solar-powered warehouses and energy-efficient transportation networks, further supports emission reduction efforts. Governments and industry leaders are also working toward regulatory frameworks that encourage carbon-neutral logistics through carbon pricing, emission caps, and incentives for adopting clean energy solutions (Nwulu *et al*., 2022; Lawal, 2024). Sustainability in supply chains is not just an environmental responsibility; it is a strategic business advantage. Companies that proactively invest in sustainable supply chain innovations can achieve cost savings, enhance brand reputation, and meet regulatory requirements while contributing to global sustainability goals. As technology continues to evolve, the integration of artificial intelligence, big data analytics, and the Internet of Things (IoT) will further optimize logistics operations, enabling real-time monitoring and reduction of emissions. The future of sustainable supply chains lies in the collaboration between governments, industries, and technology providers to implement scalable, data-driven solutions for greener and more efficient logistics networks (Onukwulu *et al*., 2024; Akinsooto *et al*., 2024).

2.2 Big data analytics in sustainable supply chain management

The rapid advancement of big data analytics has revolutionized supply chain management (SCM), providing companies with unprecedented capabilities to optimize processes, enhance decision-making, and reduce environmental impacts. Sustainable supply chain management (SSCM) focuses on balancing economic performance with ecological and social responsibility (Oyedokun *et al*., 2024). Big data analytics plays a crucial role in enabling organizations to achieve these sustainability goals by leveraging insights from vast datasets collected through IoT sensors, GPS tracking, telematics, and enterprise systems as shown in figure 1. This explores the role of big data in decision-making, its data sources, real-time monitoring for energy efficiency, and case studies demonstrating its impact on green logistics.

Big data analytics enables organizations to enhance decision-making by providing real-time insights into supply chain operations. The vast amount of data generated from various sources can be processed using artificial intelligence (AI) and machine learning (ML) algorithms to optimize logistics, reduce waste, and improve efficiency (Oyedokun *et al*., 2024). Big data allows companies to monitor and track goods at every stage of the supply chain. By analyzing this information, businesses can optimize transportation routes, minimize idle time, and reduce carbon emissions. Predictive analytics models use historical data, weather conditions, and market trends to forecast demand fluctuations, allowing companies to adjust production schedules and reduce inventory waste. Data-driven insights help organizations identify energy-intensive processes and implement efficiency measures, such as route optimization in logistics and predictive maintenance of fleet vehicles (Oluokun *et al*., 2024; Akinsooto *et al*., 2024). Governments and international bodies are increasingly mandating environmental compliance. Big data enables businesses to generate automated sustainability reports, ensuring adherence to green regulations and carbon footprint reduction initiatives.

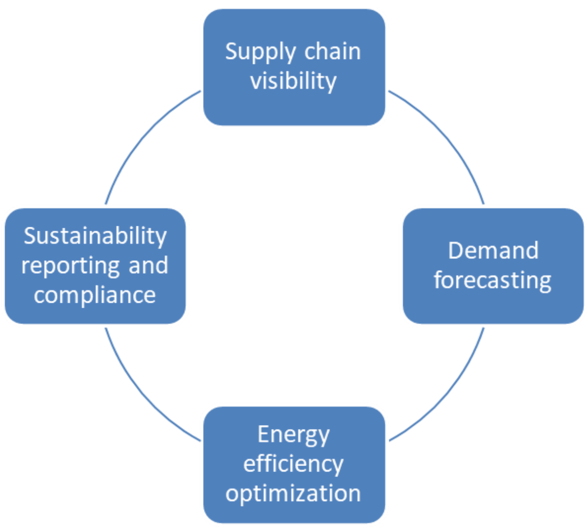

Fig 1: The role of big data in decision-making and process optimization

Through these applications, big data analytics enhances sustainability efforts while maintaining supply chain resilience and profitability. The effectiveness of big data analytics in sustainable supply chain management depends on data collected from various sources; Smart sensors installed in warehouses, trucks, and production facilities collect real-time data on temperature, humidity, fuel consumption, and emissions (Nwulu *et al*., 2024). This data helps companies optimize operations and minimize environmental impact. GPS-enabled devices provide real-time location tracking of shipments, allowing businesses to choose the most fuel-efficient routes, reduce delays, and enhance overall logistics efficiency. Telematics combines telecommunications and informatics to monitor vehicle performance. Fleet managers use telematics data to analyze driver behavior, optimize fuel consumption, and reduce emissions. Enterprise resource planning (ERP) systems platforms integrate supply chain data across various departments, enabling seamless coordination of procurement, production, and distribution processes to minimize waste and energy usage. By leveraging these diverse data sources, companies can create a comprehensive, data-driven approach to sustainable supply chain management (Arinze *et al*., 2024).

One of the most significant contributions of big data analytics to sustainable supply chain management is its ability to facilitate real-time monitoring and predictive analytics for energy efficiency (Oyedokun *et al*., 2024). By analyzing live data streams, organizations can detect inefficiencies and take corrective actions immediately. AI-driven analytics platforms analyze fuel consumption, vehicle maintenance status, and driver behavior to enhance efficiency. For example, detecting excessive idling time or inefficient fuel usage helps companies implement corrective measures, reducing carbon emissions. Using AI-powered big data analytics, logistics companies can adjust delivery routes in real time based on traffic patterns, weather conditions, and fuel efficiency considerations. This minimizes unnecessary fuel consumption and reduces environmental impact. Machine learning models analyze historical data from equipment and vehicles to predict maintenance needs before failures occur. This proactive approach reduces downtime, prevents excess energy consumption, and extends the lifespan of assets. Smart warehouse management systems use real-time data to optimize lighting, heating, and cooling systems, significantly reducing energy consumption and operational costs (Oyedokun *et al*., 2024; Ayanponle *et al*., 2024). By leveraging these capabilities, big data analytics enables supply chains to become more energy-efficient, cost-effective, and environmentally friendly.

Several organizations have successfully implemented big data analytics to enhance sustainability in supply chain logistics; United Parcel Service (UPS) developed the On-Road Integrated Optimization and Navigation (ORION) system, which uses big data analytics and AI to optimize delivery routes. By minimizing left turns and reducing unnecessary mileage, UPS has saved millions of gallons of fuel annually, significantly reducing its carbon footprint (Oluokun *et al*., 2024). DHL integrates IoT, AI, and big data to enhance eco-friendly logistics. The company uses real-time tracking, predictive analytics, and electric vehicle (EV) fleet optimization to reduce emissions and promote sustainability in last-mile delivery. Maersk, a global leader in shipping, employs big data analytics to optimize fuel consumption and improve route efficiency. The company uses AI-powered weather forecasting to adjust shipping routes, reducing fuel consumption and carbon emissions. Amazon applies big data analytics to enhance warehouse energy efficiency, optimize packaging, and implement AI-powered robotics to reduce waste (Ayanponle *et al*., 2024). The company's "Shipment Zero" initiative aims to achieve net-zero carbon emissions in its delivery network by 2040. These case studies demonstrate how leading logistics companies are harnessing big data analytics to drive sustainability in supply chain operations.

Big data analytics plays a crucial role in promoting sustainability in supply chain management by optimizing processes, improving decision-making, and reducing greenhouse gas emissions (Ajayi *et al*., 2024). By utilizing data sources such as IoT sensors, GPS tracking, telematics, and ERP systems, organizations can enhance real-time monitoring and predictive analytics for energy efficiency. Case studies from global logistics companies illustrate the transformative impact of big data on green logistics, highlighting its potential to drive long-term environmental and economic benefits. As supply chains continue to evolve, integrating big data analytics will be essential in achieving a sustainable and resilient global logistics ecosystem (Agbede *et al*., 2024).

2.3 AI-Driven optimization strategies for reducing emissions

As industries strive to reduce their environmental footprint, artificial intelligence (AI) has emerged as a transformative tool for optimizing logistics operations and minimizing greenhouse gas (GHG) emissions as shown in table 1. AI-driven strategies enhance efficiency by optimizing demand forecasting, inventory management, transportation routes, fuel consumption, and vehicle maintenance. By leveraging advanced machine learning models, reinforcement learning techniques, and real-time data analytics, AI is revolutionizing how supply chains operate, enabling more sustainable and cost-effective logistics systems (Akinsooto *et al*., 2024; Adeleye, 2024).

Table 1: Key AI-driven strategies for optimizing supply chain sustainability and reducing greenhouse gas emissions

Optimization Strategy	Description	Impact on Emission Reduction	AI Techniques Used
AI-Powered Route Optimization	Uses real-time traffic data, weather conditions, and road constraints to find the most fuel-efficient routes.	Reduces fuel consumption and carbon footprint.	Machine learning, reinforcement learning, predictive analytics.
Smart Fleet Management	Monitors vehicle performance and driver behavior to enhance fuel efficiency and reduce unnecessary idling.	Lowers emissions by optimizing fuel usage and maintenance schedules.	IoT, telematics, AI-based predictive maintenance.
Predictive Demand Forecasting	Analyzes historical and real-time data to optimize inventory management and reduce unnecessary shipments.	Minimizes excess transportation and associated emissions.	Deep learning, time-series forecasting, neural networks.
AI-Driven Load Optimization	Maximizes cargo space utilization by intelligently consolidating shipments to reduce the number of trips.	Lowers fuel consumption and transportation emissions.	Optimization algorithms, reinforcement learning.

Energy-Efficient Warehouse Operations	Uses AI for smart lighting, HVAC control, and robotic automation to reduce energy consumption in warehouses.	Lowers indirect emissions from logistics hubs.	Computer vision, IoT-based automation, AI-driven energy management.
Electrification and Alternative Fuels Management	AI identifies optimal scenarios for fleet electrification and the use of biofuels or hydrogen-based transportation.	Reduces dependency on fossil fuels, leading to lower emissions.	AI-based lifecycle analysis, simulation models.
Real-Time Carbon Tracking and Reporting	Uses AI and big data to measure and report carbon emissions in supply chain operations.	Enables compliance with sustainability targets and regulatory standards.	Blockchain, AI-powered analytics, NLP for regulatory reporting.
AI-Based Supplier Sustainability Assessment	Evaluates suppliers based on environmental impact, helping companies select low-emission partners.	Promotes a greener supply chain and reduces indirect emissions.	Natural Language Processing (NLP), sentiment analysis, machine learning.
Autonomous and AI-Assisted Vehicles	Self-driving and AI-assisted trucks optimize speed, braking, and fuel consumption.	Improves fuel efficiency and reduces human error in driving.	Computer vision, reinforcement learning, deep learning.

One of the most effective ways to reduce emissions in supply chains is through AI-powered demand forecasting and inventory optimization (Ajiga *et al*., 2024). Traditional inventory management often leads to overstocking or understocking, resulting in increased transportation needs and unnecessary emissions. AI algorithms, particularly machine learning models, analyze vast amounts of historical data, market trends, and external factors such as weather conditions and consumer behavior to predict demand with high accuracy. By optimizing inventory levels, companies can reduce the frequency of shipments and minimize the need for last-minute, high-emission transportation methods such as air freight. (Onukwulu *et al*., 2024; Ajiga *et al*., 2024) Additionally, AI-driven supply chain visibility helps companies make informed decisions about warehousing locations, reducing the distance between suppliers and consumers. This not only lowers transportation emissions but also improves overall efficiency by reducing storage costs and waste. AI-based forecasting tools such as deep learning models can continuously adapt to market fluctuations, allowing businesses to dynamically adjust their logistics strategies for maximum sustainability (Onukwulu *et al*., 2024; Kokogho *et al*., 2024).

Transportation emissions are a significant contributor to climate change, with road freight and shipping being among the largest sources of CO_2 emissions. Machine learning (ML) for route optimization and fuel efficiency plays a crucial role in reducing emissions by identifying the most efficient routes and minimizing fuel consumption (Elete *et al*., 2024; Afolabi *et al*., 2024). AI-powered routing algorithms analyze real-time traffic data, weather conditions, road infrastructure, and fuel efficiency metrics to determine optimal transportation paths. AI-driven route optimization not only reduces delivery times but also minimizes idling and fuel wastage (Sam-Bulya *et al*., 2024). Companies like UPS and Amazon have already implemented AI-powered logistics platforms that use ML algorithms to optimize delivery routes, significantly lowering their carbon footprints. Furthermore, AI enhances eco-driving techniques, where real-time driving behavior is analyzed to reduce fuel consumption. AI systems can provide real-time feedback to drivers, suggesting more fuel-efficient acceleration, braking, and speed control techniques (Akhigbe *et al*., 2024). These AI-driven fuel efficiency strategies contribute to lowering emissions while improving overall transportation cost-effectiveness.

Vehicle emissions in logistics and transportation are often exacerbated by poorly maintained fleets (Ajayi, 2024). AI-based predictive maintenance leverages machine learning algorithms and IoT sensors to monitor vehicle health in real time, allowing companies to address mechanical issues before they lead to excessive emissions or breakdowns. Predictive maintenance relies on AI-driven diagnostic tools that analyze vast amounts of sensor data, including engine performance, fuel efficiency, and exhaust emissions (Egbuhuzor, 2024; Alozie *et al*., 2024). Machine learning models detect anomalies that indicate potential malfunctions, enabling companies to proactively service vehicles before they become major polluters. This not only extends vehicle lifespan but also prevents inefficient fuel consumption caused by worn-out components. Predictive maintenance also reduces downtime and repair costs, enhancing overall supply chain resilience while promoting environmental sustainability. Companies that adopt AI-driven predictive maintenance strategies report lower operational costs and a significant reduction in their carbon footprints.

Reinforcement learning (RL), a branch of AI where algorithms learn through trial and error, is increasingly being used to optimize transportation networks for sustainability. RL models can simulate and analyze thousands of logistics scenarios, continuously improving their decision-making processes to achieve the lowest emissions possible (Ewim *et al*., 2024; Afolabi *et al*., 2024). These models can be applied to multi-modal transportation systems, integrating road, rail, air, and sea freight to create the most efficient and sustainable logistics strategies. By learning from real-time data, RL systems adapt to changing conditions, ensuring that transportation networks remain optimized even in unpredictable circumstances. Additionally, RL is instrumental in autonomous and electric vehicle fleet management. AI-driven decision-making optimizes the deployment of electric trucks, ensuring they follow routes with adequate charging infrastructure while minimizing battery degradation. RL-based systems can also manage smart traffic control, reducing congestion and emissions in urban areas by dynamically adjusting traffic light sequences based on real-time vehicle flow data. AI-driven optimization strategies are revolutionizing the logistics and transportation industry by reducing emissions and improving sustainability. Through AI-powered demand forecasting, businesses can reduce unnecessary transportation, while machine learning for route optimization ensures fuel efficiency and reduced CO_2 output. Predictive maintenance powered by AI helps fleets operate more sustainably, preventing mechanical inefficiencies that lead to excessive emissions (Collins *et al*., 2024). Finally, reinforcement learning techniques enable dynamic and adaptive transportation network optimization, leading to more sustainable urban and industrial logistics. As industries continue to adopt AI-powered solutions, the potential for achieving carbon-neutral supply chains becomes more attainable. However, widespread implementation requires investment in AI infrastructure, regulatory support, and collaborative industry efforts to maximize the impact of these technologies. By leveraging AI-driven optimization strategies, companies can significantly reduce their environmental footprint while enhancing operational efficiency and cost savings (Folorunso *et al*., 2024).

2.4 Integrating AI and big data for green logistics

The integration of artificial intelligence (AI) and big data analytics has revolutionized logistics, enabling smarter, more sustainable operations (Bello *et al*., 2024). Green logistics focuses on reducing environmental impact by optimizing transportation, warehousing, and supply chain processes while maintaining efficiency and cost-effectiveness. AI-driven solutions, in combination with big data analytics, facilitate smart fleet management, AI-driven simulations for emission reduction, supply chain transparency, and carbon footprint tracking. Additionally, blockchain technology further enhances sustainability by ensuring transparency, traceability, and efficiency in supply chain operations (Adaramola *et al*., 2024). This explores the role of AI and big data in transforming logistics into a greener, more sustainable industry. Fleet management plays a critical role in logistics, and AI-powered big data analytics has significantly improved its efficiency and sustainability as shown in figure 2. AI enables real-time analysis of vast amounts of fleet data, allowing companies to optimize operations, reduce fuel consumption, and lower carbon emissions.

Route optimization, AI-driven predictive models analyze traffic conditions, weather patterns, and fuel consumption data to determine the most efficient delivery routes. Machine learning (ML) algorithms continuously update routes to minimize fuel usage and reduce delays. Fuel efficiency monitoring, telematics systems, combined with AI, provide real-time fuel consumption insights (Ajayi *et al*., 2024). By analyzing driver behavior, engine performance, and road conditions, AI can suggest energy-efficient driving practices, such as reduced idling and optimized acceleration patterns. Predictive maintenance, AI-powered analytics detect patterns in vehicle performance data to predict potential breakdowns before they occur. This proactive approach minimizes downtime, extends vehicle lifespan, and reduces the environmental impact of frequent repairs. Autonomous and electric vehicles, AI enables the integration of autonomous driving technologies and electric vehicle (EV) fleet management. AI-powered EV charging station mapping optimizes charging schedules, reducing dependency on fossil fuels and enhancing overall sustainability. Through smart fleet management, AI and big data analytics enable logistics companies to enhance efficiency while significantly reducing their carbon footprint.

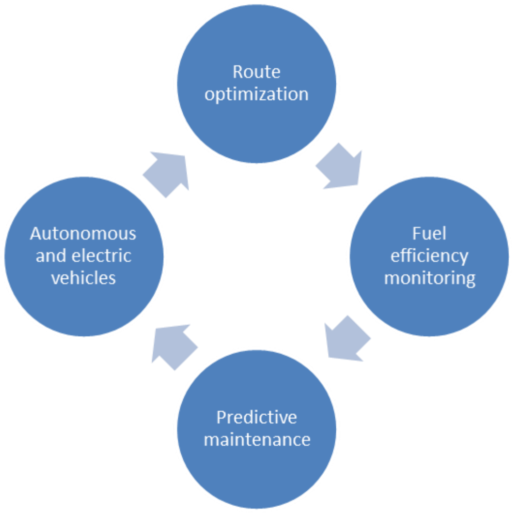

Fig 2: Smart fleet management critical roles green Logistics

Digital twins virtual models of physical assets, processes, or systems are increasingly used in logistics to optimize operations and reduce emissions (Ariyibi *et al*., 2024). AI-driven digital twins simulate real-world logistics environments, allowing companies to test various sustainability strategies before implementation. Digital twins replicate transportation networks, allowing logistics managers to experiment with different scenarios, such as adjusting delivery schedules, rerouting shipments, or switching to alternative fuels, to determine the most sustainable option. AI-driven simulations analyze energy consumption patterns in warehouses and distribution centers, optimizing HVAC systems, lighting, and automated material handling to minimize energy usage. Companies can test the impact of eco-friendly packaging, alternative transportation modes (such as rail or waterways), and consolidation strategies to determine the best approach to reducing emissions. AI-powered digital twins assess risks associated with supply chain disruptions, allowing businesses to proactively plan and implement sustainability-driven contingency measures (Adigun *et al*., 2024). By utilizing AI-driven digital twins, logistics companies can develop more environmentally friendly operations while maintaining efficiency and cost-effectiveness.

Transparency is essential in sustainable logistics, as companies must monitor and report their environmental impact (Adewuyi *et al*., 2024). AI-driven big data analytics enhances supply chain transparency by providing real-time tracking and carbon footprint analysis. AI integrates satellite imagery, IoT sensors, and geospatial data to monitor emissions from transportation and warehouse operations. This enables companies to track their environmental footprint accurately (Onukwulu *et al*., 2021). AI analyzes supply chain data to calculate the carbon footprint of products from raw material extraction to delivery. This helps businesses identify high-emission processes and implement mitigation strategies. Governments and international organizations impose strict environmental regulations on logistics companies (Adebisi *et al*., 2022). AI automates sustainability reporting, ensuring compliance with regulatory frameworks such as the EU Green Deal and the Paris Agreement. AI evaluates supplier sustainability practices by analyzing data on emissions, waste management, and ethical sourcing. Companies can prioritize partnerships with eco-friendly suppliers to enhance their overall environmental performance. AI-driven supply chain transparency tools empower businesses to make data-driven sustainability decisions, improving their corporate social responsibility (CSR) strategies and regulatory compliance (Fredson *et al*., 2022; Nwulu *et al*., 2022).

Blockchain technology, when integrated with AI, provides unparalleled transparency, security, and efficiency in green logistics. The decentralized nature of blockchain ensures that supply chain transactions and sustainability data are secure, verifiable, and tamper-proof. Blockchain records every stage of a product's journey, from raw material sourcing to final delivery (Onukwulu *et al*., 2023). Combined with AI, this ensures accurate carbon tracking and helps organizations implement targeted emission reduction strategies. AI-powered smart contracts on blockchain platforms enable automated and verifiable sustainability commitments. AI and blockchain provide end-to-end visibility into supply chains, enabling consumers and businesses to verify eco-friendly practices, such as sustainable sourcing and low-carbon transportation. Many companies falsely claim sustainability achievements (greenwashing). Blockchain, combined with AI analytics, prevents data manipulation, ensuring that sustainability claims are verifiable and credible. By integrating blockchain with AI, logistics companies can create more transparent, accountable, and sustainable supply chains. AI and big data analytics are transforming green logistics by enabling smart fleet management, AI-driven digital twins, enhanced supply chain transparency, and blockchain-based sustainability solutions (Olisakwe *et al*., 2023). These technologies optimize fuel consumption, improve route planning, and ensure compliance with environmental regulations. Digital twins and AI-driven simulations allow logistics companies to test and implement emission reduction strategies, while blockchain technology enhances supply chain traceability and accountability. As businesses and governments continue to prioritize sustainability, the integration of AI and big data in green logistics will be instrumental in reducing carbon emissions and achieving long-term environmental goals (Adebisi *et al*., 2021; Basiru *et al*., 2022).

2.5 Challenges and barriers to implementation

The integration of artificial intelligence (AI) into supply chain sustainability and emissions reduction presents immense potential, but its implementation is fraught with significant challenges and barriers (Brown *et al*., 2015; Fredson *et al*., 2021). These obstacles span across technological, financial, regulatory, and ethical domains, making it difficult for industries to fully leverage AI-driven solutions. Key challenges include data privacy and security concerns, interoperability issues, high implementation costs, regulatory constraints, and ethical considerations in AI-driven decision-making as shown in table 2. Addressing these barriers is crucial for enabling the widespread adoption of AI for optimizing sustainability in logistics and industrial operations.

Table 2: Key challenges affecting the implementation of AI-driven sustainability solutions

Challenge	Description	Impact on AI-Driven Sustainability Solutions	Possible Mitigation Strategies
High Implementation Costs	Significant investment required for AI infrastructure, data storage, and skilled personnel.	Limits adoption by small and mid-sized enterprises (SMEs).	Government incentives, cloud-based AI solutions, and cost-sharing models.
Data Privacy and Security Concerns	Handling vast amounts of sensitive supply chain data raises risks of cyber threats and data breaches.	Reduces trust in AI-driven systems and limits data-sharing among stakeholders.	Implementing robust cybersecurity protocols and blockchain for secure data exchange.
Integration with Legacy Systems	Many logistics companies use outdated IT systems that are not compatible with AI-driven solutions.	Causes inefficiencies and delays in AI adoption.	Phased integration strategies, API-based solutions, and hybrid cloud infrastructure.
Data Quality and Availability	Inconsistent, incomplete, or biased data from various sources (IoT devices, suppliers, weather forecasts, etc.).	Leads to inaccurate AI predictions and suboptimal decision-making.	Standardized data governance policies, AI-driven data cleaning techniques.
Ethical Concerns in AI Decision-Making	AI-based supply chain optimization may lead to unintended social and environmental consequences.	Potential for biased decision-making that affects sustainability goals.	Development of Explainable AI (XAI), ethical AI frameworks, and stakeholder involvement in AI model training.
Regulatory and Compliance Challenges	Evolving environmental regulations and carbon emission reporting standards vary by region.	Creates uncertainty in AI-driven decision-making and delays implementation.	AI-driven compliance tracking, collaboration with regulators.
Scalability Issues	AI models require extensive computational power and real-time processing for large-scale supply chains.	Limits real-time optimization and predictive analytics capabilities.	Edge computing, distributed AI models, and cloud-based solutions.

AI-driven sustainability solutions rely heavily on large-scale data collection from satellites, IoT sensors, logistics systems, and enterprise databases (Adebisi *et al*., 2022). However, the vast amount of data required for AI-driven decision-making raises significant concerns regarding privacy, security, and interoperability. Data privacy regulations, such as the General Data Protection Regulation (GDPR) in Europe and the California Consumer Privacy Act (CCPA), impose strict guidelines on how data can be collected, stored, and processed. These regulations can restrict companies from sharing critical supply chain data needed to improve AI models, thereby limiting the effectiveness of AI-powered sustainability initiatives (Fredson *et al*., 2023; Onukwulu *et al*., 2023).

Additionally, cybersecurity threats pose a major risk to AI-driven platforms. Hackers and cybercriminals can exploit vulnerabilities in data transmission and storage, leading to breaches that compromise sensitive corporate and environmental data. AI models that rely on cloud computing for real-time decision-making are particularly vulnerable to cyberattacks, ransomware, and unauthorized data access. Strengthening cybersecurity protocols, data encryption, and secure cloud architectures is essential to ensuring the integrity of AI-driven sustainability initiatives (Adewoyin, 2021).

Interoperability is another critical issue, as many supply chain and logistics companies use legacy systems and proprietary software that are not compatible with modern AI platforms (Onukwulu *et al*., 2023). The lack of standardized data formats and integration frameworks makes it challenging to seamlessly connect AI solutions across different stakeholders, industries, and geographic regions. Establishing universal data-sharing standards and promoting open-source AI platforms can help mitigate these challenges.

One of the most significant barriers to implementing AI-driven sustainability solutions is the high cost of technology deployment and adoption. AI models require advanced computational power, cloud infrastructure, and continuous model training, which demand significant financial investments. Small and medium-sized enterprises (SMEs) may lack the capital to invest in high-performance computing (HPC) systems, AI development teams, and data infrastructure necessary for optimizing supply chain sustainability. Beyond financial costs, technological adoption barriers hinder AI implementation. Many organizations lack the technical expertise needed to develop, train, and deploy AI models effectively. The complexity of AI-driven logistics optimization requires data scientists, AI engineers, and domain experts who understand both machine learning and supply chain dynamics Onukwulu *et al*., 2021; (Basiru *et al*., 2023). However, there is a global shortage of skilled AI professionals, making it difficult for companies to build and maintain AI-driven sustainability initiatives. Another challenge is resistance to change within organizations. Many logistics and industrial companies have established traditional operational workflows, and transitioning to AI-driven systems requires organizational restructuring, retraining employees, and overcoming skepticism toward automation. Ensuring smooth workforce transitions through training programs and demonstrating the economic and environmental benefits of AI adoption can help mitigate these barriers (Onukwulu *et al*., 2021).

The deployment of AI-driven sustainability solutions is further complicated by regulatory inconsistencies across different regions. Environmental policies, carbon taxation, and emissions reduction targets vary widely between countries, creating uncertainty for multinational corporations seeking to implement standardized AI-driven sustainability initiatives. In contrast, some developing economies may prioritize economic growth over sustainability initiatives, leading to lower incentives for AI-based emissions reduction strategies. Furthermore, AI-powered monitoring systems that track carbon emissions, supply chain inefficiencies, and environmental impact may face resistance from industries with strong lobbying influence. Oil and gas companies, heavy industries, and certain logistics providers may oppose AI-driven regulations that mandate emissions transparency and real-time monitoring, fearing increased operational costs and regulatory scrutiny (Akinsooto, 2013). Addressing these challenges requires harmonized international regulations, government incentives, and collaborative policymaking that encourage AI-driven sustainability without imposing excessive compliance burdens on businesses. Public-private partnerships can also facilitate AI innovation in sustainable supply chains by providing funding, subsidies, and infrastructure support.

AI-driven decision-making in sustainability initiatives raises important ethical concerns related to fairness, accountability, and transparency. AI models are trained on historical data, which may contain biases that lead to inequitable decision-making. Additionally, lack of explainability in AI models often referred to as the black-box problem makes it difficult for policymakers and business leaders to trust AI-driven recommendations. When AI-powered emissions monitoring systems detect violations or inefficiencies, companies and regulators must be able to interpret the reasoning behind AI decisions to ensure accountability and compliance (Farooq *et al*., 2023). There are also ethical concerns related to job displacement. AI-driven automation in logistics and supply chain management has the potential to replace traditional roles in warehouse operations, fleet management, and manual emissions reporting. While AI can create new job opportunities in AI development and sustainability analytics, ensuring a just transition for affected workers is essential to maintaining ethical AI adoption. To address these ethical concerns, companies must adopt responsible AI governance frameworks that prioritize fairness, transparency, and stakeholder engagement. AI models should be audited for biases, and explainable AI (XAI) techniques should be employed to improve decision transparency. Furthermore, governments and industries must collaborate on ethical AI policies that balance technological innovation with social responsibility (OPIA *et al*., 2022). While AI-driven sustainability solutions have the potential to revolutionize emissions reduction and supply chain optimization, several key challenges hinder their full implementation (Oteri *et al*., 2023). Data privacy, security, and interoperability issues present technical barriers, while high implementation costs and skill shortages make adoption difficult, particularly for smaller enterprises. Additionally, regulatory inconsistencies and lobbying pressures create legal uncertainty, and ethical considerations regarding bias, transparency, and job displacement must be carefully addressed. Overcoming these barriers requires a multi-stakeholder approach involving governments, businesses, and researchers to create standardized regulatory frameworks, increased funding for AI adoption, and ethical AI governance structures. By addressing these challenges proactively, AI can be leveraged as a powerful tool for achieving sustainable logistics, reducing emissions, and fostering environmentally responsible industrial development (Onukwulu *et al*., 2021; Agho *et al*., 2021).

2.6 Future trends and opportunities

The integration of artificial intelligence (AI) and big data analytics is rapidly transforming supply chain management, particularly in the pursuit of sustainability and carbon emission reduction (Onukwulu *et al*., 2022). As the logistics and transportation industry continues to embrace digital transformation, new advancements in AI, the emergence of quantum computing, and global policy initiatives are shaping the future of green supply chains. These innovations provide opportunities for businesses to optimize sustainability, improve efficiency, and move closer to achieving net-zero emissions as shown in figure 3. AI is evolving rapidly, with new algorithms being developed to enhance decision-making in sustainable supply chain management. Machine learning (ML) and deep learning techniques are improving the ability to analyze and predict carbon emissions, optimize logistics operations, and enhance energy efficiency (Onukwulu *et al*., 2021).

Advanced AI models can forecast demand fluctuations, optimize transportation routes, and reduce unnecessary energy consumption (Nwulu *et al*., 2022). These predictive analytics tools allow businesses to preemptively adjust operations, minimizing environmental impact. AI-powered reinforcement learning is enhancing dynamic route planning by continuously learning from real-time traffic data, fuel efficiency metrics, and weather conditions. This reduces fuel usage and emissions while ensuring timely deliveries. AI-Enabled Smart Warehouses Automated warehouses use AI-driven robotics, IoT-enabled sensors, and energy-efficient systems to optimize inventory management, reduce waste, and lower energy consumption. Advanced AI models are integrating sustainability parameters such as carbon footprint, energy consumption, and environmental impact alongside traditional cost and efficiency metrics to create holistic decision-making frameworks for logistics firms (Akhigbe *et al*., 2022). As AI continues to evolve, its application in sustainability-focused supply chains will become more precise, efficient, and effective (Akhigbe *et al*., 2021). Quantum computing is poised to revolutionize big data analytics in supply chain management by solving complex optimization problems at unprecedented speeds. The ability of quantum computers to process massive datasets in parallel will significantly enhance decision-making in logistics, particularly in sustainability efforts. Quantum algorithms can solve intricate supply chain optimization problems, such as minimizing transportation emissions while balancing delivery speed and costs. Quantum computing enables more accurate predictions of energy demand and supply fluctuations, optimizing the integration of renewable energy sources into supply chain operations (Ajayi *et al*., 2022). Quantum-enhanced AI models can simulate the long-term effects of different supply chain strategies on global emissions, helping businesses implement sustainable practices with greater certainty. Quantum computing can significantly reduce the time required to train AI models for sustainability analytics, enabling faster adoption of intelligent logistics solutions. Although quantum computing is still in its early stages, its future integration with AI and big data analytics will unlock powerful new capabilities for sustainable supply chain management.

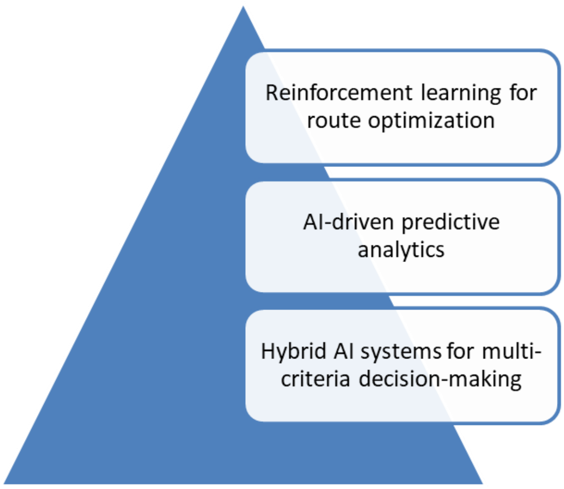

Fig 3: Future trends and opportunities

Governments, industry bodies, and international organizations are intensifying their efforts to establish policies and initiatives that promote sustainable supply chains. AI and big data analytics play a crucial role in helping businesses comply with these regulations and meet carbon reduction targets.

Several countries are implementing carbon pricing systems that require companies to account for and reduce their emissions. AI-powered tracking systems help businesses monitor and optimize their carbon footprints to comply with these regulations. Initiatives such as the Global Logistics Emissions Council (GLEC) Framework and SmartWay Transport Partnership encourage companies to adopt fuel-efficient technologies and sustainable logistics practices. AI-driven route optimization and fleet management solutions are key enablers of these programs (Onukwulu *et al*., 2022). The European Union’s Green Deal mandates stricter carbon reduction targets for logistics companies. AI-based sustainability analytics platforms assist businesses in aligning with these regulations and avoiding penalties. Major corporations are setting ambitious net-zero goals, such as Amazon’s Climate Pledge and Walmart’s Project Gigaton. AI and big data analytics facilitate the tracking, reporting, and optimization of emissions to achieve these objectives.

These policies and initiatives provide a strong foundation for integrating AI-driven sustainability measures into global supply chain operations (Oluokun, 2021) the ultimate goal of sustainable supply chain management is to achieve net-zero emissions, where carbon output is minimized and any remaining emissions are offset. AI and big data analytics are fundamental to this transition. Advanced analytics platforms leverage AI and IoT sensors to measure emissions at every stage of the supply chain, from raw material extraction to final product delivery. AI optimizes the deployment of electric and hydrogen-powered vehicles, charging infrastructure, and fuel-efficient logistics networks to transition away from fossil fuel dependency. AI-integrated blockchain solutions facilitate transparent carbon credit trading and offset mechanisms, ensuring that businesses can achieve verifiable net-zero emissions. AI-based auditing tools assess the environmental impact of suppliers, manufacturers, and distributors, allowing companies to prioritize partnerships with low-emission businesses (Onukwulu *et al*., 2023). By harnessing AI and big data analytics, supply chain managers can systematically work toward net-zero logistics while maintaining operational efficiency and profitability. The future of sustainable supply chain management is closely tied to advancements in AI, big data analytics, and emerging technologies such as quantum computing. AI-driven sustainability optimization, real-time carbon tracking, and smart logistics solutions are driving greener operations. Quantum computing promises to unlock even greater efficiencies in big data processing, accelerating sustainability efforts. Additionally, evolving global policies and industry-wide initiatives are shaping a regulatory framework that supports carbon-neutral logistics (Onukwulu *et al*., 2021). As businesses increasingly prioritize environmental responsibility, AI and big data analytics will be indispensable in achieving net-zero supply chains, paving the way for a more sustainable global economy (Sobowale *et al*., 2021; Elete *et al*., 2023).

3. Conclusion

AI and big data analytics have emerged as transformative tools for advancing sustainability in logistics and supply chain management. By leveraging AI-powered demand forecasting, route optimization, and predictive maintenance, businesses can significantly reduce greenhouse gas (GHG) emissions and enhance operational efficiency. Additionally, machine learning models, deep learning techniques, and IoT-driven real-time monitoring contribute to more accurate emissions tracking and optimization. These innovations not only improve environmental sustainability but also lead to economic benefits, such as cost savings and improved resource allocation. However, despite these advancements, significant challenges—such as data privacy, regulatory constraints, high implementation costs, and ethical concerns—still hinder widespread adoption.

Addressing these barriers requires collaborative efforts among industry stakeholders, including governments, corporations, technology providers, and research institutions. Policymakers must work alongside AI developers to establish standardized regulations, secure data-sharing frameworks, and incentive structures that promote sustainable AI adoption. Additionally, industries must foster public-private partnerships to bridge the gap between technological innovation and real-world implementation. Cross-sector collaboration is essential to ensure that AI-driven green logistics solutions are scalable, transparent, and socially responsible.

To further advance AI-driven sustainability in logistics, continued research and policy development are necessary. Future studies should focus on improving AI model interpretability, enhancing multimodal data integration, and addressing the socio-economic impact of AI automation in supply chains. Governments should also prioritize funding AI-driven sustainability projects and develop global emissions monitoring frameworks to align with climate action goals. By investing in AI-powered solutions and robust policy frameworks, businesses and societies can move towards a more sustainable, efficient, and environmentally responsible future in logistics and supply chain management.

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