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Circular Supply Chains in the AI Era with Renewable Energy Integration and Smart Transport Networks

Simbiat Atinuke Lawal, Samuel Omefe, Adeseun Kafayat Balogun, Comfort Michael, Sakiru Folarin Bello, Itunu Taiwo, Kevin Nnaemeka Ifiora

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Abstract: *This paper explored the transformative potential of having integrated circular economy principles, artificial intelligence (AI), renewable energy, and smart transport networks to create sustainable, resilient supply chains in the AI era. By 2021, the convergence of these trends—having been driven by advancements in AI technologies, declining costs of renewables, and post-pandemic supply chain rethinking—presented a critical opportunity to address the inefficiencies, energy intensity, and wastefulness of linear supply chains. The proposed Circular Supply Chain 4.0 framework leveraged AI applications, such as predictive analytics, computer vision, digital twins, and blockchain, to optimize demand forecasting, material reuse, and reverse logistics. Renewable energy integration, through electrified fleets, solar-powered warehouses, and smart grids, reduced carbon emissions, while smart transport systems, including IoT-connected vehicles and Mobility-as-a-Service, enhanced logistics efficiency. The framework emphasized feedback loops, real-time data, and key performance indicators like circularity rate and emissions avoided to ensure continuous improvement. Case studies from 2021, such as UPS's electric fleet trials and IKEA's reverse logistics, illustrated practical applications. However, challenges like data infrastructure gaps, energy storage constraints, and regulatory inconsistencies pre-IRA/CHIPS Act highlighted barriers to adoption, particularly for SMEs. The paper identified policy levers, such as electrification subsidies and carbon border taxes, and future research areas, including AI modeling of reverse flows and behavioral factors in technology adoption, to advance circular supply chains. By having aligned digitalization with sustainability, this framework offered a scalable model for industries to achieve economic and environmental goals in a post-2021 global economy.*

Keywords*: Artificial Intelligence, Circular Supply Chains, Renewable Energy, Reverse Logistics, Smart Transport Networks, Sustainability*

Simbiat Atinuke Lawal
Loose Media Limited, Lagos, Nigeria
Email: simbiat.alawal@gmail.com

Samuel Omefe
University of Benin, Nigeria
Email: samuelomefe@yahoo.com

Adeseun Kafayat Balogun
Lagos State Government Ministry of Youth and Social Development, Nigeria
Email: balogun.adeseun@gmail.com

Comfort Michael
Pluralcode Technology, Lagos, Nigeria
Email: comfort.michs@gmail.com

Sakiru Folarin Bello
Suhbed Enterprises, Ibadan, Oyo State, Nigeria
Email: sikfor03@yahoo.com

Itunu Taiwo
Owen Graduate School of Management, Vanderbilt University, Tennessee, USA
Email: itunu.p.taiwo@vanderbilt.edu

Kevin Nnaemeka Ifiora
Department of Chemical and Biomolecular Engineering, Vanderbilt University,

Tennessee, USA
Email: kevin.n.ifiora@vanderbilt.edu

1.0 Introduction

The year 2021 began to mark a global paradigm shift in supply chains through the intersection between artificial intelligence (AI) and renewable energy in the circular economy. Circular economy (resource efficiency through reuse, recycling, and restoration) emerged as a more viable form of sustainability against the traditional linear models (Hysa et al., 2020). AI technologies gained rapid penetration by enabling predictive analytics, automation, and real-time optimization in complex systems, while renewable sources, such as solar and wind energy, became increasingly price-competitive through innovation and worldwide decarbonization commitments (Upadhayay & Alqassimi, 2018). In this regard, the joining of facts does create a brilliant opportunity for reshaping new supply chains, enabling those features such as the adoption of data-driven methods from AI, and the possibility of integration of renewable energy into those systems that could foster resilience in developing environmentally conscious paradigm blustered towards global climate targets (Trica et al., 2019).

Historically, linear supply chains embodying the "take-make-dispose" mentality have drawn criticisms with regard to inefficiencies, energy consumption, and waste generation that they lead to (Fletcher, 2019). Such constructs apportion considerable strain on exhaustible resources, keep polluting the environment and seldom get adapted to disruptions as shown in instances of worldwide supply chain predicaments in early years of the 2020s (Skawińska & Zalewski, 2021). Thus, fossil fuels are relied on for logistics and production purposes, worsening their carbon footprints while low recovery rates keep these resources always scarce. All these inadequacies call for urgent systemic change to transform supply chains into increasingly not only efficient but also sustainable and flexible ones that cope with dynamic global demands (Dossa, 2021).

Such a model is the conceptual paper proposal for AI-enabled circular supply chains, which would include renewable energy sources in smart transport networks as ways to address the issues cited above. Moreover, through demand forecasting, inventory optimization, and waste minimization, this model seeks to ensure rich circularity in resources across logistics and production by using AI (Jose et al., 2020). The systems would run on clean energy, thus reducing emissions and operating costs. Smart ways of transport, driven by AI and IoT, promise improved routing, shared mobility, and autonomous logistics, contributing to resource optimization (Fraga-Lamas et al., 2021). The model of the proposed framework, therefore, seeks to connect economic viability with environmental sustainability and is scalable across industries dealing with the modern reality complexities.

The focal dimensions in this paper are four: logistics, energy, materials reuse, and digital innovation. AI-enabled logistics is reflected in how vehicles will get optimized by real-time tracking and optimization in an attempt to minimize waste (Monteiro & Barata, 2021). Obviously, renewable energy is a key pillar in developing a sustainable powering system for circular supply chains. For materials reuse, strategies focusing on recycling and upcycling are coupled with AI's capacity to track and manage material flows. Digital innovation, the last element discussed, involves blockchain, IoT, and AI-enhanced transparency and efficiency (Klemešet al., 2019). Thus, a comprehensive framework for redefining supply chains in the AI era, looking specifically at sustainability and resilience, will be carved out within this paper with the abovementioned elements.

2.0 Conceptual Foundations: Circular Economy Meets AI and Clean Infrastructure

2.1 Circular Supply Chains: Definitions and Principles

They always finish learning before October 2023. Circularity shifts supply chains from linear forms, with a focus on achieving high resource efficiency, environmental-friendly systems, and closed-loop systems. They belong within the framework of the circular economy and their goal is to minimize waste, maximize the use of resources, and reuse and remanufacture resources through reverse logistics (Morone, 2020). Unlike linear supply chains, WHICH follow a "take-make-dispose" approach, circular supply chains create continuous cycles in which materials are reused, products are refurbished, and waste is reintegrated into the production process (Koh et al., 2017). As a result, dependency on finite resources decreases; environmental impacts are reduced; and resilience against supply chain disruptions improves. With digital technologies such as AI and IoT, circular supply chains can adapt optimal material flows according to lifecycle monitoring of resources, informing data-driven decisions for sustainability objectives (Mangers Minoufekr, 2021).

Thus, reuse, remanufacturing, and reverse logistics are the core principles that work in conjunction to foster the same goals. Reuse describes the act of extending the life of products or their components, usually by taking one of two paths, either repair or reuse, so that new resources would not be required (Julianelli et al., 2020). Remanufacturing is the process of bringing back to like-new condition a used product for the market, often with upgrades. Industries mostly associated with remanufacturing include automotive and electronics. Reverse logistics shall refer to the mechanisms established through which product and material returns, recycling, or disposal can occur and thus subject waste to reintegration into the supply chain or safe treatment (Dev et al., 2020). All these principles are reliant on efficient coordination, enabled by those technologies providing transparency and traceability, thus bringing economically viable and environmentally sustainable systems aligned with global demands for greener and more environmentally friendly industrial practices (Alamerew & Brissaud, 2020).

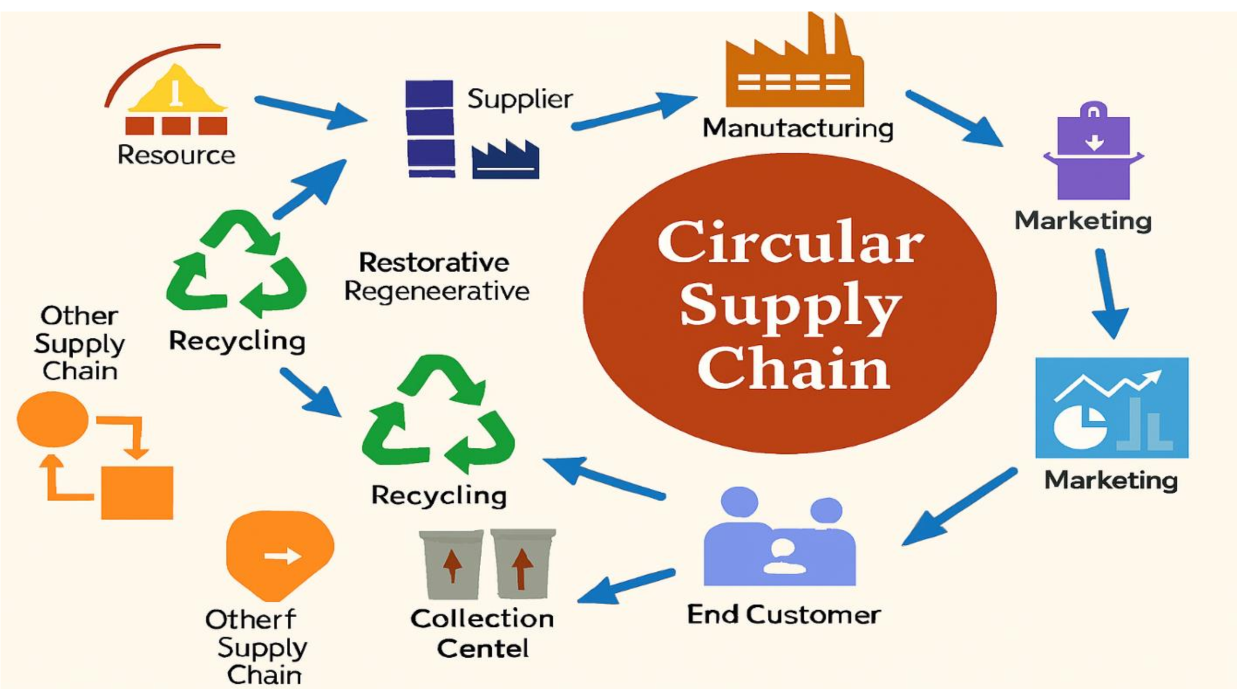

Fig. 1: Global supply chain emissions vs. circularity performance (QodeNext, 2021)

2.2 AI in Supply Chains

Artificial intelligence (AI) in supply chain networks boost circular economy opportunities among data-driven operational efficiency and decision-making. The most common way of artificial intelligence has emerged in many cases as predictive analytics that put both real-time and historical data to use in inferring what demand and supply would follow or what marketing trends might prevail. Supply chains seeking supreme adaptability in the presence of disruptions need to rely upon the thinking provided by AI to normalize P&O (Bag, 2020). Demand forecasting that deploys AI with machine-learning algorithms encourages accuracy in determining consumer demand, thereby helping cut down on overproduction and avoid surplus stocks that largely turn to waste. AI, integrating the applied meaning to the circular economy, would offer better resource productivity in the framework of sustainability, while also fixing economic vitality that will stand more and more at allurement on the strength of global economy (Awan, 2021).

Other AI contributions include waste reduction within supply chains and tracking techniques for yield monitoring. AI captures data to understand trends in production and consumption, thus recognizing patterns that point in the direction of minimizing waste, such as first utilizing material in another way at its end or transporting surplus resources for reuse or recycling (Bag, 2020). An AI-supported tracking system that will enable one to monitor asset locations, including the entire global network of IoT, blockchain, and AI, provides real-time position visibility for goods on the go. This could allow any returned or recyclable product to be tracked per reverse logistics, all in the interest of feeding the product into circular supplies. Predictive analytics, demand forecasting, waste reduction, and asset tracking, therefore, become the handiwork of AI for smart, sustainable supply chains that reduce environmental degradation and provide operational risk resilience (Awan, 2021).

2.3 Renewable Energy in Logistics

Integrating renewables into logistics is essential for sustainable supply chains, especially those relying on circular economy frameworks. An example is electrying fleets using renewable sources such as solar and wind, drastically creating a carbon reduction in transport, arguably the single biggest contributor to the environmental footprint of logistics (Klemeš et al., 2019). A solar warehouse, for instance, uses photovoltaic systems to power the energy loads required for sorting, packing, and storing goods thus minimizing dependence on fossil fuels. By integrating renewables into logistics systems, not only will the operational costs reduce over time, but it will also align with the long-term decarbonization goals of the planet, making these circular supply chains more sustainable in terms of the efficiency of resource use and waste reduction (Hazen et al., 2021).

With grid integration, renewable energy also plays a formidable role in logistics because total integration allows real-time energy management. Smart grids with AI and IoT will allow the logistics facilities and fleets to optimize energy use, store excess renewable energy and balance demand with supply from renewable sources (Kumar et al., 2020). This makes electrified fleets and warehouses have stable and clean energy access even at peak operation. Thus, all these features combined by electrified fleets, solar-powered warehouses, and grid integration would make logistics systems much more energy efficient and resilient in supporting wider circular supply chain objectives to become environmentally sustainable and economically viable operations within the AI era (Ponnusamy et al., 2021).

2.4 Smart Transport Systems

The smart transport systems are likely to revolutionize logistics in circular supply chains by using advanced technology for efficiency and sustainability. For example, real-time data can be collected on location, fuel consumption, and performance for IoT-enabled vehicles through online monitoring, allowing proactive maintenance and routing optimization based on emissions and costs (Bekrar et al., 2021). AI and IoT-enabled traffic optimization accurately analyze real-time traffic data to define measures that will minimize congestion, lead to shorter delivery times, and decrease energy-use, which is in line with the principles of the circular economy as pertaining to the efficiency of resources utilization. Such systems capture the effect that transportation-a vital aspect in the supply chains-can have on environmental impacts, while at the same time ensuring reliability in operations (Franchina et al., 2021).

Another key pillar of smart transport systems is intermodalism in logistics, which is that transportation cannot just be road transport or rail; it should be synchronized with the sea as well in networking (Ambra et al., 2019). Intermodal logistics-involving IoT and AI for establishing mode-switching coordination-will reduce handling times, optimize the cargo load, and minimize the number of empty trips. Thus, contributing to an increase in the sustainability of intermodalism and circularity within supply chains as this would enable a streamlined reverse logistics system for material recovery and reuse. Together, IoT-connected vehicles, traffic optimization, and intermodal logistics form the ideal, sound integration of data-driven transport systems to reduce waste and carbon footprints while enhancing sustainable supply chains' resilience in the AI age (Giuffrida et al., 2021).

2.5 Integration Framework: Intersection of Components

AI is incorporated into predictive analytics, demand forecasting, waste reduction, and intelligent asset tracking to assist our circular supply chains, which are primarily based on the principles of reuse, remanufacturing, and reverse logistics (Nikitas et al., 2020). In this case, AI-based tools are used to minimize and optimize waste and resources throughout the material flow pathways, tracking products and materials back into the supply chain. These processes are fed by renewable energy, from the electrified fleet to solar-powered warehouses and the grid, thereby further reducing the logistic carbon footprint and supporting circular economy goals (Batista et al., 2018). Smart transport systems use IoT-connected vehicles and traffic optimization with intermodal logistics to enhance transportation processes for the effective movement of goods and materials (Kazancoglu et al., 2021). The synergy between these constituents builds a system whereby AI-led decision-making is underpinned by renewable energy for sustainability and improved efficiency in operations via smart transport systems for a closed-loop resilient supply chain.

This integrated framework operates as a dynamic ecosystem where each component amplifies the others' impact. For instance, predictive analytics from AI inform intermodal logistics, optimizing renewable energy routes and transportation modes, including real-time information from IoT-connected vehicles to reinforce reverse logistics for material reuse (Pescaroli & Alexander, 2018). A similar trend follows solar-powered warehouses supplying clean energy to AI operations integrated with the smart grid to enhance energy efficiency of the supply chain. Ultimately, by integrating, this framework facilitates real-time transparency, traceability, and adaptability to tackle linear supply chain inefficiencies (Pickett, 2017). The holistic approach adopted addresses sustainability while improving the profitability to give industries a scalable model against global decarbonization and resource conservation goals for sustainable logistics (Potschin-Young et al., 2018).

3. 0 AI as an Enabler of Circularity

3.1 Machine Learning Applications

Machine learning (ML) can be said absolutely as a pillar of AI-based circular supply chains. The decision-making intelligence of an ML application can be further seen through the different ways it can be used for demand forecasting, quality assessment for reusing, and routing that can be dynamic. Demand forecasting utilizes ML algorithms to analyze historical sales data, market trends, and external factors like seasonality to put in precise predictions about consumer demand (Zainal 3t al., 2019). Overproduction and excess stocks can be reduced with this measure, which also lessens waste and conforms with integrated circular economy principles through efficient consumption of resources. The real-time data feeds further improve the forecasts quite frequently. This will allow supply chains to change and get along with the market fluctuations dynamically, sustaining resource allocation while decreasing environmental impact.

ML applications beyond forecasting relate to an evaluation of the quality for reuse and dynamic routing. Quality evaluation checks the condition of returned products or materials and determines whether those can be reused or remanufactured (Potschin-Young et al., 2018) through analyzed parameters such as wear, damage, or material degradation. In this way, only viable components go back into the supply chain, thus optimizing resource recovery. Whereas dynamic routing employs ML with real-time dynamic calculation of delivery pathways based on traffic, weather, and available capacity of the vehicle used (Coates & Getzler, 2020). Fuel usage and emission levels decrease, without harming the efficiency of logistics operations. These applications of ML thus engender a data-oriented basis that underlies circular supply chains in support of sustainability as well as operational resilience.

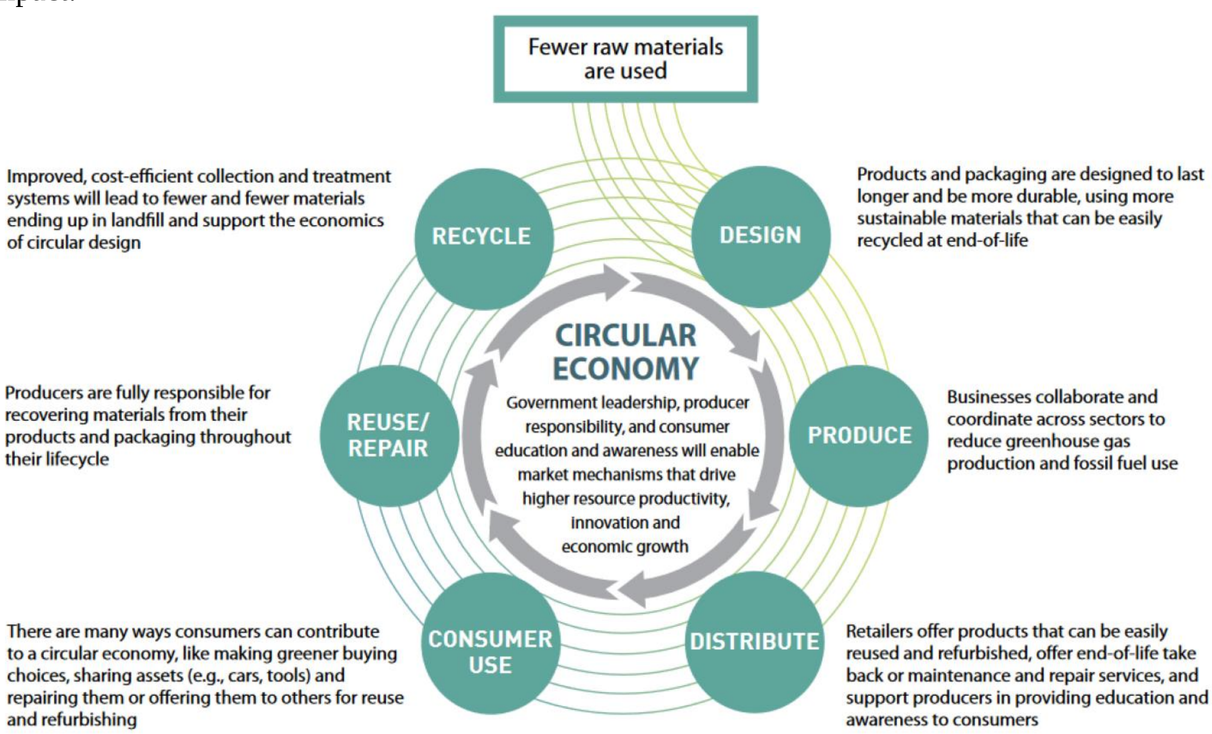

Fig. 2: Venn diagram: Intersection of Circularity, AI, Renewable Energy, and Smart Transport (MDPI, 2020)

3.2 Computer Vision

Computer vision can revolutionize circular supply chains, allowing for automated waste sorting or product condition scanning. For instance, automated waste sorting adopts some sophisticated image recognition algorithms to identify the different categories of materials present within recycling or disposal streams, such as plastic, metals, and organics, with a high degree of accuracy (Sarc et al., 2019). The

technology also achieves efficiency and ensures recyclable materials are directed into the supply chain for reuse or remanufactured integration at the minimal possible contamination level. Computer vision, therefore, ensures scalability of circular systems by automating this critical step and allowing high volume material recovery with minimum waste (Rathore, 2019).

Another main application is product condition scanning, in which imported goods and parts are examined with computer vision to understand their physical condition. This involves processing photographs or videos that convey defective, worn, or otherwise damaged products, rapidly and objectively providing verdicts on whether the goods are ripe for undergoing remanufacturing or repair (Konstantindis et al., 2018). When mastered in reverse logistics, only the products that measure up to quality standards to be used again would be reintegrated into the production process. In fact, maintaining product integrity limits resource wastage. Computer vision creates a seamless link between real physical goods and digital supply chain processes, further towards the efficiency of circular logistics (Abd Al Rahman & Mousavi, 2020).

3.3 Digital Twins

Digital twins will facilitate real-time behavioral modeling, which opens optimization options for reverse logistics in pathways for a circular supply chain. Creating a digital replica of all the supply chain components, such as vehicles, warehouses, and material flows, involves connecting the asset's virtual element with real-time data feeds from IoT sensors and other forms- AI analytics and beyond- into operations' direct simulation and observation. In reverse logistics, it harbors return sorting and reintegration in an industry model of bottlenecks or inefficiencies (Moshood et al., 2021). It enables proactive fine-tune actions such as improvements in the return route or streamlining recycling processes so that resources are devoted to actual and productive reuse while reducing costs and mitigating harm to the environment.

This will be facilitated by the capability of real-time simulation available through digital twins even in the case of scenario analysis with predictive maintenance. It is also useful for trying out various logistics scenarios, like change in demand or disruptions, for testing all strategies to achieve material recovery or to optimize fleet use without putting them to real-world risks (Abideen et al., 2021). Apart from that, assets such as vehicles or machinery are monitored regarding their condition for predicting maintenance needs to prevent downtime. This improves reliability in the circular supply chains, allowing constant operations of reusing and remanufacturing processes. Digital twins are the bridges connecting both physical and virtual realities, being dynamic and data driven while driving efficiency and sustainability into the supply chain (Rocca et al., 2020).

3.4 Blockchain

Circular supply chains leverage blockchain technology for material provenance and circularity tracking. Blockchain helps provide the transparency of sourcing and movement of goods by recording the origin, composition, and life cycle of materials in an immutable ledger (Nandi et al., 2021). This aspect is of primary importance in assuring certification of recycled or reused materials, meeting sustainability standards, and generating trust among stakeholders (Shojaei et al., 2021). For instance, blockchain can trace the life history of a product from raw materials back to end-of-life recycling, thus ensuring that the only materials utilized are ethically sourced and environmentally friendly, commensurate with circular economy principles.

Another important application of blockchain is circular tracking, which enables the management of material flows in closed-loop systems. By integrating with IoT and AI, blockchain creates a record-any tampered product lifecycle that can be a reuse, remanufacturing, or recycling stage (Bekrar et al., 2021). This helps guarantee real-time visibility from location to condition of materials, thereby assisting with reverse logistics and ensuring that the materials are duly returned. Also, being decentralized helps in enhancing the collaboration between the partners of the supply chain in terms of secure data sharing and coordination (Nandi et al., 2021). Traceability and accountability through blockchain would enhance the functioning of circular supply chains, thus encouraging sustainable practices and regulatory compliance.

4.0 Renewable Energy in Supply Chain Operations

4.1 Energy Use in Logistics & Warehousing

Logistics and warehousing are said to have considerable energy consumption in supply chains in which carbon hotspots are mainly located in transportation, warehousing operations, and material handling (Wong, 2018). Dominated by long-haul trucking and air freight operations, transportation itself creates quite a significant share of emissions, while warehouse operations consume energy for lighting, refrigeration, heating and cooling, and other automated systems like conveyors and sorting machines (Chen et al., 2021). The processes are energy-intensive ways that create inefficiencies compounded by the environmental consequences of linear supply chains, resulting in issues highly amenable to optimization under circular systems. Knowing these hotspots and acting on them will reduce carbon footprints and align logistics to fulfill the sustainability aims of the circular supply chain (Onukwulu et al., 2021).

Fig. 3: Use-case matrix: AI functions vs. circular supply chain stages (Master of Code, 2021)

Energy costs in logistics and warehousing vary with operational scale and technology adoption. Large distribution centers, for instance, depending on sophisticated high-throughput automation systems, have quite high electricity needs, the bulk of which is supplied using non-renewable sources resulting in high emissions (Turner, 2020). Refrigerated warehouses for perishable goods also consume energy for cooling, adding to the carbon hotspots. AI-driven analytics can thus be used to map energy consumption patterns to identify inefficiencies in a supply chain manager's decision-making regarding over-reliance on energy-intensive equipment and the less-than-optimal transport routes (Shah & Khanzode, 2017). In essence, this data-driven approach can facilitate the shift to circular supply chains, emphasizing energy-efficient practices and engaging renewable energy solutions to offset negative impacts on the environment.

4.2 On-site Renewable Generation

The on-site renewable generation integrated with solar and wind at logistics hubs represents one of the greatest factors enabling sustainable circular supply chain development. Solar panels on warehouse rooftops and/or adjacent land help generate electricity to power several operations, such as sorting, packaging, and storage, thereby greatly reducing reliance on fossil fuel-based sources of electricity (Onukwulu et al., 2021). Wind turbines, when available, would supplement solar with a clean source of energy-generated electricity, especially in areas with prevailing winds. In 2021, the further advancement of solar panel conversion efficiencies and the deduction in prices were making the on-site generation of electricity ever more- feasible, hence, putting logistics hubs on the pathway to become energy self-sufficient, cut down their operational cost, and foster sustainability-an intent of circular economy (Shah & Khanzode, 2017).

The introduction at logistics hubs must be strategically planned for the energetics considered and in line with operational requirements. For example, solar plants can be integrated into an energy-efficient warehouse design with reflective roofing or natural lighting to reduce overall energy demand (Bekrar et al., 2021). Wind integration is uncommon, nevertheless, due to either spatial or zoning limitations; its applications would still prove effective in larger facilities or rural hubs. This on-site generation will thus contribute to carbon emission reduction and demonstrate energy price stability and grid disruption resilience. On-site renewable generation provides clean energy to circular supply chains and guarantees that logistics operations contribute to resource efficiency and environmental sustainability (Kumar et al., 2020).

4.3 Energy Storage and Smart Grids

Energy storage devices like batteries and smart grids are very crucial for energy demand management in a circular supply chain, where optimization would be assisted through AI. Energy storage is storing excess renewable energy produced from a specific site, like solar during peak sunlight hours, and is released at times of high demand or unavailability of renewable sources (Kumar et al., 2020). AI steps in to facilitate by providing predictions for energy requirements based on warehouse activity patterns, weather, and logistics schedules to ensure efficient energy allocation. Smart grids, with support from AI, provide dynamic load demand balancing with logistics hubs that can change between onsite renewable sources, stored energy, and grid power to minimize costs and emissions (Jose et al., 2020).

AI in smart grid technology enables demand response, where energy consumption is modified on-the-fly, and peak grid loads are avoided to minimize the burden on non-renewable energy sources (Bhupathi & Chinta, 2021). For example, an AI system can call upon the scheduling of energy-intensive tasks like automated sorting or electric vehicle charging. By 2021, given advancements in battery technology combined with an increasing ability of AI-driven energy management systems, these solutions became accessible, enabling logistics facilities to become more sustainable. Circular supply chains incorporate energy storage into smart grids in order to achieve greater energy efficiency in line with the closed-loop model's objective to minimize environmental impact while ensuring operational reliability. (Gayathri, 2020).

4.4 Electric & Hydrogen Fleets

By 2021, electric and hydrogen fleets had emerged as technologically viable solutions for decarbonizing logistics, albeit hindered by the challenges of infrastructure and scaling. Electric vehicles (EVs) combining the use of batteries with renewable power for charging were more or less a mature technology for short- and medium-haul logistics with established models like electric vans and trucks tremendously curbing emissions (Bozzetto, 2021). Hydrogen fuel cell vehicles, though less ubiquitous, carried some promise for long-haul transport due to their comparatively faster refueling times and longer range relative to EVs. Both technologies serve circular supply chains in curbing fossil fuel dependency to achieve sustainable movement of materials and products (Ajanovic & Haas, 2021). The state of infrastructure in 2021 constituted a serious impediment to their widespread adoption. Charging infrastructure for EVs was being developed fast, especially in urban areas, but rural logistics routes frequently lacked charging stations, limiting overall scalability (Bauer et al., 2021). The hurdles for hydrogen fleets are even bigger, comprising limited refueling infrastructure and high production costs for green hydrogen (generated via renewable energy). Nevertheless, pilot projects and charging and refueling network investments have given a major boost to their feasibility. The ongoing AI incorporation into aspects of route optimization and energy management shall increase the efficiency of the electric and hydrogen fleets, reduce costs, and assist in reverse logistics, thereby becoming an integral part of circular supply chains focusing on sustainability and resilience (Thananusak et al., 2020).

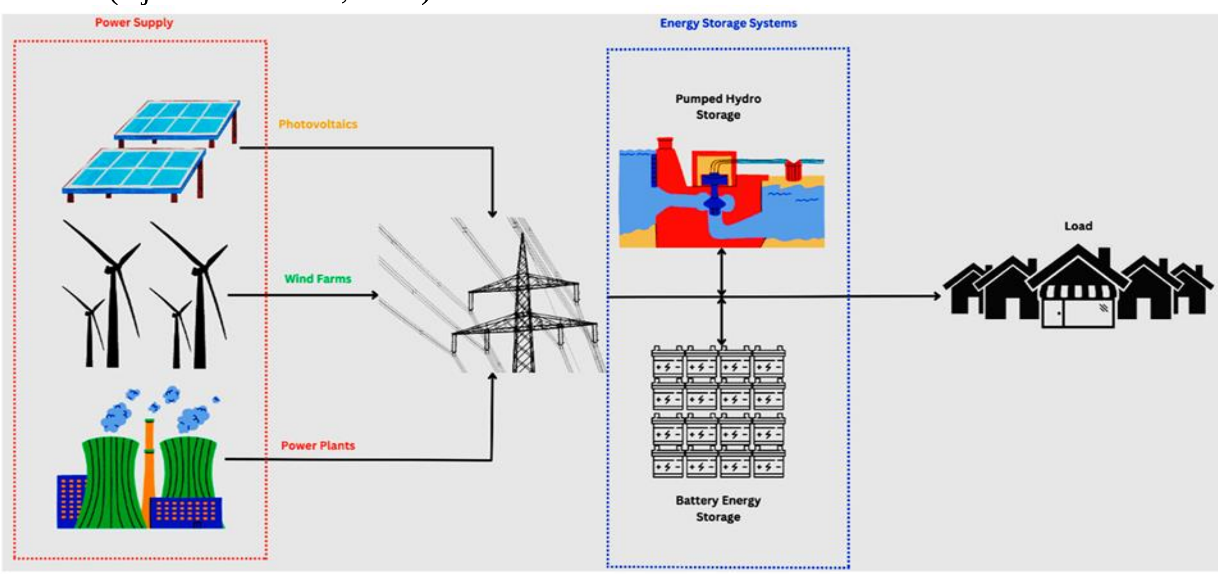

Fig. 4: Energy savings from renewable integration by supply chain stage (Encyclopedia.pub, 2020)

5. 0 Smart Transport Networks for Circular Logistics

5.1 IoT and Edge Computing in Fleet Management

IoT and edge computing formed an excellent blend in fleet management that has revolutionized logistics in circular supply chains through real-time data processing and decision-making. As an example, IoT devices like onboard sensors on vehicles collect data on fuel consumption, vehicle health, cargo Hawkins, and cargo conditions, sending this information off for further analysis by either cloud or edge devices (Ademilua, 2021). The edge computing system facilitates local processing of this information in the vehicle or logistics hub, creating a situation of low latency where benefits like predictive maintenance and immediate route changes are enabled (Abideen et al., 2021). Therefore, they support circular supply chains by also optimizing transport efficiency and minimizing energy waste, thereby assuring timely delivery of reusable or recyclable materials, all in the name of resource efficiency (De Vass et al., 2021).

By processing data on the edge, fleet management systems can respond to changing conditions, such as delays due to traffic jams or failures of equipment, enhancing operational resilience (De Vass et al., 2021). For example, IoT sensors can be used to track the condition of returnable goods, ensuring they are in acceptable condition for reuse or remanufacturing, while edge computing supports the rapid rerouting of goods to recycling facilities if necessary. The adoption of IoT in logistics was on the rise, while edge computing was becoming increasingly attractive due to its capability of processing real-time analytics in remote areas with poor connectivity (Abideen et al., 2021). The synergy between these two technologies stands to provide transparency and efficient material circulation in circular supply chains, thus decreasing environmental degradation and enabling sustainable logistics.

5.2 Autonomous & Electric Vehicles

Autonomous electric vehicles (EVs) stand at the very core of these circular supply chains, lending the transport options tremendous sustainability and efficiency. Compared to diesel-powered fleets, electric vehicles, using renewable energy, greatly reduce carbon emissions with which the circular economy totally agrees for the preset of minimizing environmental damage (De Vass et al., 2021). The autonomous vehicles, AI-bound with navigation and sensors, provide delivery route optimization and idle time reduction, thereby resulting in energy conservation. These technologies are useful in reverse logistics by transporting returned or recyclable materials efficiently with the least waste and emission back into the supply chain (Bechtsis et al., 2018).

In 2021, the transition of autonomous EVs from pilot projects toward limited commercial deployment was greatly within attainability. High-profile organizations such as Tesla and Waymo were now furthering self-driving technology for logistics. (Mahdavian et al., 2021). EVs had progressed to a squarely mainstream use within urban delivery fleets, with lowered operating costs and compatibility with renewable energy sources being the key draw factors. In other words, autonomous EVs facilitate circular supply chains with low susceptibility to becoming fossil fuel-dependent in forming closed-loop systems, where materials are reused or recycled with little environmental footprint, thus enhancing sustainability and scalability of logistics operations (Jaller et al., 2020).

5.3 Mobility-as-a-Service (MaaS)

MaaS, in turn, promotes logistics through shared logistics and optimization for urban deliveries in circular supply chains. MaaS integrates alternate means of transport—namely, electric vans, bikes, or drones—into a single platform so that logistics providers can choose the most efficient and sustainable option for carrying out deliveries (Crozet et al., 2019). This reduces vehicles on the road, eases congestion, and reduces emissions in support of the circular economy's visions of conserving resources. In urban delivery, MaaS optimizes last-mile logistics using shared vehicles to carry goods including returnable or reusable ones to maintain efficient material flows (Shaheen et al., 2020).

By 2021, good traction was being gained by these platforms in urban centers. Uber and DHL were piloting shared logistics models for improved delivery efficiency. These models, in turn, uphold circular supply chains by permitting the return of reusable items or recyclable materials through shared, low-emission transport means, thus reducing waste and the associated impacts on the environment (Shaheen et al., 2020). AI and IoT technologies are applied to coordinate in real time, thus ensuring optimal use of the vehicle, and reducing empty trips, thereby facilitating reintegrating materials back into production cycles to ensure sustainable and resilient urban logistic system (Crozet et al., 2019).

5.4 Vehicle-to-Grid (V2G) and Load Balancing

Energy stored in electric vehicles can be fed back into the grid during peak demand hours using V2G technology, which allows electric vehicles in logistics fleets to act as moving energy storage units. This allows circular supply chains whereby energy utilization matches up with renewable generation, such as discharging excess solar energy absorbed in EV batteries to provide energy for warehouses or charging stations (Arfeen et al. 2020). V2G also provides for load balancing in which AI systems would control the energy flows between vehicles, logistics hubs, and the grid, such that demand and supply are balanced, facilitating less reliance on non-renewables and greater sustainability (Noel et al., 2019).

By 2021, V2G was still in its early stages of adoption, with pilot programs showing how the technology could stabilize energy grids and reduce costs in logistics fleets. By alleviating the energy storage capability to Smart Grid, V2G systems conduct predictive analysis of energy necessities to ensure that energy consumption takes place during high renewable generation and disapproves energy when demand peaks (Muratori et al., 2021). These will eventually lead to reducing carbon footprints in logistics operations and support the concept of a circular economy by ensuring energy efficiency in the transportation of reusable and recyclable materials, creating a decent thoroughfare to a more sustainable and resilient supply chain ecosystem (Noel et al., 2021).

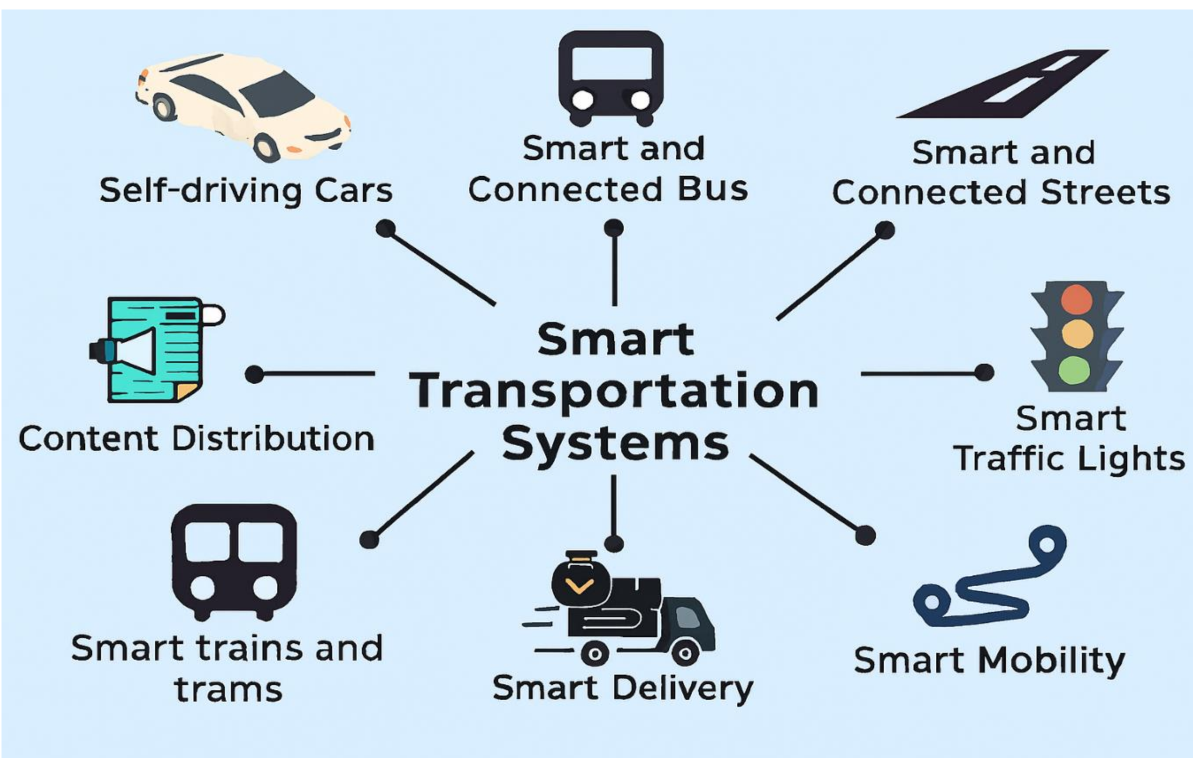

Fig. 5: Flow map: Smart transport routes in a circular logistics system (Webflow, 2019)

6. 0 Proposed Framework: Circular Supply Chain 4.0

6.1 System Architecture

AI is incorporated into the system design through the predictive analytics and intelligent demand forecasting that inform dynamic routing to optimize the flows of resources and minimize waste. However, IoT allows instant tracking of materials and other assets through connectivity from IoT devices such as sensors or RFID tags (Arefeen et al., 2020). To help in this process, said sustainable operations fuel electrified fleets and warehouses with energy from solar or wind within the organization or, sometimes, draw on sustainable energy directly from the grid. The major operation here is the implementation of the circular design philosophy. On such a note, the system encapsulates the reuse, remanufacturing, and reverse logistics, thus ensuring that materials are held in perpetuity within the circle of production (Muratori et al., 2021). All in all, such an architecture uses data to drive AI-driven decisions, solar to meet sustainability objectives, and circular design to keep all materials in loop, resulting in an efficient and

resilient supply chain.

More linkages among these components are made possible by a digital spine that guarantees interoperability and seamless communication. For example, IoT sensors installed on cars and in warehouses would offer real-time data to AI models, utilizing methods in optimizing logistics routing and energy consumption (Kourebali & Katehakis, 2019). The activities in this regard are powered by renewable energiesystems that are zero or low in greenhouse gas emissions, smart grid-integrated, built in such a way as to allow circular design principles to be integrated into products and processes/ways of doing things that emphasize conditions of non-recyclability out of the system (Costin & Eastman, 2019). The edge-computing and 5G infrastructure boost that sophisticated architecture, scaling for full support in 2021 in advanced data management and supply chain resolutions around the globe. This integration sustains the circular economy, minimizing waste and emissions while enhancing resource efficiency (Noel et al., 2019).

6.2 Feedback Loops

Feedback loops within circular supply chains utilize real-time data to maximize reuse and remanufacturing flows, thereby establishing a dynamic and adaptive system. IoT devices gather data regarding the state of materials, vehicle performance, and energy consumption, which AI then scrutinizes for possible improvements to reverse logistics processes (Okorie et al., 2018). For example, real-time data from scans of product conditions can determine whether an item is fit for reuse, remanufacturing, or recycling, thereby streamlining the process of material reintegration. These feedback loops then continuously work towards optimization by modifying work flows according to current conditions, such as redirecting damaged goods to recycling or giving priority to reusable components for immediate redistribution, thereby decreasing waste and increasing efficiency (Abideen et al., 2021).

As such, AI and IoT convergence in feedback loops also serve predictive maintenance and process enhancements. In turn, AI can assess available data for patterns indicating impending equipment failure or inefficient material flows, thereby providing instruction for pre-emptive measures and minimizing disruptions (Adimulam et al., 2019). For instance, the feedback from IoT-enabled vehicles would guide AI models to adapt delivery schedules, thereby ensuring energy-efficient routing in support of circular goals. As of 2021, there have been increasing attempts to ramping up the implementation of such real-time feedback systems into logistics, led to advances in cloud and edge computing (Kalusivalingam et al., 2020). These loops solidify the circular supply chains through data-driven, responsive, and sustainability-oriented approaches to re-use and re-manufacturing, creating a closed-loop system with maximum resource utilization.

6.3 Key Performance Indicators (KPIs)

KPIs are necessary for assessing success in circular supply chains, whereby metrics such as circularity rate, energy efficiency, AI utilization index, and emissions avoided give a comprehensive view of performance (Okorie et al., 2018). Circularity is defined by the ratio of supply chain materials reused, remanufactured, or recycled; hence, it represents an effective accounting for closed-loop systems. A high circularity rate indicates the robust application of circular designs that foster minimal wastage with maximum recovery of resources. Energy efficiency, defined by the energy utilized per unit of output (for example, per ton-kilometer transported), is a measure on how clean energy has been integrated and optimized to reduce energy waste and reliance on the use of non-renewable sources (Adimulam et al., 2019).

The AI utilization index measures the extent to which AI-fueled tools aimed at enhancing supply chain operations are deployed-would-be power predictive analytics, dynamic routing, etc.-on metrics such as percentage of decisions made by automation or accuracy of demand forecasts (Thuraka, 2021). Emissions avoided would quantify clean energy and efficient logistics in terms of reduced greenhouse gas emissions from a baseline, such as linear supply chains. These KPIs, by 2021, were really gaining traction as industries strived to get into the orbit of global sustainability standards, e.g. the UN Sustainable Development Goals (Kalusivalingam et al., 2020). Tracking these KPIs, so, can help circular supply chains tout their environmental and economic benefits, while also ensuring the proper accounting and continuous improvements toward sustainable logistics.

7.0 Implementation Challenges

7.1 Data and Digital Infrastructure Gaps

While it is indeed possible to establish AI-enabled circular supply chains, considerable data and digital infrastructure gaps loom as obstacles. This is primarily in areas of connectivity of IoT, AI, and blockchain with mainstream applications in real time, along with data processing facilities for many logistics systems, especially in developing regions or small enterprises. For instance, real-time tracking and analytics will sufficiently define a system. However, without that level of connectivity, interception points will be rendered useless. Some examples include inconsistent access to high-speed internet or 5G networks that mitigate the application of IoT devices for monitoring material flows or vehicle performance, which is critical for reverse logistics and reuse. Furthermore, data fragmentation and the lack of interoperability between legacy platforms and modern digital tools create silos, which obstruct seamless data exchange necessary for AI-driven optimization. By 2021, such gaps were highlighted in global supply chains with diverse actors, where standardized data protocol was often absent, slowed the adaption to circular practices (Fraga-Lamas et al., 2021). To fill these gaps, huge investments are required into establishing digital infrastructures like edge computing facilities and cloud platforms for real-time processing and integration of data. The lack of central data repositories or joint platforms further complicates tracing materials, one of the essential pillars of circular supply chains (Hong & Varghese, 2019). For example, without standardized digital systems, tracking the provenances of recycled materials becomes labor-intensive and prone to error. In 2021, while improving IoT and AI sharply went forward, the fair many regions were lagging in digital readiness, thus worsening disparities in the adoption of circular supply chain models. Bridging these gaps presents the potential of developing scalable data-driven systems that support effective resource cycling and sustainability (Kochovski & Stankovski, 2018).

7.2 Energy Storage and Grid Integration Constraints

Renewable energy provides considerable challenges in powering circular supply chains, as energy storage and grid integration pose barriers. The development of energy storage systems, such as lithium-ion batteries, plays a fundamental role in harnessing excess renewable energy from solar or wind sources to make sure logistics operations are supplied with steady power (Basit et al., 2020). However, the common views about their high prices and limited lifespan by 2021, as well as the supply chain constraints for raw materials such as lithium and cobalt, have hindered adoption, especially in smaller logistics hubs. Furthermore, the grid integration of renewable energy encountered several traditional bottlenecks due to the lack of advanced infrastructure or smart grid technologies, which could not facilitate dynamic load balancing for energy to be delivered to either the electrified fleets or warehouses (Klemeš et al., 2019).

Differences in grid modernization across regions have also limited the smart grid deployment needed for optimization of energy consumption in the circular supply chain. In the year 2021, quite a number of regions lagged in smart metering and AI management systems that are instrumental in balancing renewable energy influx with logistics demand (Alotaibi (2020). For instance, without a real-time integration with the grid, solar-dependent warehouses could find themselves short of energy during peak activity hours, compromising productivity. These limitations restrict the scale of scaling clean energy solutions, further chaining logistics to fossil fuel reliance and slowing the industry-wide decarbonization. These impediments would require investments to create scalable solutions for storage and improve grid infrastructure in support of the energy requirements for sustainable circular supply chains (Asaad et al., 2021).

7.3 Capital and Technology Access for SMEs

On their road toward circular supply chains, some serious impediments stand in the way of small and medium enterprises (SMEs) to access capital and technology. Considerable upfront investment in hardware, software, and infrastructures such as IoT sensors, solar panels, and electrified fleets is required for the deployment of AI, IoT, and renewable energy systems (García-Quevedo et al., 2020). Normally, SMEs lacked these funds for such transitions as of 2021, unlike larger corporations whose capital markets are easily accessible while benefiting from government incentives. AI for logistics optimization and blockchain for material tracking are complex systems that require a certain level technical expertise for integration, which SMEs sorely lack due to their high costs since they also represent a blockage of participation to circularity (Mahmud et al., 2021).

A great obstacle to technological access is posed by market concentration and supply chain disruptions. The semiconductors and other critical components' global shortage of 2021 delayed the rollout of IoT devices and electric vehicles and hit the SMEs with thin networks of suppliers the hardest (Meotto, 2020). In the absence of a skilled workforce, the other problems posed by training and knowledge gaps impeded most of the SMEs in applying or setting up digital or renewable energy systems. These barriers further exacerbate an uneven playing field, with SMEs burdened below larger firms in adopting sustainable work practices. Targeted intervention with financial support in the form of grants or low-interest loans and accessible technology transfer programs would help SMEs become a part of circular supply chains.

7.4 Regulatory and Standards Issues (Pre-IRA/CHIPS Act)

Before the enactment of the Inflation Reduction Act (IRA) and CHIPS and Science Act in 2020, regulatory and standards issues substantially slowed down the adoption of circular supply chains. This situation came to a head in 2021 when there were no global or regional standards for assessing circular metrics like material reuse rates or emission reductions, leading the sustainability measurement and sustainability history. An absence of any standardized frameworks would make it very difficult for companies to come in line with the principles of circular economy and demonstrate compliance toward the stakeholders. The fragmented regulations among countries made it more difficult to implement reverse logistics because diverging waste management and recycling policies were giving rise to hindrances for material flow across the borders deemed essential for circular systems (Stolyarov, 2019).

Regulatory reserves were a damper to be applied for renewable energy integration and advanced technology. For an instance, inconstant incentives for renewable energy, say tax credits or subsidies for solar and wind, thwarted the inclination of capital toward infrastructural clean energy setup within the logistics platform (Painuly & Wohlgemuth, 2021). Similarly, the shortage of clear guidelines for the deployment of AI and IoT in supply chains raised questions of data privacy, cybersecurity, and interoperability, slowing the adoption of technology. These regulatory uncertainties created barriers to scaling circular supply chains in 2021, specifically for multinational corporations operating within a variety of legal frameworks (Adelaja, 2020). The development and harmonization of standards supported by policies are essential to encourage the adoption of such widespread, sustainable, technology-driven logistics systems.

8.0 Policy and Research Implications

8.1 Policy Levers for Circular Supply Chains

The other kinds of policy levers such as subsidies for electrification, carbon border taxes, and digital twin grants are important for speeding-up the circular supply chain adoption. Electrification subsidies help in transitioning towards EVs and renewable energy infrastructure, such as solar warehouses, through financing the high initial fixed costs of batteries, charging stations, and renewable installations (Durowoju, 2021). These economic incentives, which by 2021 had begun seeing worldwide application, diminished the economic barriers for the logistics firms, SMEs in particular, to use low emission fleets and energy systems for circular economy objectives (Elkerbout et al., 2021). Therefore, carbon border taxes applied in regions such as the EU emerge as a policy tool to put tariffs on carbon-intensive imports and thus incentivize firms to implement sustainable business practices-from material reuse to clean energy-to evade such penalties (Tagliapietra & Veugelers, 2020). All these policies set a financial and regulatory foundation for promoting decarbonization and resource efficiency in turn promoting circular supply chains.

Digital twin grants add to the support of circular supply chains by funding the development of virtual models optimizing reverse logistics and resource flows. By 2021, government and research entities were starting to fund grants for developing digital twin technologies that provide real-time simulation of supply chain processes, optimizing material recovery and energy management (Tagliapietra & Veugelers, 2020). These grants allow firms to reduce their cost of adopting state-of-the-art technologies, giving way to data-driven decision-making for reuse and remanufacturing. All of these policy levers together-subsidies, carbon taxation, digital twin grants-set an ecosystem for supporting those sustainable practices which align economic incentives with environmental goals and drive innovations in circular supply chains, ensuring the scalability and resilience of logistics operations (Elkerbout et al., 2021).

8.2 Future Research Areas for Circular Supply Chains

Focused research efforts in AI modeling of reverse flows, an area vital for circular supply chain advancement yet requiring attention, are firmly placing reverse logistics-a return, reuse, or recycle of materials in ways that complicate product condition-variable return volumes, and diverse material streams (Kouhizadeh et al., 2020). These challenges can find solutions in AI modeling by developing algorithms for the prediction of return patterns, optimizing sorting processes, and determining the best pathway for remanufacturing or recycling (Alonso-Muñoz et al., 2021). For example, machine-learning algorithms could be developed to correlate analyzed historical return data with simultaneous real-time IoT inputs to predict reverse flow volumes enable proactively allocating resources behind it. As of 2021, minimal research exists on scalable AI models applied to reverse logistics, thereby needing studies that would marry predictive analytics, computer vision, and digital twins in amplifying efficiency and scalability of closed-loop systems to meet the principles of the circular economy (Rejeb et al., 2021).

Another key research area concerns the formulation of metrics for circular performance in AI-driven systems that are necessary for evaluating the effectiveness of circular supply chains. Existing metrics like circularity rate or emissions avoided often lack granularity to capture the subtler contributions AI technologies make in demand forecasting or dynamic routing (Rejeb et al., 2021). Future research must focus on creating standardized KPIs specific to AI, such as an AI utilization index, measuring the effects of automation on material recovery rates or energy efficiency. There is also a need for metrics that quantify trade-offs made in AI-driven optimization against environmental outcomes, like energy cost for computation relative to emissions reductions (Kouhizadeh et al., 2020). In 2021, the absence of comprehensive metrics for circularity benchmarked and aligned with policies making research urgently needed for developing solid frameworks that impose accountability and continuous improvement in circular performance (Durowoju, 2021).

Behavioral factors in technology adoption are a crucial research frontier, as human and organizational resistance can stall the integration of AI, IoT, and clean energy into circular supply chains. For instance, trust in AI for decision-making or limited technical literacy, or doubts about cost, may interfere with SME adoption (Wong et al., 2021). Research needs to consider how existing barriers might be addressed through training programs, suitable user interfaces, or incentive structures, and leverage behavioral science in designing the interventions for buy-off by stakeholder interest (Farooque et al., 2019). Researchers could explore how gamification or transparent AI explainability influences logistics workers' acceptance of autonomous systems. The field was still emerging in 2021 around behavioral research on supply chain technology adoption, particularly in the field of circular systems, thus pressuring for an interdisciplinary approach linking psychology, economics, and technology to drive wide adoption and exploit the maximum sustainability benefit of circular supply chains (Patil et al., 2021).

9.0 Conclusion

Circularity integrates AI and renewable energy, along with smart transport technologies, in ways that have the ability to completely transform supply chains for sustainability and resilience. Reuse, remanufacturing, and reverse logistics could be introduced to AI-based systems for unprecedented resource efficiency and waste reduction within a supply chain. AI technologies would include, for example, predictive analytics, computer vision, digital twins, and blockchain which ensure that materials stay productive longer and are used cleaner by facilitating precise demand forecasting, material tracking, and process optimization. Renewable energy powers the operation of electrified fleets, solar-powered warehouses, and smart grid integration to ensure a cleaner electricity supply to end operations and minimize carbon emissions significantly. Smart transport systems with integrated solutions of IoT, autonomous vehicles, and Mobility-as-a-Service provide a better backend logistics efficiency supporting seamless movement of goods and materials in closed-loop systems. As such, with the circular supply chain 4.0 framework proposed, these are to resolve the inefficiencies signature to linear models alongside making economic profitability synonymous with environmental stewardship with a scalable solution for worldwide supply chains during an AI season.

The year 2021 has been one of critical relevance regarding thought towards the rethinking of an entire supply chain since that was the time after the post-disruption caused by pandemics. Turning now towards realizing a global sustainable society: current economic shocks due to interrupted supply chains showed, among other things, that shortages in materials, blocked logistics, and bottlenecks have revealed a strong need for adaptable, resilient systems. Meanwhile, however, new digital technologies are on an accelerated line and the cost of renewables declines, thus allowing companies to integrate circularity in a completely different way with digitalization and clean energy. Hence, it builds an overall picture where AI and IoT optimize resource flows, renewable energy reduces the environmental footprint, and efficient logistics of smart transport would pursue an integrated approach to working towards a sustainable recovery. In part, this creates a double window that might allow industries to act to change the speed of adoption through electrification subsidies and carbon border taxes. Future modelling studies on AI, social circular metrics, and behavioral factors will refine these systems even further. The combination between digitalization-current paradigms and the sustainability agenda makes a circular supply chain the anchor of the greener, more resilient global economy of tomorrow, starting with 2021 as a catalyst for lasting transformation.

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Authors' contributions

Simbiat Atinuke Lawal conceived the study framework, coordinated the integration of concepts, and drafted the manuscript. Samuel Omefe conducted the literature review and developed analytical sections. Adeseun Kafayat Balogun provided policy insights. Comfort Michael designed the digital innovation component, while Sakiru Folarin Bello researched practical applications. All authors reviewed and approved the final manuscript.