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Blockchain for Supply Chain: Technology and Revolution for Education and MSME Businesses

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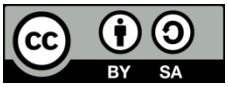
ABSTRACT

The supply chain of Indonesian MSMEs (Micro, Small, and Medium Enterprises) faces classic problems such as lack of transparency, weak audit trails, and difficulty in accessing financing. At the same time, the education sector is not yet ready to produce human resources who are competent in modern logistics technology such as blockchain. This study uses a qualitative approach with a library research method. The data analysis technique used is qualitative content analysis with a thematic approach. The results of the study show that: 1). The Foundation of Blockchain Technology and Its Application Model in Modern Supply Chain Systems is that blockchain, as a secure and immutable distributed ledger, provides a foundation of trust and transparency for modern supply chains. With the integration of IoT and Smart Contracts, this technology enables real-time asset tracking and process automation, reducing inefficiencies and manual errors. 2). The Transparency and Sustainability Revolution: The Impact of Blockchain on Operational Efficiency and Trust in the MSME Supply Chain is that for MSMEs, blockchain becomes an empowerment tool by creating verifiable product records, increasing consumer trust, and opening access to premium markets. 3). Blockchain Integration in Education Curricula: Preparing Competent Human Resources for the Logistics 4.0 Era is that to support technology adoption, education must adapt. Curricula need to integrate logistics knowledge, blockchain technology, and entrepreneurship. Project-based learning methods and practical simulations, supported by collaboration with industry. 4). Business Models and Adoption Strategies: Roadmap for Blockchain Implementation for MSMEs in the National Supply Chain Ecosystem is that blockchain implementation for MSMEs requires a collaborative approach through sectoral consortia to share costs and resources.



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1. Introduction

The global business world is currently in the midst of an unprecedented digital transformation, driven by the convergence of technologies that are the pillars of the Fourth Industrial Revolution. At the heart of this transformation, the concept of the supply chain has evolved from a simple linear sequence of logistics processes into a complex, dynamic network ecosystem that is highly dependent on fast and accurate data exchange. However, behind the visible progress, the global supply chain still harbors a deep paradox: the more technologically connected it is, the more vulnerable it is to inefficiencies, mistrust, and opacity. Systems that still rely heavily on centralized databases and paper documents create information silos, slow down processes, and open the door to errors, fraud, and non-compliance with sustainability standards. This data fragmentation not only hinders real-time visibility but also erodes the foundation of trust among stakeholders, from raw material producers to end consumers (Queiroz et al., 2021). This is where blockchain technology emerges as a new paradigm, not just as additional software, but as an architectural foundation that promises a fundamental reconstruction of how we record, share, and trust transactions and asset movements across a vast network.

At its core, blockchain is a distributed ledger that offers decentralization, controlled transparency, immutability, and cryptographic security. These unique characteristics theoretically provide a direct solution to many chronic problems in supply chain management. This technology enables the creation of a single, indisputable shared record for every event in a product's life cycle, from the origin of raw materials, manufacturing processes, and logistics, to delivery to consumers. Thus, blockchain has the potential to become the backbone for creating a truly transparent, traceable, and efficient supply chain. Its integration with supporting technologies such as the Internet of Things (IoT) for automatic data collection and Smart Contracts for independent transaction execution further strengthens its value proposition. Smart Contracts, as programs that run independently based on "if-then" logic, can automate payments, document release, and other obligations, thereby eliminating bureaucratic delays and reducing the risk of disputes (Wang et al., 2020).

While the potential of this technology for corporate giants such as Walmart or Maersk has been well documented, its most revolutionary impact may be felt by the economic pillars that are often most affected by supply chain inefficiencies: Micro, Small, and Medium Enterprises (MSMEs). In many developing countries such as Indonesia, MSMEs are the backbone of the economy, but they are often trapped in opaque local supply chains and face significant barriers to scaling up. Their main challenges include difficulty proving product quality and authenticity to attract premium markets, inefficiencies in administration and logistics that erode already thin profit margins, and most critically, limited access to formal financing due to a lack of verifiable credit history and bank-acceptable collateral (Kshetri, 2021). Blockchain offers a democratic solution to these structural problems. By providing a platform to prove provenance and sustainability practices, blockchain empowers MSMEs to build brands, trust, and added value. Smart Contracts can simplify payment processes and reduce working capital requirements. More transformatively, reliable and verified transaction data on the blockchain can become a valuable "digital footprint," opening the

door to inclusive supply chain finance models, such as real-data-based invoice financing, which were previously difficult to access.

However, the path to widespread and meaningful blockchain adoption, especially among SMEs, is fraught with complex and interrelated obstacles. These obstacles are no longer predominantly technical in nature, but have shifted to the realms of human resources, business models, and policy. The first major obstacle is a wide skills gap. The digital supply chain revolution requires talent that not only understands traditional logistics but is also digitally literate, capable of understanding the principles of blockchain, IoT, data analytics, and cybersecurity. Unfortunately, higher education and vocational systems in many countries, including Indonesia, are still lagging behind in responding to these rapidly changing curriculum needs. Graduates often leave without a practical understanding of the technologies that are reshaping the industries in which they will work, creating a serious mismatch between labor supply and industry demand (Frank et al., 2020).

The second obstacle is the lack of clear and affordable business models and adoption strategies for SMEs. Blockchain is not an effective technology if adopted by a single entity; its true value lies in networks and collaboration. For MSMEs with limited resources, developing or even subscribing to individual blockchain solutions is an unrealistic burden. Innovative collaborative business models are needed, such as sector-based or geographically-based consortia, where costs and benefits can be shared. In addition, a realistic, phased adoption roadmap is needed, starting with simple applications such as product tracking before moving on to more complex automation and financing. Without a clear model and roadmap, blockchain will remain an elitist technology that fails to achieve inclusive economic and social impact (Cole et al., 2022).

The third obstacle is an immature regulatory and policy environment. The legal validity of smart contracts, personal data protection in distributed systems, tax treatment for digital asset transactions, and national interoperability standards are gray areas that require clarity. This regulatory uncertainty creates risks that discourage investment from the private sector and participation from formal financial institutions. The government plays a crucial role not only as a regulator but more importantly as an enabler and catalyst. Visionary leadership is needed to develop a national roadmap, create a regulatory sandbox for innovation, and provide appropriate incentives to encourage collaboration between the business world, academia, and the technology community (Wamba & Queiroz, 2022).

The MSME supply chain and education sector in Indonesia face interrelated challenges in the digital era. On the one hand, the MSME supply chain is still characterized by a lack of transparency, mistrust between partners, weak audit trails, and difficulty in accessing financing. Meanwhile, the education sector lags behind in preparing curricula and teaching staff capable of producing human resources with specific competencies in the field of advanced logistics technology such as blockchain. There is a gap between rapid technological advances and the adoption and readiness of human resources in the field. This study departs from the main problem: how can blockchain technology be effectively adopted

to revolutionize the MSME supply chain, and at the same time, how must the education ecosystem adapt to support this revolution?

This research is urgent for two main reasons. First, the competitiveness of national MSMEs in the global market increasingly depends on the ability to prove the authenticity, quality, and sustainability of products, which can be guaranteed by blockchain. Without adopting this technology, MSMEs risk being left behind. Second, disruption in the logistics sector demands rapid transformation in the education sector. If the integration of Supply Chain 4.0 technology knowledge into the curriculum is not addressed immediately, Indonesia will experience a severe talent deficit, hampering national productivity and innovation. Therefore, research that bridges the aspects of technology, MSME business, and education is crucial for developing a holistic and timely strategy.

The main objective of this research is to comprehensively analyze the potential, strategies, and implementation framework of blockchain technology in the context of the Indonesian supply chain, with a dual focus on empowering MSMEs and transforming education. Specifically, this research aims to: (1) Examine the foundations of blockchain technology and its most relevant application models for modern supply chains; (2) Analyze the revolutionary impact of blockchain on transparency, operational efficiency, and financial access for MSMEs; (3) Formulate a model for integrating blockchain concepts into vocational and higher education curricula to prepare competent human resources; and (4) Develop a feasible roadmap and collaborative business model for blockchain adoption by MSMEs in the national ecosystem.

2. Methods

This study uses a qualitative approach with a library research method. This method was chosen based on the exploratory and descriptive objectives of the study to build a comprehensive, in-depth, and holistic understanding of the convergence of Blockchain technology in the supply chain, education, and MSME ecosystems. Library research is considered the most appropriate because the object of study is a rapidly developing technology with multidisciplinary implementation, requiring synthesis from various literature sources to identify the underlying patterns, principles, and conceptual frameworks. This research does not involve the collection of primary data in the field, but focuses on tracing, reviewing, and critically analyzing secondary data in the form of published scientific papers. Thus, this study aims to construct a systematic body of knowledge, analyze the latest developments, and formulate theoretical and practical implications based on findings that already exist in the literature (Sugiyono, 2022).

The data sources used in this study are limited to published and reliable scientific text documents, with the main publication period between 2020 and 2025 to ensure the freshness and relevance of the findings to the context of highly dynamic technological and business developments. The primary data sources for this study consist of three categories. First, textbooks and scientific monographs, both international and national, that specifically discuss Blockchain, digital supply chain transformation, the digital MSME economy, and

technological education curriculum innovation. Books were chosen as a fundamental source because they provide in-depth, structured, and conceptual discussions. Second, scientific journal articles indexed in reputable databases such as Scopus, Web of Science, ScienceDirect, and Sinta-accredited national journals. Journal articles were selected to obtain empirical research findings, the latest models, and specific and up-to-date academic discussions. Third, research reports and policy papers from renowned research institutions (such as the World Economic Forum, McKinsey Global Institute), government agencies (e.g., Bappenas, Kemenperin), and relevant industry associations. These reports provide secondary data, policy analysis, and practical case studies that enrich the analysis (Creswell & Poth, 2023).

The data collection technique applied is a systematic documentation technique. This process begins with search strategy planning using main keywords and their combinations in Indonesian and English, such as "blockchain supply chain small business," "blockchain curriculum logistics education," "MSME adoption of blockchain," "smart contract sustainability traceability," and "digital transformation of MSMEs." The search was conducted electronically through academic search engines (Google Scholar), digital library portals, and the aforementioned journal databases. Each document obtained was then selected through inclusion-exclusion criteria, such as topic relevance, year of publication, publisher credibility, and citation level. Documents that passed the selection were then documented by creating data cards or using reference management software (such as Mendeley or Zotero) to record important metadata such as title, author, year, abstract, and keywords. Recording of potential citations relevant to the research focus was also carried out at this stage to facilitate further analysis (Azwar, 2021).

The data analysis technique used is qualitative content analysis with a thematic approach. Textual data from various sources are not analyzed statistically, but rather through a process of interpretation to identify, organize, and formulate core themes that answer the research questions. The analysis process follows an interactive model consisting of three concurrent activities: data reduction, data presentation, and conclusion drawing/verification. First, data reduction is carried out by closely reading all selected documents, then coding the parts of the text that are relevant to the four sub-topics of the research. These initial codes are then grouped based on similarities in meaning ( ) to form broader categories. Second, data presentation is carried out by arranging these categories into a matrix or thematic chart to see the relationships and patterns between categories, thereby presenting a complete and structured picture. Third, conclusions were drawn by interpreting the identified patterns, relating them to the existing theoretical framework, and then formulating a synthesis of new knowledge, recommendations, and conceptual models proposed in this study (Creswell & Poth, 2023).

Data Validity Testing Techniques in this qualitative literature study prioritize credibility and dependability, which are tested without involving informants, but rather through procedures for examining sources and analysis processes. For credibility (internal validity), data source triangulation techniques are used. This means that findings or statements regarding one aspect (for example, the benefits of blockchain for MSME financing) must be concluded

based on confirmation from more than one type of data source, such as textbooks, empirical journal articles, and central bank reports. This is done to ensure that the conclusions drawn do not come from only one perspective or one type of literature, so that the research results are richer and more reliable. Furthermore, for dependability (reliability), this study applies a strict audit trail. The entire research process, from search keywords, document selection criteria, data cards, coding notes, to analysis drafts, is documented neatly and systematically. This process documentation allows other researchers to track and re-examine the course of the research, so that the level of dependence of the research results can be tested. In addition, a discursive peer review was also conducted by discussing the initial findings and interpretations with peers or supervisors who have expertise in related fields to obtain input and corrections before compiling the final report (Sugiyono, 2022).

3. Result and Discussion

A. The Technological Foundation of Blockchain and Its Application Model in Modern Supply Chain Systems

Blockchain, in essence, is a distributed ledger that records transactions or data points in blocks that are linked and secured using cryptography. Its main characteristics of decentralization, controlled transparency, immutability, and consensus make it an ideal solution to overcome fundamental problems in modern supply chains: lack of trust, weak audit trails, and inefficiencies due to isolated information systems (Tapo & Sari, 2023). In the context of supply chains, Blockchain functions as a neutral layer of trust, where every exchange of physical assets (raw materials, components, finished products) is represented by digital assets (digital twins) whose movements can be tracked by all authorized parties in the network.

Its application does not stand alone, but is integrated with supporting technologies. The Internet of Things (IoT) acts as the "nerve center" that connects the physical world to the digital world. RFID sensors, GPS, and scanners collect real-time data on location, temperature, humidity, or the condition of goods. This data is then automatically and immutably recorded in the Blockchain, ensuring its authenticity. Smart Contracts are the engine of automation. They are program codes that are executed automatically when agreed-upon conditions are met, such as automatic payment once goods arrive at the warehouse and are verified by sensors, eliminating the need for manual administrative processes and reducing the risk of delays (Kshetri, 2022).

There are several architectural models that can be adopted. Public blockchains (e.g., Ethereum) offer full decentralization but have limitations in terms of scalability and business data privacy. Conversely, private or permissioned blockchains (e.g., Hyperledger Fabric) are more commonly implemented in corporate and consortium contexts. In this model, participation in reading or writing data is controlled by one or a group of organizations, maintaining competitive secrecy while still providing transparency among selected partners. Hybrid models are also developing, where sensitive data is stored privately, while its hash or cryptographic proof is uploaded to a public blockchain for external verification (Kumar

et al., 2021). The choice of model depends heavily on collaboration needs, regulations, and the complexity of the supply chain.

Real-world implementations can already be seen on a global scale. Companies such as Walmart are working with IBM Food Trust to track the origin of food products from farmers to supermarket shelves in seconds, rather than days. Maersk, through its TradeLens platform (although currently in transition), has demonstrated how customs documentation and container tracking can be automated, significantly reducing costs and transit times. These pioneering cases show that the technological foundation is mature and ready to be adapted to a broader scale, including for the SME context.

Blockchain, in essence, is a paradigmatic breakthrough in how information and value are recorded and transferred. This technology functions as a distributed ledger that is not managed by a single authority, but rather by a peer-to-peer network. Each "block" in the chain contains a number of transactions or data records that are validated by the consensus of network participants, then cryptographically encrypted and linked chronologically and inseparably to the previous block. These key characteristics decentralization, transparency, immutability, and consensus make it an ideal solution for the chronic problems of traditional centralized and fragmented supply chain systems. The global supply chain, with its many players from manufacturers to logistics to retailers, often operates in information silos. Each party maintains its own records, resulting in a lack of overall visibility, vulnerability to errors, fraud, and high-cost inefficiencies for reconciliation processes. Blockchain provides a neutral and single layer of digital trust, where all authorized parties can access and verify the same version of the truth regarding the movement of an asset (Saberi et al., 2019).

The application of blockchain in the supply chain is not simply a matter of replacing old databases with new ones. It involves a fundamental transformation in which physical assets such as a sack of coffee, a container of electronics, or a bottle of medicine have a "digital self" or digital twin that lives and moves in tandem with its physical counterpart in the real world. However, to bridge this physical and digital world, blockchain requires a supporting technology partner. This is where the Internet of Things (IoT) plays a central role as a sensory nervous system. Devices such as RFID temperature and humidity sensors, GPS, and smart tags are attached to products or packaging, continuously collecting real-time data on conditions and location. The data collected by these sensors, for example, confirmation that a sack of coffee beans has arrived at the port at a certain temperature, is then automatically recorded as a transaction on the blockchain. This process creates an objective and indisputable audit trail, eliminating reliance on manual data entry that is prone to errors and fraud (Kouhizadeh et al., 2021).

While IoT provides the "eyes and ears," Smart Contracts act as the "muscles and autonomic nervous system" that drive transaction execution. A smart contract is a computer program stored within the blockchain that automatically executes predefined commands when certain conditions are met. In the context of supply chains, this revolutionizes business processes that have traditionally relied on paper and manual intervention. For example, a smart contract can be programmed to automatically release payment to suppliers as soon as IoT sensors in

the recipient's warehouse detect and verify the arrival of goods, and the inventory system records the corresponding quantity. A process that previously took weeks for invoice payments can now be completed in minutes, dramatically improving liquidity and reducing administrative friction and dispute risk (Wang et al., 2022).

When choosing a blockchain architecture for the supply chain, there is no one-size-fits-all approach. Public blockchains such as Ethereum or Algorand offer the highest level of decentralization and security because they are open to anyone, but they often face challenges in scalability, energy consumption (for Proof-of-Work models), and most crucially, data privacy. Exposing price, volume, and trading partner data to the public is unacceptable in competitive businesses. Therefore, for corporate contexts and multi-organization collaborations, Permissioned (or Private) Blockchains such as Hyperledger Fabric or R3 Corda are the more dominant choice. In this model, participation in reading, writing, or validating transactions is controlled by a consortium or managing authority. This architecture allows for the necessary transparency among selected trading partners while maintaining the confidentiality of sensitive data from competitors and the public. Hybrid models have also emerged, where the core business data is run on a permissioned blockchain, but the hash (digital fingerprint) of important transactions is published to a public blockchain, creating an indisputable external notary for auditing and legal compliance purposes (Hastig & Sodhi, 2020).

Technical challenges to implementation remain significant. Interoperability is one of the biggest obstacles. The real-world supply chain involves many different platforms and systems. A chain involving farmers using Platform A, transport companies using Platform B, and retailers using Platform C will face deadlock if these platforms cannot communicate and share data smoothly. Efforts to standardize data and develop protocol bridges are being promoted, but they are not yet mature. In addition, the challenges of scalability and transaction costs (gas fees) are still relevant, especially for public blockchains. Processing thousands of IoT sensor transactions per second can be a heavy technical and financial burden (Cole et al., 2019).

Despite these challenges, there is growing evidence of the successful implementation of this technology. IBM Food Trust, built on Hyperledger Fabric, is the most well-known example. This platform enables the food chain from producer to consumer to be tracked in seconds. When an E. coli contamination outbreak occurred in romaine lettuce, Walmart, which uses Food Trust, was able to trace the source of the product to a specific farm in 2.2 seconds, compared to the traditional process that took weeks. Another example is TradeLens, initiated by Maersk and IBM, which aims to digitize and automate global logistics workflows, although it is currently in a transitional phase. This platform demonstrates how customs documents, container status, and waybills can be managed collaboratively, reducing delays and significant administrative costs (Kshetrri, 2022).

A deeper impact of blockchain adoption is its potential to drive the circular economy and sustainability. With its indisputable tracking capabilities, companies can verify claims about recycled materials, renewable energy, or ethical farming practices. End consumers can scan

QR codes on products and view their entire journey history, promoting transparency that builds trust and enables more responsible consumption choices. Thus, blockchain not only improves operational efficiency but also enables more sustainable and value-based business models (Kouhizadeh & Sarkis, 2021).

Thus, the foundation of blockchain technology combined with IoT and smart contracts has created a solid foundation for revolutionizing supply chain management. The permissioned architecture model of has addressed the privacy needs of the business world, while global case studies have proven its real value in increasing speed, trust, and resilience. Although technical barriers such as interoperability still need to be overcome, the technological roadmap is clear. The success of future implementations no longer depends solely on technological maturity, but on the collaborative willingness of organizations to adopt common standards, invest in process changes, and build an open yet trusted digital ecosystem. This transition marks a new era in which the supply chain is transforming from a series of hidden transactions into a transparent, automated, and accountable value network.

B. The Transparency and Sustainability Revolution: The Impact of Blockchain on Operational Efficiency and Trust in the MSME Supply Chain

For Micro, Small, and Medium Enterprises (MSMEs), integration into global or national supply chains is often hampered by structural challenges: inability to prove credibility, difficulty accessing financing, and logistical inefficiencies that erode profit margins. This is where Blockchain offers a democratic revolution. By creating an unforgeable record of each stage of added value, Blockchain empowers MSMEs to prove the quality, authenticity, and sustainability practices of their products (Wijaya, 2022).

The first and most immediate impact is on traceability and authenticity assurance. An SME producing organic Arabica coffee from Toraja, for example, can record every stage from harvesting, drying, packaging, to shipping in Blockchain. Each coffee package is equipped with a QR code that can be scanned by end consumers. The scan results will show the complete journey of the product, validated organic certification, and even the farmer's profile. This not only prevents counterfeiting, but also builds a strong brand narrative, increases consumer trust, and opens access to premium markets that care about origin and ethical sourcing. This transparency also serves as a powerful verification tool for sustainability claims, such as the use of environmentally friendly materials or fair trade practices (Tapscott & Tapscott, 2020).

The second impact is increased operational efficiency. Manual administrative processes, such as issuing invoices, waybills, and customs documents, are prone to errors and delays. Smart Contracts can automate these workflows. The receipt of goods at the distributor's warehouse, confirmed by IoT scanning, can immediately trigger partial payments to MSMEs as suppliers, increasing business liquidity. This automation drastically cuts transaction costs and order cycle times.

The third, transformative impact is access to financing. One of the biggest obstacles for MSMEs is the lack of collateral and documented credit history to apply for loans. Blockchain changes this paradigm by creating asset tokenization in the supply chain. Proof of ownership

of in-transit inventory or receivables from credible buyers can be represented as digital assets that can be used as collateral. Financial institutions can access, with permission, transparent and verified MSME transaction history data on the blockchain. This reduces information asymmetry and risk for banks, opening the door to more affordable and inclusive supply chain finance products for MSMEs (Prasetyo & Hidayat, 2021). Ultimately, this revolution is not only about efficiency, but also about equalizing economic opportunities.

Amidst the tide of globalization and increasingly critical consumer demands, Micro, Small, and Medium Enterprises (MSMEs) often face a huge wall that hinders their full integration into competitive modern supply chains. This wall is built from three main bricks: the inability to prove credibility and quality, operational inefficiencies that erode thin margins, and chronic difficulties in accessing formal financing. Traditional supply chains tend to favor large players with integrated systems and strong capital, while MSMEs are trapped in a cycle of mistrust and uncertainty. The advent of blockchain technology, however, offers not just a patchwork solution, but a democratic revolution capable of tearing down these walls with its powerful weapons: unalterable transparency and reliable automation. This revolution transforms MSMEs from passive suppliers into equal partners with strong digital evidence, paving the way to broader markets, leaner operations, and previously closed access to capital (Bai & Sarkis, 2020).

The most immediate and visible impact of blockchain on MSMEs lies in the areas of provenance tracking and authenticity assurance. In traditional supply chains, claims of "organic," "local," or "handmade" by an MSME are merely claims on a label, vulnerable to falsification and difficult to verify. Blockchain fundamentally changes this narrative. Every stage of value addition, from planting raw materials, small workshop production processes, packaging, to delivery to distributors, can be recorded as time-stamped and immutable transactions in a distributed ledger. A silver craft product from Kota Gede, for example, can be equipped with a unique QR Code. When scanned by consumers, the code reveals a complete digital story: who the craftsman is, when the work was completed, where the silver ore came from, and even photos of the manufacturing process. This complete transparency is a powerful weapon against product counterfeiting, which often harms high-quality MSMEs. More than that, it builds emotional trust with consumers who are increasingly concerned about ethics and sustainability. A buyer in Europe can ensure that their weaving truly originates from a weaving group in Sumba and is paid a fair price, making them willing to pay a premium. Thus, blockchain transmutes the "story" of SME businesses from mere marketing into auditable factual evidence, which directly increases brand value and competitiveness (Kumar et al., 2020).

Behind the scenes, blockchain revolutionizes operational efficiency through smart contract mechanisms. For SMEs, administration is a hidden burden that consumes valuable time and resources. Processes such as issuing invoices, sending waybills, confirming receipts, and billing payments involve a lot of manual communication, paper documents, and delays. Smart contracts automate these rigid business workflows with "if-then" logic that is executed independently. For example, when an IoT sensor in a partner's logistics truck confirms that the goods have arrived at the destination warehouse and the weight/quantity data matches

the order, the smart contract can automatically: 1) update the order status in all parties' systems, 2) generate a digital invoice, and 3) initiate a progress payment from the buyer to the SME's account. This automation reduces the order-to-cash cycle time from weeks to hours or minutes, significantly improving business liquidity, which is the lifeblood of SMEs. Additionally, by reducing reliance on human intervention, the risk of errors, disputes, and even corruption in the logistics process can be minimized, creating a more predictable and fair business environment (Pournader et al., 2020).

However, the most transformative impact offered by blockchain may lie in the realm of inclusive financial access. The "collateral paradox" has long shackled MSMEs: they need credit to grow, but cannot obtain credit because they are considered to lack collateral or a track record that can be verified by financial institutions. Blockchain solves this paradox by creating trustworthy digital collateral. Through the concept of supply chain asset tokenization, proof of ownership of in-transit inventory, receivables from corporate buyers with a good reputation, or even future contracted harvests, can be represented as unique and non-duplicable digital tokens on the blockchain. These tokens become digital representations of physical assets whose value can be tracked and verified. An SME furniture manufacturer with orders and digital waybills from a well-known hotel can use tokens representing these receivables as collateral to apply for working capital loans. Banks, with access to permissioned blockchain networks, can verify the authenticity of orders, buyer reputation (hotels), and fulfillment status in real-time, thereby greatly reducing information asymmetry and credit risk. This mechanism opens the door to broader and fairer Supply Chain Finance (SCF) products, such as factoring and invoice financing, which have been difficult for MSMEs to access due to high due diligence costs for banks (Gurtu & Johny, 2021).

This transparency revolution also has profound implications for sustainability practices, which are increasingly demanded by the global market. Blockchain enables rigorous verification of environmental and social claims. An SME in the fashion sector can accurately track the use of organic cotton, record the carbon footprint at each stage of transportation, and prove the implementation of decent work standards in its production units. This data, which is stored permanently and transparently, enables cheaper, faster, and more tamper-proof sustainability certification (such as Fair Trade, Global Organic Textile Standard). Consumers and B2B buyers can make purchasing decisions that have a truly positive impact, while SMEs can communicate their sustainability commitments not as greenwashing, but as measurable accountability. This creates strong competitive differentiation in an increasingly environmentally conscious market (Kouhizadeh et al., 2021).

However, the path to full adoption is not without obstacles. Digital literacy, initial implementation costs (although these can be reduced through consortium models), and reluctance to share operational data remain psychological and technical barriers. Nevertheless, the value proposition offered by blockchain, particularly in building trust the most valuable currency in business is far greater. Blockchain does not merely make SMEs more efficient; this technology fundamentally redefines their bargaining power within the supply chain ecosystem. From entities whose trustworthiness is "verified," SMEs transform into entities that "provide proof of trust." This paradigm shift empowers them to not only

survive but also thrive and compete on a larger stage, while contributing to the development of a more transparent, resilient, and sustainable global supply chain.

C. Blockchain Integration in Education Curriculum: Preparing Competent Human Resources for the Logistics 4.0 Era

Massive adoption of technology will be futile without competent human resources to design, implement, manage, and utilize it. Currently, there is a wide skills gap between the increasingly technocratic needs of the logistics 4.0 industry and the competencies of vocational and higher education graduates. To bridge this gap, the integration of Blockchain literacy into the education curriculum is a strategic necessity. The integration approach should not be limited to the technical aspects of programming alone. A comprehensive curriculum must be multidisciplinary and applicable. At the higher education level (Strata-1 and vocational), special courses or concentrations need to be developed that combine three pillars of knowledge: (1) Core Logistics & Supply Chain Knowledge: operations management, global logistics, and warehouse management; (2) Digital Technology Knowledge: the basics of Blockchain, IoT, Data Analytics, and Cyber Security; and (3) Business & Entrepreneurship Knowledge: digital business models, innovation management, and business feasibility analysis (Sutarman & Aini, 2024).

The learning method must shift from classic lectures to experiential learning. Project-based learning (PjBL) is the most effective method. Students can be given real case studies, such as designing a simple Blockchain solution to track the supply chain of local products (e.g., honey or handicrafts). They will go through the process from business process analysis, selection of technology architecture models, design of simple Smart Contract workflows, to presentation of their business models. Simulations using Blockchain sandbox platforms (such as Hyperledger Fabric Composer or Ethereum educational tools) will provide hands-on experience without financial risk.

Collaboration with industry and professional associations is key to success. Internships at companies that have adopted this technology, guest lectures by practitioners, and joint curriculum development (curriculum co-creation) will ensure that the learning materials are relevant to the needs of the job market. Industry-recognized micro-credentials can also be developed to accelerate graduate absorption. Education should not stop at university; continuous training and certification programs for working professionals are also needed for upskilling and reskilling (Daniel & Allas, 2021). Thus, the education ecosystem is transforming into a talent producer ready to become architects and drivers of the digital supply chain revolution in Indonesia.

The Industrial Revolution 4.0, with digitalization and automation as its main drivers, has transformed the face of the global logistics and supply chain sector into a complex, connected, and data-driven ecosystem known as Logistics 4.0. In this ecosystem, technologies such as the Internet of Things (IoT), artificial intelligence (AI), and especially blockchain, are no longer just tools, but the backbone of operations that determine efficiency, security, and sustainability. However, the exponential pace of technological advancement has created a deep and widening gap between the industry's thirst for digital talent and the

competencies of graduates from vocational and higher education institutions. This gap, known as the skills gap, poses a serious threat to national competitiveness. If the education sector does not adapt and evolve immediately, then large investments in national supply chain technology infrastructure will only result in a series of sophisticated devices without competent operators. Therefore, integrating blockchain literacy and competencies into the education curriculum is no longer just an option or a trend, but a strategic necessity to prepare human resources who are not only capable of operating systems, but also designing, managing, and innovating within the dynamic Logistics 4.0 ecosystem (Sutarman & Aini, 2023).

First and foremost, the approach to integrating blockchain into the curriculum must move beyond the narrow paradigm that views it solely as a technical programming course for computer science. The nature of blockchain as an enabling technology that permeates various fields demands a multidisciplinary and contextual curriculum approach. For directly related study programs such as Logistics Management, Industrial Engineering, Digital Business, and Accounting, blockchain must be presented as a strategic toolkit. A comprehensive curriculum needs to be built on three interlinked pillars of knowledge. The first pillar is Core Field Knowledge, such as supply chain management principles, cost accounting, or business law. The second pillar is Digital Technology Knowledge, which includes a conceptual understanding of how blockchain works, its role alongside IoT and big data, the basics of smart contracts, and awareness of cybersecurity and data privacy. The third pillar is Business and Analytical Application Knowledge, which includes the ability to analyze business processes for automation, evaluate the economic impact of technology adoption, and design new business models enabled by blockchain. With this three-pillar approach, graduates are expected to not only know how technology works, but also why and where it should be applied to create added value (Rizal & Fahmi, 2022).

Furthermore, learning methods must undergo a radical transformation from a passive, one-way lecture model to a participatory and in-depth experiential learning model. Project-Based Learning (PjBL) has proven to be the most effective methodology for this context. In PjBL, students are no longer passive recipients of information, but active problem solvers. They can be given real challenges, for example: "Design a blockchain-based solution to increase the transparency and selling value of the forest honey supply chain from indigenous communities in Halmahera." To complete this project, students will go through a complete cycle: conducting business process analysis and stakeholder mapping in the field (simulation), selecting the appropriate blockchain architecture (private vs. consortium), designing the data flow from IoT sensors in beehives to end consumers, creating a simple smart contract prototype for automatic payments to farmers, and compiling a pitch deck to convince "investors" or "local governments" of the feasibility of their solutions. The use of blockchain sandbox platforms such as Hyperledger Fabric Playground or online simulations provides a valuable virtual laboratory, offering hands-on experience without real financial risk (Prasetyo & Darmawan, 2021).

The key to the success of all these efforts lies in close collaboration between the academic world and the industry/practitioner world. Curricula developed in isolation within the ivory

towers of academia will quickly become outdated and irrelevant. Therefore, a mechanism for co-creation of curriculum must be implemented. This can be done through the formation of joint task forces consisting of lecturers, representatives from logistics companies, supply chain professional associations, and even MSME players who have begun to adopt the technology. The role of industry should not be limited to providing advice, but should also involve active participation in the form of guest lectures by practitioners, company visits to digitized distribution centers, the provision of real case studies, and certified internship programs focused on supply chain digitization projects. In addition, the development and recognition of specific micro-credentials, such as "Blockchain Tracking Specialist for Supply Chains" or "Smart Contract Developer for Logistics," which are designed in collaboration with and recognized by the industry, will serve as a highly effective bridge between campuses and the job market, accelerating the absorption of graduates (Hidayat & Suryana, 2024).

The challenges in implementation should not be underestimated. The readiness of teaching staff (lecturers) is one of the main determining factors. Many senior lecturers in the fields of logistics and management may not be familiar with blockchain technology. Therefore, intensive training of trainers (ToT) programs, training, and opportunities for lecturers to be involved in applied research projects with industry are absolutely necessary. In addition, there needs to be a revolution in teaching materials. Conventional textbooks, which take a long time to publish, are often outdated by the time they reach students. The solution is to develop dynamic digital learning modules, e-modules, video tutorials, and online case study repositories that can be updated regularly in line with the fastest developments in the industry. A hybrid learning approach that combines face-to-face meetings for conceptual discussions with online learning for technical exploration and simulation is the most suitable model for such a rapidly developing topic (Wijaya & Santoso, 2020).

Therefore, education for the Logistics 4.0 era does not stop at university. It must be seen as a lifelong learning ecosystem. Educational institutions must open themselves up by organizing short professional training programs (short courses) and boot camps for workers who are already involved in the logistics industry but need to upskill or reskill. Partnerships with online learning platforms can also expand the reach. Thus, integrating blockchain into the curriculum is not merely adding a new course. It is a transformative educational movement that aims to produce a generation of blockchain-literate talent, namely individuals who have an analytical mindset, understand the strengths and limitations of distributed technology, and are able to translate technical complexities into valuable business solutions for MSMEs and national industries. Only in this way can Indonesia turn the threat of digital disruption into a golden opportunity to become a major player in the increasingly digital global logistics and trade arena.

D. Business Model and Adoption Strategy: Roadmap for Blockchain Implementation for SMEs in the National Supply Chain Ecosystem

Blockchain implementation for MSMEs cannot be done in isolation and requires a phased strategy and ecosystem collaboration. The most suitable business model for the Indonesian

context is the Sector-Based or Cluster-Based Blockchain Consortium model. In this model, a group of MSMEs in the same sector (e.g., fashion, processed food, or handicrafts), supported by industry associations, logistics institutions, banks, and local governments, jointly adopt a shared Blockchain platform (shared infrastructure). This model spreads development and maintenance costs, creates uniform data standards, and strengthens collective bargaining power (Santoso et al., 2023).

The adoption strategy should follow a Phased Adoption approach to minimize risks and obstacles. The roadmap can be divided into three main phases: Phase One: Product Tracking and Certification (0-18 Months). Focus on recording the origin of raw materials, production processes, and certification (halal, organic, geographical indication) into the Blockchain. The main output is transparency for consumers and proof of quality. Phase Two: Logistics and Transaction Automation (18-36 Months). Integrating logistics partners and implementing Smart Contracts for shipping documents, automatic partial payments, and inventory management. The main output is increased operational efficiency. Phase Three: Tokenization and Financing (36-60 Months). Develop a tokenization scheme for supply chain assets and integrate it with banking or fintech financing platforms. The main output is broader access to liquidity.

However, the path to full adoption is fraught with challenges. At the technical level, interoperability between different Blockchain platforms remains an issue. The initial investment costs in technology and training can be a barrier. Uneven digital literacy among MSME players also needs to be addressed through intensive mentoring. From a regulatory perspective, the legal framework for the legal validity of Smart Contracts, personal data protection, and taxation of digital transactions still requires clarification (Bappenas, 2020).

Therefore, the role of the government as a catalyst and enabler is very important. Policy recommendations that can be issued include: (1) Development of a National Blockchain Roadmap for Supply Chains involving all stakeholders; (2) Fiscal and non-fiscal incentives for MSME consortiums that adopt this technology; (3) Development of a Regulatory Sandbox Platform so that innovations can be tested in a controlled environment; and (4) Initiation of a "National Movement for Digital MSME Assistance" program involving universities and technology communities to assist with on-boarding. With an integrated, collaborative, and gradual ecosystem approach, the potential of the Blockchain revolution to empower MSMEs and transform the national supply chain can be realized in an inclusive and sustainable manner.

The implementation of blockchain technology in the national supply chain ecosystem, particularly to empower Micro, Small, and Medium Enterprises (MSMEs), is not a technological leap that can be made spontaneously and in isolation by individual business actors. This technology, with its nature of encouraging collaboration and building trust- s through shared infrastructure, requires a systemic, collective, and well-planned approach. The main challenge no longer lies solely in technological readiness, which has been proven through various global pilot projects, but rather in aspects of sustainable business models and realistic adoption strategies for Indonesia's highly diverse context. Without the right

model and strategy, blockchain risks becoming a solution in search of a problem, an advanced technology adopted only by a handful of large companies and failing to reach the grassroots of the national economy, namely MSMEs. Therefore, this discussion will outline a collaborative business model framework, a phased adoption roadmap, and the central role of the government as a catalyst to ensure that the blockchain revolution has an inclusive and transformative impact on the entire national supply chain ecosystem (Kadir et al., 2021).

First and foremost, the most feasible business model that suits the characteristics of Indonesian MSMEs is the Cluster- or Sector-Based Blockchain Consortium Model. This model recognizes that the strength of MSMEs lies in groups and local wisdom, rather than as individual players standing alone. A consortium can be formed by a group of MSMEs operating in the same sector and with similar value chains, such as the Gayo Arabica Coffee Cluster, the Flores Ikat Weaving Cluster, or the Bandung Processed Food Cluster. This consortium then partners with other key stakeholders such as industry associations, leading logistics companies, financial institutions (banks or fintech), and local governments. Together, they fund and adopt a shared blockchain platform (shared blockchain infrastructure) that is managed collectively. This model has several strategic advantages. First, it spreads the significant initial investment costs for platform development, system integration, and training among many members, so that the burden on individual MSMEs is very light. Second, the shared platform creates uniform data standards and protocols for the entire sector, facilitating interoperability and collaboration both within the cluster and with large buyers (off-takers) such as hotel chains, modern retailers, or exporters. Third, the consortium model strengthens the collective bargaining power of MSMEs. A buyer who wants to obtain traceable coffee supplies will find it easier to negotiate with a single consortium representing 100 farmers and millers than with 100 individual businesses. Thus, blockchain becomes a tool for consolidation and digital economies of scale (Saputra & Wijaya, 2022).

Once the collaborative business model is established, the next step is to design a realistic Phased Adoption Roadmap. A "big bang" or full-scale implementation approach is risky and potentially doomed to failure due to its complexity. An effective roadmap should break down the adoption journey into several sequential phases, where the success of each phase becomes the foundation for the next. The First Phase (0-18 months) should focus on Product Provenance & Certification. In this phase, the main objectives are to establish basic transparency and prove the concept of value. Key activities include registering MSME members on the platform, training them in recording production data (type of raw materials, harvest/production date, location), and integrating existing certifications (e.g., halal, organic, or geographical indication certificates) into the digital ledger. The output is the ability to track products from upstream, and most importantly, the ability for end consumers to scan QR codes and view this brief history. This phase provides immediately visible benefits, namely increased consumer confidence and product differentiation, thereby motivating MSMEs to continue their involvement (Pratama & Haryanto, 2023).

Once the tracking foundation is established, Phase Two (18-36 months) can begin with a focus on Logistics & Transaction Automation. In this phase of the , the consortium begins

integrating logistics partners (shipping companies, warehouses) into the platform. Simple IoT sensors can be introduced for truck location tracking. Smart Contracts begin to be implemented for more complex digital documents, such as Digital Waybills (e-Waybills) and Proof of Delivery (e-POD), which can automatically update delivery status. Furthermore, smart contracts for conditional automatic payments can be introduced. For example, when the system records that goods have been received and their quality verified by the buyer at the destination warehouse, a portion of the payment can be immediately transferred to the SME's account. This phase significantly reduces administrative errors, accelerates cash flow, and improves the operational efficiency of the entire chain (Nugroho & Sari, 2024).

The Third Phase (36-60 months) is the most mature and transformative phase, namely the Tokenization & Financing phase. In this phase, the consortium blockchain platform has become a single source of truth that is rich in credible and verified transaction data. This data forms the basis for the tokenization of supply chain assets. For example, MSME receivables from bona fide corporate buyers (such as hotel chains or exporters) can be represented as digital tokens (crypto assets backed by real receivables). These tokens can then be traded on the secondary market or used as digital collateral to apply for loans. Financial institutions that are part of or have access to the consortium can easily verify the health of SME businesses, their transaction history, and the quality of their receivables, thereby drastically reducing credit risk. This opens up access to inclusive Supply Chain Finance products, such as invoice financing or pre-harvest financing, which have been very difficult for SMEs to access. This phase fundamentally changes the relationship between SMEs and the formal financial system (Indrawan & Setiawan, 2023).

Although the roadmap is clear, the journey towards full adoption will face a number of major challenges. Technical barriers such as interoperability between different blockchain platforms and the need for integration with the legacy systems of MSMEs and logistics partners remain an issue. Human resource barriers in the form of low digital literacy among some MSMEs and the limited availability of technical talent who understand blockchain at the local level are also very real. Regulatory barriers are perhaps the most crucial; the legal uncertainty surrounding smart contracts, the taxation of digital transactions and asset tokenization, and the protection of personal data in distributed systems require certainty from regulators (Firdaus & Ashar, 2022).

This is where the government's role as a catalyst and enabler becomes absolute and irreplaceable. The government must not be a spectator, but rather the architect of the ecosystem and the main facilitator. The strategic steps that must be taken include: First, developing a National Blockchain Roadmap for the Supply Chain involving the Coordinating Ministry for Economic Affairs, the Ministry of Industry, the Ministry of Finance, the Financial Services Authority (OJK), and business associations. This roadmap must outline technical standards, sector priorities, and clear incentives. Second, providing concrete fiscal and non-fiscal incentives for pioneering MSME consortiums, such as tax breaks, training subsidies, or co-funding for pilot platforms. Third, establish a Regulatory Sandbox managed by the OJK and the National Development Planning Agency (Bappenas), where consortiums can test asset tokenization models and blockchain-based financial

products in a controlled and supervised environment before releasing them to the wider market. Fourth, launch a "National Movement for Digital MSME Assistance" program that utilizes talent from vocational colleges, blockchain developer communities (such as the Indonesian Blockchain Network), and technology companies to assist with on-boarding, training, and technical problem-solving for MSMEs in the field. With this comprehensive policy package, the government can effectively reduce risks, create a conducive environment, and ensure that the blockchain- t revolution leaves no one behind, especially the nation's largest economic actors, namely MSMEs (Bappenas, 2023).

Therefore, the application of blockchain for MSMEs in the national supply chain ecosystem is a medium- to long-term collaborative transformation journey, not an instant technology project. Its success depends on the selection of a smart consortium business model, the disciplined execution of a phased roadmap, and most importantly, the government's leadership and political commitment to creating a strong supporting ecosystem. If these three elements can be synergized, blockchain will not merely be a tracking technology but a digital trust infrastructure that opens the door to inclusive, sustainable, and globally competitive SME growth, while also strengthening the foundation of national supply chain resilience in the digital era.

4. Conclusions

Blockchain technology is an innovative foundation capable of revolutionizing modern supply chain systems, particularly in empowering MSMEs and preparing a relevant education ecosystem. Technologically, Blockchain, with its characteristics of decentralization, immutability of records, and controlled transparency, has proven to be mature and ready for adoption, especially when integrated with IoT and Smart Contracts to create reliable audit trails and process automation. For SMEs, this technology offers a democratic solution that addresses root problems such as mistrust, operational inefficiencies, and difficulties in accessing financing through improved traceability, automation, and asset tokenization. However, the success of mass adoption is highly dependent on the availability of competent human resources. Therefore, transforming the education curriculum to be multidisciplinary, applicable, and project-based is a must to create talents who are ready to face the era of Logistics 4.0. Ultimately, effective implementation requires a collaborative and phased strategy through a consortium model, supported by a national roadmap and the active role of the government as a facilitator.

The results of this study can be implemented through several concrete actions by various stakeholders. First, for the Government and Policy Makers, it is necessary to develop a National Blockchain Roadmap for MSME Supply Chains that adopts a phased adoption strategy, starting with pilot projects for tracking regional flagship products (such as coffee, honey, or textiles) before expanding to automation and financing. Second, for Educational and Training Institutions, implementation is carried out by integrating hybrid curriculum modules that combine logistics principles, the basics of Blockchain technology, and entrepreneurship into vocational and undergraduate study programs. Third, for Industry

Associations, Financial Institutions, and Business Actors, implementation begins by forming Cluster-Based Blockchain Consortia according to leading sectors (e.g., the Bali Fashion Blockchain Consortium or the Aceh Coffee Supply Chain).

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