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Blockchain for Transparent and Green Commerce

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Abstract

This examines how blockchain technology can foster transparency and sustainability in global supply chains against the backdrop of worsening climate change and resource scarcity. Organisations are putting more focus on decreasing greenhouse gas emissions, but the high complexity of value chains requires verifiable tracking of environmental impact using distributed ledger technology (DLT). DLT allows for unchangeable records, tracing of provenance and accountability of stakeholders without a reliance on centralised trust. There are a number of core mechanisms to ensure the effectiveness of the commodity standards. These include ensuring traceability of goods from origin to disposal; compliance audits; public dashboards for key performance indicators (KPIs) such as GHG and water intensity; and efficiency gains that help cut down on waste and emissions. Case studies in agri-food and circular economy recyclables and green procurement have pointed out some real benefits, while overcoming challenges of scale, data quality, governance and energy use, accompanied by policy roadmaps for adoption.

Keywords: *Blockchain, sustainability, supply chain, transparency, green commerce.*

1. Introduction

Given dwindling resources coupled with increased commercial activities, climate change is a big challenge. There's an increasing recognition by corporations that sustainability is a commercial imperative, which results in the commitment to lower greenhouse gas emissions. The initial steps will involve working on emissions profiles related to their direct operations, and further progress will depend on expanding efforts to assess externalities within the wider supply chains. To meet these goals, greater transparency across complex value chains is necessary. The relevance of multimodal transport is retained, for instance, in the sourcing of standardised goods from resource-rich countries or in capital-intensive manufacturing. According to the organisation, it is necessary to conduct impact assessments and have (well-defined) key performance indicators to ensure accountability.

Solutions under consideration for verifiability and transparency include conventional auditing, enhanced disclosure, and the adoption of distributed ledger technology (Ahlstrand, 2018). Blockchain permits public visibility of transactions without requiring trust in individuals or organisations. By installing an independent, immutable record of decisions, parties hold each other accountable. Technically, centralised solutions lacking broad data access do not leverage the full potential of distributed ledgers. Full disclosure does not offer significant business value when counterparty transactions remain undisclosed. Encrypted data, accessible only to selected actors, prevents oversight and liability for eradicated records or inadmissible alterations.

2. Foundations of Blockchain in Sustainable Trade

Blockchain's potential to enhance the transparency and sustainability of international commerce arises from its core characteristics of decentralisation, immutability, and transparent consensus. These capabilities derive from the merging of distributed ledger technology (DLT) with programmable currency. DLT allows for a de facto human and machine consensus on a shared transaction history to be established without relying on a central authority or visible intermediaries. In particular, it opens up a digital space for monitoring sustainable trade practices.

Sustainability encompasses ecological, social, and asset-economic trade-off considerations, yet the considerable and, in many cases, accelerating degradation of climatic, soil, biosphere, and atmospheric conditions since the mid-20th century has fuelled growing momentum for phasing out the accumulation of harmful emissions, toxic waste, and abject poverty. Transparency, distinct from sustainability, refers to the capacity of different stakeholders to access the same accurate, timely information on various elements of the social, economic, health, environmental, and regulatory contexts underpinning traded products, services, and transactions.

The technology of distributed ledgers opens up five avenues of transparency that can provide enduring economic and ecological benefits across different sectors. To know about the first, this allows tracking and monitoring of the provenance and traceability of goods throughout their life cycle, from raw materials through to end-of-life disposal. Another benefit is that it creates, stores and makes available immutable records of compliance to sustainability policies for stakeholders. It enables formal audits and verification by third parties to monitor compliance with sustainability targets. Third, it renders superior public accountability through instantaneous information release on monitored sustainability states and transaction particulars through digital dashboards to wide stakeholder groups. Lastly, it aids in achieving substantial enhancements in supply chain efficiency, leading to savings of materials, energy and time. In the long run, the higher output can be obtained by using smaller amounts of raw materials and toxic emissions. Moreover, this helps document sustainability-related metrics linked to the traceability of provenance, dynamic efficiency, circularity, as well as other sustainability criteria, generating data necessary for impact assessments of ongoing sustainability activities (Guo et al., 2024; Zhang et al., 2023; Ahlstrand, 2018).

2.1. Blockchain Fundamentals and Trust

A blockchain is a distributed ledger that holds time-stamped records of the transactions common to all parties. Using a cryptographic hash, each transaction is tied to the previous one, creating the chain. For an update to be coherent, it must be agreed upon via a consensus by the transactions, as the ones that are not agreed upon will not receive validation (Shee, 2020). When a transaction is once inserted, it cannot be modified. This ensures reliable management of digital assets and, in turn, builds trust among participants. Furthermore, the decentralised aspect of blockchain reduces reliance on central trusted parties, thus reducing the level of trust that different stakeholders need to place in any one party (Yavaprabhas et al., 2022).

In sustainable trade, such trust assumptions are pivotal. Assurance of financial authenticity is crucial to encouraging investment in ventures that directly impact emission reduction, like renewables or energy efficiency. Reliable, context-rich data on green attributes of products enables claiming and verifying commercial decarbonization—essential prerequisites for trading carbon credits and tax benefits. Moreover, credible assurance during operations, such as that ensuring the correction of defective streetlights, underpins the effectiveness of public-private partnerships aimed at wider social objectives.

2.2. Environmental Footprint Metrics in Commerce

Environmental footprint metrics can guide how commercial activities impact the natural environment, enhancing transparency efforts and supporting green commerce. Four fundamental measures apply to most products and services—Greenhouse Gas intensity and Water intensity indicators—and two additional ones specifically assist in circular economy-related decisions: Energy intensity indicators and Circularity indicators—and all four depend on the availability of appropriate data.

Greenhouse Gas intensity indicators quantify the climate impact of a product or service, expressed as the amount of Carbon Dioxide equivalents emitted per physical unit of output. Water intensity indicators quantify the demand for freshwater resources, expressed as the volume of freshwater consumed per physical unit of output. Energy intensity indicators quantify the indirect consumption of energy resources, such as fossil fuels, nuclear, solar, wind, hydropower, and geothermal primary energy sources, expressed as the amount of energy per physical unit of output. Circularity indicators identify the share of materials from recycled products within a commercial entity, assisting in decision-making about products and services with the aim of closing material loops.

Environmental Footprint Metrics

Metric	**Definition**	**Measurement Unit**	**Purpose in Sustainability**
Greenhouse Gas Intensity	Amount of CO_2 equivalents emitted per physical unit of output	CO_2e per unit	Quantifies climate impact
Water Intensity	Volume of freshwater consumed per physical unit of output	Litres per unit	Tracks freshwater resource demand

Metric	**Definition**	**Measurement Unit**	**Purpose in Sustainability**
Energy Intensity	Energy consumed (fossil, nuclear, renewables) per physical unit of output	MJ or kWh per unit	Measures indirect energy use
Circularity Indicators	Share of materials from recycled products in a commercial entity	Percentage of recycled materials	Supports circular economy decisions

3. Transparency Mechanisms Enabled by Distributed Ledger Technology

In the financial sector, it is challenging to establish the requisite integrity and trust without a shared or distributed ledger. This, in turn, allows to implementation of interoperability mechanisms. Business conduct underlies complex networks of goods and information. Value flows between upstream suppliers and manufacturers and downstream customers. The origin, method of production, quality, and environmental performance of traded products are essential contributors to transparency; however, they are difficult to trace and audit. Over the last few years, blockchain technology and other distributed ledger technology (DLT) platforms have emerged as a powerful means…. According to Ahlstrand (2018), DLT can collect data records generated by every flow of goods or information and present them in accessible and verifiable dashboards, easy to interpret by various stakeholders.

Traceability and provenance mechanisms refer to recording the creation and transfer of individual goods or streams of information from one party to another, where and when. Manufacturers and customers can get insight across the entire value chain. The history of materials is fully trackable at all times, starting from the origin through the various processing and production steps to the final products. Improved traceability incentivises effective disclosure, allowing for further quantification of environmental value through mutual recognition of compliant systems. To advance sustainable development, mutual records must portray organisation goals, interdependencies and performance across systems. According to Guo et al. (2024), verifiable public dashboards make reported sustainability outcomes more credible by allowing independent monitoring of adherence to such commitments.

3.1. Provenance and Traceability of Goods

A number of transfers of goods may take place before they reach the end user. As a result, it is difficult to monitor the origins and processing and distribution of products. The rising popularity of green, sustainability, organic or equitable trade concepts leads to wanting to know where the components come from and how the production processes meet specific sustainability criteria. Documents certifying ethical or green compliance, like Fair Trade or organic certificates, can easily be forged, thus removing a desirable basis for consumer trust. If there is a transparent system that would report on provenance and compliance with sustainability standards at product or company, or supply-chain levels, it would help a person or entity decide on the trade practices and sustainability performance of a potential supplier.

Provenance is the origin of an object and the history of ownership changes of an object. Provenance assurance for items without a digital footprint, e.g. food, medicine, clothes, is still required across the supply chain, as the risk of tampering, counterfeiting, or fraud exists with these too. There must be copious use of tracking both change events and certificates, not the least reference to Sustainability Claims such as "organic" (M. Kim, Laskowski, 2016). Cutting-edge systems for using provenance or certificates or both may entail intensive human work and are not feasible in practice. It is, therefore, important to study how distributed ledger technology can make provenance and sustainability tracking more meaningful and implementable, one that citizens easily understand, comply with more readily, and ultimately trust.

The supply chain tracking of goods is a result of provenance and traceability. But should this information were widely disseminated, it could cause privacy issues. Traceability networks can involve multiple parties in private data exchanges, creating scope for errors or malicious activities, like illegal materials appearing on food labels. With the blockchain technology's potential for transparency and accountability, its security verification is essential to prevent manipulative tampering and all the more. Incorporating reliable auditing mechanisms, such as off-chain storage and trusted third parties, may improve security by disclosing public transaction data. By keeping a transparent record, blockchain assists manufacturers and suppliers in sustainably collaborating. Moreover, it can reduce audit costs and increase credibility. The concept of a permissioned trusted audit chain, based on the principle of blockchain, has been proposed to ensure food safety and traceability (Lei et al., 2022).

3.2. Immutable Records and Auditability

Blockchain systems create a transaction record that does not change and shows tampering. The sequence of events is permanently stored along with version indices for every object, which indicate their current state. These features help regulators check that participants are compliant and accountable for what they claim. Tamper evidence and audit trails have many uses. Regulatory compliance is enabled as the data of communication and transaction can be produced to show compliance (Bhasi Thazhath et al., 2022). Audit trails are valuable not just for legal compliance but also in CSR, ESG, and similar programs. Companies and organisations commit to sustainability principles for numerous reasons, shareholder pressure and risk prevention are just two, while audit logs prove compliance.

The versioning functionality is relevant for certification frameworks requiring periodic renewals. Certificates often follow a set lifespan and need to be renewed—a new inspection or confirmation may be required, for instance, while the need for audit records remains. Versioned records allow the previous state of the system to be retained for audit purposes even after upgrading to a new version (Daniel & Tschorsch, 2021).

3.3. Enhanced Public Accountability and Stakeholder Reporting

Timely, transparent, and justifiable reporting of economic, environmental, and social key performance indicators (KPIs) is essential for the fulfilment of sustainability goals (Ahlstrand, 2018; Guo et al., 2024; Zhang et al., 2023). An environmentally friendly company using a multi-product, multi-industry structure will have varying metrics compared to companies with a single product focus. Emission regulation-linked metric models assume the absolute emission approach, while those linked to broader objectives, such as carbon neutrality or similar frameworks, will use a reduction framework. Multi-product, multi-industry, and beyond-compliance models describing the measures are essential to determine whether True Zero is justified and how other metrics can also drive sustainability initiatives. To ensure the adoption of public accountability and stakeholder reporting is implemented across applicable standards and regions, Tier 1, 2, and 3 industries with varying levels of investment, technological control, traceability, verification, and normative shielding should be differentiated (Guo et al., 2024; Zhang et al., 2023). High-tier industries are already in widespread use and are usually satisfaction-based, while True Zero frameworks are limited to the Tier 0.5 industry.

Environmental Metric	Definition	Blockchain Application in 3.3	Industry Tier Relevance
GHG Intensity	CO_2e emitted per unit output	Public dashboards for emission verification	Tier 1-3 (High traceability)
Water Intensity	Freshwater consumed per unit output	Immutable records for resource accountability	Tier 2-3 (Compliance audits)
Energy Intensity	Energy (fossil/renewables) per unit output	Real-time KPI monitoring via DLT	All tiers (Efficiency gains)
Circularity Indicators	% recycled materials in products	Stakeholder verification of circular claims	Tier 0.5 (True Zero focus)

4. Economic and Environmental Impacts of Blockchain-Driven Commerce

Blockchain technology has potential economic and environmental benefits for participants in commerce systems, depending on implementation details. These outcomes arise from improved supply chain efficiency, reduced energy use for energy-intensive blockchains, and the ability to measure the impact of blockchain-enabled sustainable trade on decarbonization efforts.

Supply chain streamlining and waste minimisation help in cost reduction, lowering inventory and lead time. The participants in the systems can eliminate duplicate processing, manage the processing step, redesign the network, and adjust schedules and routing to decrease total costs while meeting service requirements. Reducing waste helps increase the life of assets, while a secular uptrend in upstream material prices gives a much stronger incentive for waste minimisation. Cash-to-cash cycles, asset turnover, effective inventory days, and working capital are in proportion to annual revenue, are often used to gauge supply chain efficiency. According to Guo et al. (2024), excess and obsolete inventory, excessive scrap and spoilage, equipment underutilization, and wasted transportation miles are reference points for measuring supply chain waste.

Decentralised consensus models are well-suited for sustainability-focused commerce systems. Various models exist, each characterised by different energy requirements for operations such as transaction validation, data injection, and record write (Ahlstrand, 2018). Sustainable commerce efforts utilise energy-metric-based modelling to ascertain whether blockchain-supported resource pooling and energy foregone in the value delivery chain, in round figures, materialise positive rather than negative site green credential effects.

4.1. Supply Chain Efficiency and Waste Reduction

Although no single strategy can decouple economic growth from carbon emissions, improving supply chain efficiency and reducing waste represent substantial opportunities to promote sustainable business (Ahlstrand, 2018). Greater efficiency in the use of physical assets, materials, energy, and water can lower operating costs and increase margins at the same time as reducing demand for new materials and energy. The digitisation of supply chain processes in combination with blockchain technology has been shown to enhance organisational performance and sustainability in several sectors.

For example, through analysis of the pharmaceutical supply chain, it has been demonstrated that improved visibility and traceability of information can reduce wastage as much as 20%. In general, low inventory levels along a supply chain—often determined by the slowest-moving item—are associated with high wastage. When organisations cannot see where items are in the supply chain, control how many units are in stock, or track expiration dates, they may hold excessive safety stock to avoid stockouts. A logistics solution that enables end-to-end visibility of shipments and stock levels can relieve excessive safety stocks, thereby enhancing performance.

Inventory optimisation represents one possible benefit of blockchain-enabled traceability, although the actual percentage of performance gain remains with only anecdotal evidence depending on specific circumstances. More generally, performance metrics such as the Allen curve, accuracy of forecast versus actual commitment, and order fulfilment cycle time for inventories are also suitable candidates.

4.2. Energy Considerations and Decentralised Consensus

As per Westphall & Everson Martina (2022), Blockchain Technology, whose secure peer-to-peer energy-sharing transactions are enabled for the prosumers, a decentralised energy-trading system could result. Although they exist, many challenges hinder the development of energy-trading and prosumer-centric models. First and foremost come concerns about privacy, scalability, other user acceptance, data security, and low-latency. However, the existing studies showed that blockchain can help energy markets and achieve a greater satisfaction of techno-economic and environmental specifications through the electricity value chain.

The energy-consumption metrics attributed to the use of blockchain within the framework of sustainable trade depend heavily on a reliable and accurate quantification of the energy profile of the specific consensus protocol employed. One of the primary advantages of blockchain technology is the opportunity it affords to eliminate the need for trust in trade transactions and broader supply-chain engagement through the introduction of immutable record-keeping mechanisms and additional transparency. Avoiding reliance on user trust inherently requires that trust be reallocated to the protocols underpinning both the network and the consensus activities involved, as a corollary to blockchain technology's initial objectives. Consequently, foundational protocols released before the emergence of blockchain were often designed with security and privacy as primary objectives, rather than with decentralisation as a (Sun et al., 2024).

4.3. Measurement of Decarbonization Outcomes

Blockchains can help secure and determine the impact of decarbonization claims. Such claims can be expressed in terms of emissions avoided, curbed procurement, or procurement improvement; a statement of the reduction pursued; and the baseline used to estimate effort. In addition, the specification can include key performance indicators, the attribution method followed, and the degree of uncertainty associated with the reduction claimed.

Decarbonization claims can be made in terms of

(i) emissions avoided (not emitted) at the point of trade on products or services with a lower overall content (origin footprint) of carbon dioxide equivalent, water, energy, or other desired metrics;

(ii) curbed procurement (total emissions reduced from stopping buying unnecessary goods or services / total emissions without stopping and based on averaging coupon frequency); or

(iii) efficiency improvement both in origin footprint and delivery distance.

Such claims, combined with supporting statements, constitute the offer; the 9th dimension constrains climate externalities traced back along the material introduction and auction routes in a system economically replacing the original product or service, thus reinforcing the offer and indicative buyers. The baseline can depend on the new product or service, and a retroactive description of the old one can be introduced even after further trade on the new description.

5. Governance, Standards, and Interoperability

Blockchain innovation has become a viable tool for the promotion, audit, and verification of sustainable supply chains. By using a decentralised public ledger, stakeholders can safely share relevant information on provenance, inventories and compliance and retain control of that information. Blockchain has accountability features that support sustainability. The sustainability advantages of blockchain, nevertheless, are very context-dependent. Commercial supply chains lack proper governance frameworks for many projects. Dominant firms are often reluctant to share even aggregated data for fear of disclosing competitive information, causing blockchain designs unsuitable for sustainability. The trade-off between transparency and privacy compounds the issue (Ahlstrand, 2018) and encompasses three other broad criteria (besides environmental protection): social responsibility, stakeholder engagement (Guo et al., 2024), and economic fairness (Zhang et al., 2023). Most supply chain projects on blockchain have focused on compliance. The lack of considering sustainability is hampering decisions about investment, technology and design principles.

People frequently suggest that sustainable stewardship can secure the shared value creation and win-win collaboration in the sharing economy. It may not be possible to use the blockchain system anymore for the development of technology without proper competency in academia and industry. There is a pressing need for multifaceted frameworks and approaches to address complex issues. In addition, integrated sustainable systems require effective governance, standards for data sharing, and interoperability models across multiple blockchains. Extra consideration should also be given to short supply chains, sustainable regimes, decentralised governance, democratic models, combinations with social currencies, and so on.

5.1. Governance Models for Sustainable Blockchains

Governance models of a blockchain solution should promote transparency and traceability; underpin integrity and accuracy; and reduce energy consumption, to support sustainable supply chains. SCM is responsible for innovation, cost reduction and competitive advantage throughout the economy. Although in developing countries a lot of firms do not have an SCM system, current models may not be trustworthy and transparent enough for a firm's green image. These issues can be tackled using blockchain technology. Due to its decentralised and transparent characteristics and tamperproof capability, blockchain enables various parties across a supply chain management (SCM) to securely share data. This avoids asymmetries, counterfeiting, and fraud. Blockchain can enhance efficiency and decisions through the traceability of green information throughout the supply chain SCM, which reduces resource consumption and energy footprint and promotes wider environmental sustainability Guo et al 2024; Zhang et al 2023.

5.2. Standards, Certification, and Data Interoperability

The establishment of analytical and accounting standards, certification and verification schemes, open data formats, and data-interoperability protocols constitutes a necessary foundation for the design of the incentive structure, choice of implementation platform, and all additional governance questions discussed above. Transparency and sustainability are subjective concepts whose interpretation can vary significantly across sectors and application contexts; formal definitions capable of framing and bounding the problem are hence essential for meaningful discussion. Consequently, identification of widely recognised analytical frameworks and responsible-commodity initiatives compatible with blockchain remains a high priority across the green blockchain community.

Numerous internationally recognised standards exist for environmental assessment and reporting of products and organisations, many of which are applicable specifically to supply-chain sustainability. The Greenhouse Gas (GHG) Protocol, ISO 14040/44, PAS 2050, and the Circular Economy Indicators Framework developed by Circle Economy and supported by the European Commission represent key international standards for sustainable-product analytics. The publicly available Good Practices, Audit Protocols and Action Plan of the Sustainability Institute, LEED 2009 for Core and Shell Development, ISO 14001, International EPD®, The Framework for ESG and Sustainability Data & Disclosure of Proton Capital, and BREEAM-NCD are similarly recognised in the commercial real-estate sector. Extensive additional standards for the commodity and service domains also exist (Neisse et al., 2019).

5.3. Privacy, Security, and Compliance Implications

There has been a greater demand for eco-friendly goods. Many organisations focus on sustainable trade but don't have the capacity to demonstrate the origin, processing, and end-of-life of physical products. Hence, "greenwashing" gets bigger. The solutions must ensure that sustainability assessment and compliance information is credible, independent and persistent. The way blockchain transactions are immutable and decentralised helps satisfy this requirement, and in fact drives accountability, which enhances monitoring and governance.

Privacy, security, and compliance issues merit consideration as organisations contemplate the use of blockchain to foster environmentally oriented and transparent commerce. Supply-chain data often resides on systems that protect transparency, curb "greenwashing" abuses, and facilitate verification. In contrast, public blockchains like Bitcoin rely on unrestricted access to transactions that are both wholly visible and queryable. Although similar transparency enhances blockchain's utility for tackling "greenwashing," it raises questions about exposure to competitors and enforcement of operational compliance. Data-exchange models prevent certain confidential information from appearing in the public domain. Transparent permissioned blockchains that permit organisations to share specific information under strict access controls constitute another option. Restricting transaction-access permission by role can further curtail the visibility an organisation has over the overall chain, making only the intersection of all involved participants visible. (Ahlstrand, 2018)

6. Case Studies in Transparent and Green Commerce

China actively advocates and encourages the green promotion of the circular economy and low-carbon development as a national strategy. A key precondition for achieving this objective is the facilitation of green technology innovation. Green supply chain management (GSCM) aims to protect the environment through a myriad of progressive supply chain activities while also providing significant financial gains. Nonetheless, the establishment of GSCMs is seriously impeded by Trust, information asymmetry, obscurity, counterfeiting and. Blockchain is a distributed and transparent information technology that cannot be tampered with. It has been perceived as an effective technical solution to the information-sharing and trust problems of all members in a GSCM. It can efficiently facilitate the establishment of a GSCM. Most of the Chinese enterprise takes the lead in implementing GSCM; many industries rely on whether the current information resources of supply-chain members can be shared safely and credibly, to set up GSCM. To support GSCM, some large commercial companies have embedded blockchain technology into their supply-chain information systems, and a few service platform providers have launched the blockchain-as-a-service (BaaS) to help companies quickly build green supply chains (Guo et al., 2024). Sustainable practices significantly contribute to meeting public concern for information and corporate demand for performance improvement (Ahlstrand, 2018).

6.1. Case Study A: Transparent Supply Chains in Food and Agriculture

Blockchain technology has been proposed several times as a solution for traceability problems in agri-food supply chains (Ahlstrand, 2018). Tracing is feasible as information from various stakeholders during the entire supply chain can be uploaded and stored on the blockchain. The information can include basic supplier and distributor information, shipment dates, transportation conditions, contracts, certificates, trading and delivery progress, food quality sensors, and smart contracts from cryptocurrencies. The framework helps consumers visualise food origins with professional equipment and credentials while lowering transportation costs between urban and rural areas.

Advantages and drawbacks of the implementation of blockchain technology in agricultural supply chain tracing have been reported. A traceability system based on RFID and blockchain, illustrated as a framework for agri-food supply chains, demonstrates the role of blockchain in this field.

6.2. Case Study B: Circular Economy and Recyclables Tracking

The concept of circular economy is promising in terms of resource use and waste; however, the practice is not circular (Kayikci et al, 2022). Achieving circularity is an enormous challenge with complicated geographic logistics like plastic flotilla recycling. Due to the shipment of products worldwide, often across several continents, it is difficult to know and check the status of the circularity compliance. For example, to ascertain a standard's recyclability of a product, and the extent to which the plastics were cellular, chemical or mechanical recycled; the serial number of those physical goods, and the specific actors and actions which performed the actions, as well as the accreditation they have, is essential to build that chain of accountability.

The audit and tracking of plastic flotilla recycling operations or certification of recyclability of circular economy credentials could be done digitally through the application of twin technologies (Jakubowicz & Yarahmadi, 2024). A plastic bottle starts its supply chain as resin pellets. These pellets are then manufactured into a bottle. The consumer who purchases the bottle completes this chain. However, the bottle still has a supply chain process taking place after consumer use. The supply chain includes the collection and waste management of the bottle. The intricate process chain makes tracking and verification or auditing difficult, but the plastic bottle's supply chain can be digitally tracked and built into a blockchain system through Digital Twin technologies, as well as Internet of Things (IoT) technologies. There is a plastic bottle's lifecycle tracking framework from resin to end-of-life, and a recyclability tracking framework that highlights the recyclability of a plastic bottle while helping to track the waste management process of the bottle. These can provide the digital twin model for the product circularity and auditing framework to help with the anti-plastics regulations and basic supply chain regulations for the product circularity.

6.3. Case Study C: Green Procurement in Public Institutions

Public institutions may adopt green procurement policies to direct their purchasing power toward materials and services that meet energy and environmental criteria. France, for instance, launched a "Buy Green" initiative covering energy and biodiversity for public contracts, as part of efforts to transform existing economic development policies into a green economy. Public authorities are also expected to conduct a green procurement assessment. During the certification process of Environmental Management System (ISO14001) at a local government in Korea, green procurement was set as one of the core elements in implementing an effective Environmental Management System. Following the establishment of the Group ISO14000 Road Map, the Group Green Procurement Guidelines were prepared to provide the standards of green procurement at a national level. Public institutions, such as the National Institute of Environmental Sciences, provide green product purchasing guidelines to help public agencies conduct green purchasing activities. Findings also indicate that more than 3000 procurement items were regularly examined to identify greener substitutes, and this information is actively disseminated to a wide audience through the nationwide Green Purchasing Network regarding green procurement as a hot national issue (Ahlstrand, 2018).

7. Challenges and Limitations

Even though adopting blockchain technology for transparent and green commerce has huge benefits, there are many issues and limitations. Foremost amongst these questions are B. scalability, environmental impact, data quality, and stakeholder alignment. Different blockchain designs offer different levels of anonymity and privacy; there are important trade-offs between energy consumption and decentralisation. The supply chains in today's economies are so complex that tracking physical products or their effects is not easy. This is because in many cases, products are located physically hundreds and even thousands of kilometres away from where they are produced or first sold. As a result, compliance with standards... In order to develop buy-in and collaboration across relevant stakeholders from an ecosystem, an initiative that aims to advance transparency and sustainability goals requires it. The capacity to monitor data flows, along with assessing impacts based on records of provenance, processing, and use and final destination, extends the range of tradable attributes that Blockchain can support. This engages actors with sustainability or goals. (Ahlstrand, 2018)

7.1. Scalability, Energy Use, and Green Consensus Mechanisms

Blockchain-based commerce projects face critical challenges in scalability and energy consumption. The frame of reference depends on the intended system architecture and application domain. Scalability is widely discussed in concerns around smart contract platforms supporting decentralised finance (DeFi) and non-fungible tokens (NFTs) on Ethereum; intradomain scalability issues (between transport, processing, storage, and other services within a broad smart contract platform) are often overlooked.

Blockchain-driven applications in sustainable trade have relatively modest scalability requirements (Westphall & Everson Martina, 2022). Focus is on transaction throughput and finality rather than the distributed ledger's total capacity. For many supply chain transactions, a capability capable of processing 3–30 tps with finality within seconds to minutes suffices. Energy trade-offs between Bitcoin, Ethereum, and other platforms differ depending on user assumptions about transaction volume, settlement latency, and system size, etc. Viable approaches exist that can achieve sustainable energy footprints across a range of physical and economic contexts.

7.2. Data Quality, Encoding, and Verification

A substantial part of data quality concerns data provenance, that is, knowledge about where, when, and how the data were collected. Ensuring trustworthy data provenance in a system where numerous stakeholders can contribute data collected in different ways presents a major challenge. Prior studies have dealt separately with data qualification for some specific kinds of data in a defined setting. Measures involving crowdsensing and reputation systems might be good solutions to address data quality issues. The proximity of a crowd, however, still allows the physical aspect of data collection at least to be qualified and consequently, approaching data qualification through a consortium and specifying solely data accuracy and integrity is the natural, the simplest, and the recommended solution.

There are various codes, such as the W3C Verifiable Credentials Data Model, which is an open standard, as well as the W3C Data Cube Vocabulary. There are specifications to encode footprint data that comply with the technical standard ISO 14067. Special attention should be paid to universal standards that cover all footprints that need to be reported, that enable the information to be machine-readable, and that allow the possibility of adding new footprints (hence wider environmental disclosures) as the organisation that documents the information moves along its sustainability journey.

Even with trustworthy data provenance and appropriate encoding, data still require verification before being considered credible for governance within a DLT. The information can be verified against multiple tracks within the traceability or tracking system; even in the absence of proper provenance, redundancy, and consensus among the data collected in 10–20 % of the life cycle stages by the stakeholders having corresponding involvement, it can also provide the level of assurance necessary to consider the information acceptably valid. (Ahmed et al., 2021)

7.3. Adoption Barriers and Stakeholder Alignment

Many organisations intending to adopt DLT-based solutions for sustainable supply chains encounter considerable challenges. The foremost barriers include a lack of compatibility between existing digital and procurement systems and blockchain-based traceability platforms, the absence of relevant standards that would enable effective interoperable exchanges of traceability data and the educational effort necessary to raise awareness of the technology's functions and benefits throughout the supply chain (Kromes et al., 2024). Such issues are commonly described as a technology push (the supply of innovation-driven applications) and an organisational pull (the need for traceability) that do not match.

In the absence of solutions to these interoperability and awareness hurdles, organisations are likely to remain reluctant to initiate stepwise adoption of applicable DLT-based methods and tools in the procurement eco-system (Guo et al., 2024). Progress could be consolidated through the establishment of cross-organisational collaborative forums to raise awareness and allow the public dissemination of insights gained from pilots of different solutions in conjunction with complementary technologies. The forums could also enable the analysis of potential opportunities for interoperability across the various standards for which different suppliers are advocating, thereby alleviating the burden of duplicate work associated with frameworks requiring the implementation of more than one standard.

8. Policy Implications and Roadmaps for Implementation

According to Government and Industry Stakeholders, new technologies will help boost the sustainability of commercial activities in an increasing number of sectors. The progression of blockchain is already enough for legislators to discuss its regulation. The OECD has proposed four classes of blockchain policy. These are related to security and privacy, guaranteeing a level playing field in the provision of services, facilitating public trust, and enabling innovation, experimentation and responsible use. The strategies of measuring positive impact and guidance for pilot experimentation are the additional policy components that need to be looked into further (Ahlstrand, 2018). A variety of standards to promote transparency and sustainability in supply chains is also emerging. One case in point is the effort by the Global Reporting Initiative (GRI), the Sustainable Accounting Standards Board (SASB), the International Organisation for Standardisation (ISO), and the World Economic Forum (WEF) to bring together existing inter-governmental, national and industry framework standards under the Universal Framework for ESG Reporting. As will be shown in this section, the extent of demand for genuine progress in supply chain sustainability already exceeds the capacity of the existing measures and pilot actions informed by new guidance can still pay off now.

8.1. Policy Instruments to Incentivise Transparency and Sustainability

The introduction of additional tax deductions or exemptions for technologies that facilitate fungible, verifiable, and traceable environmental transparency in marketplaces can benefit both the long-term human race and planet Earth. Such technologies include blockchain systems that meet cryptocurrency laws, fungible tokens that are legally and morally linked to certificates, marketplaces where token prices are primarily set by supply and demand, and exchanges that allow electrons and certificates of origin to be linked and unlinked freely. Blockchain applications record certificates of origin to ensure that environmental interchange does not become an isolated process, legally and morally separate from actual environmental practices. Transparent and visible approximations based on the economic theory of trading across fungible environmental transparency, total price, observable supply, and other elements can be traded in any open market, even those on the darker side of economic transparency. Negative feedback within such systems guarantees sustainability for the long-term human race and signals to market participants to preserve worthy environmental assets for the long-term common benefit of humanity. Blockchain also allows big players to focus on real and critical sustainable actions that contribute to global sustainability while signalling the long-term economic concerns of the environmental parameters. Long-chain tracking of fungible and yet traceable total-carbon production systems is also applicable to these kinds of technologies (Ahlstrand, 2018; Guo et al., 2024).

8.2. Roadmaps for Institutional and Industrial Adoption

Transparency and sustainability-based business models, enabled by blockchain technology, can be implemented by public institutions and private enterprises through a series of clear and rigorous steps. The roadmap organises steps into two distinct phases: an initial phase emphasises the basic prerequisites for exploring transparent and green commerce practices; subsequent steps build on those prerequisites to establish and scale blockchain-based transparent and green commerce.

The first phase consists of three steps.

1) Institutions and enterprises should map their core objectives and the economic, environmental, and social benefits of establishing a blockchain-based, transparent and green commerce initiative.

2) A stakeholder mapping exercise can identify key internal and external stakeholders (e.g., senior executives, policy makers, public opinion leaders) and their interests, motivations, and goals regarding the initiative to understand stakeholder alignment and misalignment.

3) Based on the preliminary stakeholder mapping exercise, institutions and enterprises should conduct a more detailed assessment of stakeholders to identify their relative importance, the degree of alignment with the transparent and green commerce initiative, and the decision rights and interests of each stakeholder in adopting blockchain technology.

The second phase encompasses four steps.

1) Institutions and enterprises should develop a joint, inclusive governance mechanism with key stakeholders to coordinate joint action and steering of the initiative, while still preserving independent decision-making authority over choices regarding the internal blockchain, platform, governance, and technology standards.

2) Consultation with a broader group of internal and external stakeholders on both the governance structure and the design of the transparent and green commerce initiative can clarify stakeholder priorities and facilitate system adoption. Clear articulation of the initiative’s ambition, objectives, governance, scope, and technology choices can further foster widespread alignment.

3) A pilot project of varying scale can clarify detailed objectives, gather data

related to the initiative, assess potential impacts, and validate technology choices.

4) The complete initiative should be launched, potentially alongside additional pilot projects, development of public monitoring dashboards, or wider external consultation on the implementation plan (Ahlstrand, 2018; Guo et al., 2024).

9. Conclusion

Blockchain, or distributed ledger technology, has the capacity to increase operational management and reduce the consumption of natural resources and thus promote transparency and sustainability in commerce. The application of particular solution areas in business domains, which are compliant with the transparency requirements and based on commercially viable technology, facilitates the assessment of involvement and impact. The described examples also help define the roles, responsibilities, and interventions needed for scaling. Three of these cases pinpoint significant efficiency boosts throughout the supply chain, creation of a circular economy via energised material loops and the designation of transparent and green criteria for public procurement. By creating benchmarks for credibility and strength on commercial activity, organisations can signal the scale and longevity of their decarbonisation efforts. Future research will look towards emerging data and technical specifications to bootstrap a consultation on appropriate metrics. These are essential guidelines for building a scalable architecture to enable interoperability in specific domains or verticals.

Over the last five decades, sustained economic development has enhanced material intensity by four times. Due to this, depletion of non-renewables is happening faster than nature can produce them. Moreover, in most large economies, there is a use of material that is one ton or more per person annually. In the long run, these materials persist in urban areas. Global supply chains lack sufficient transparency for questioning, not being set up, or enhancing compliance across distributed processes and equipment. For such verification of compliance, information on transactions, materials, energy, packaging and transport and their consequent impact and conditions of supply at all nodes of networks is important. In order to measure the footprints of GHGs, energy, water and circularity effectively, data collection needs to be comprehensive across a web of processes and nodes. The reliable foundation for firms to share private information about transactions and attributes, and thus approaches for trust establishment, is what such data is contingent on. DLT with an appropriate consensus mechanism offers one such trust model capable of supporting operational arrangements needed in sustainable trade, as they are designed for non-collaborative environments or transaction verification. (Ahlstrand, 2018).

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