Digital Transformation in Supply Chain Management: Leveraging Blockchain for Transparency and Sustainability

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Abstract- Digital transformation is reshaping supply chain management (SCM), with blockchain technology emerging as a pivotal tool for enhancing transparency and promoting sustainability. This paper uses its immutable, decentralized ledger to explore blockchain's potential to address key SCM challenges, such as traceability, ethical sourcing, and operational inefficiencies. The discussion highlights blockchain's role in fostering transparency through real-time tracking and secure data sharing while enabling sustainable practices by reducing waste and ensuring responsible sourcing. Despite its advantages, barriers such as cost, scalability, regulatory concerns, and resistance to change hinder widespread adoption. The paper examines emerging trends like Artificial Intelligence (AI) and the Internet of Things (IoT) as complementary technologies that amplify blockchain's capabilities. Recommendations are provided for businesses, policymakers, and technologists to overcome implementation challenges and unlock blockchain's transformative potential. Stakeholders can build resilient, transparent, and sustainable supply chains by addressing these issues collaboratively.

Indexed Terms- Blockchain, Supply Chain Management, Transparency, Sustainability, Digital Transformation, Emerging Technologies

I. INTRODUCTION

1.1 Background on Digital Transformation in Supply Chain Management

Digital transformation has become a cornerstone of innovation across industries, reshaping traditional practices and enabling businesses to thrive in a rapidly evolving technological landscape. Supply chain management (SCM), as the backbone of global trade, is no exception. SCM encompasses the intricate network of processes and stakeholders involved in producing, distributing, and delivering goods and services (Omol, 2024). Historically reliant on manual operations and siloed systems, supply chains are now embracing digital transformation to address inefficiencies, improve decision-making, and adapt to the demands of a globalized economy. Technologies like artificial intelligence (AI), the Internet of Things (IoT), and blockchain are pivotal in driving this transformation (Aldoseri, Al-Khalifa, & Hamouda, 2024).

The adoption of blockchain technology, in particular, has emerged as a game-changer, offering unparalleled transparency, security, and operational efficiency. This paradigm shift marks a departure from conventional SCM systems to interconnected, decentralized networks, enabling seamless stakeholder collaboration (Raza & Wang, 2023).

Transparency and sustainability have become critical priorities in modern supply chain operations. Consumers and regulatory bodies alike are demanding greater accountability regarding the sourcing, production, and environmental impact of goods. Transparency in SCM refers to the ability to track and trace every product transaction, movement, and transformation across the supply chain. It empowers

businesses to identify inefficiencies, ensure compliance, and build customer trust (Taherdoost, 2024). Conversely, sustainability focuses on minimizing environmental impact and promoting ethical practices throughout the supply chain. This involves reducing waste, optimizing resource utilization, and ensuring the responsible treatment of workers and communities. In a world of climate change and ethical concerns, sustainable practices are no longer optional but essential for long-term viability (Ismail, Hidajat, Dora, Prasatia, & Pranadani, 2023).
Achieving these objectives with traditional SCM methods is challenging due to fragmented systems, lack of interoperability, and vulnerabilities to fraud or human error. This is where blockchain technology offers transformative potential, enabling a level of transparency and sustainability previously unattainable.

1.2 Overview of Blockchain Technology as a Transformative Tool

Blockchain is a distributed ledger technology that records transactions in a secure, immutable, and transparent manner. Each transaction, or "block," is chronologically added to a "chain" of previous transactions, creating a tamper-proof record accessible to all authorized participants in the network. The decentralized nature of blockchain eliminates the need for intermediaries, reducing costs and enhancing trust among stakeholders (Mukherjee & Pradhan, 2021).

In the context of supply chain management, blockchain's capabilities are particularly significant. Blockchain addresses key pain points in traditional supply chains by enabling real-time tracking of goods, verifying the authenticity of products, and ensuring compliance with standards (Esmaeilian, Sarkis, Lewis, & Behdad, 2020). For instance, a blockchain-enabled supply chain can provide end-to-end visibility, allowing stakeholders to trace the journey of a product from raw material to finished goods. Smart contracts—self-executing agreements encoded on the blockchain—automate payments, quality checks, and regulatory compliance, reducing delays and human intervention (BOPPANA, 2024). Moreover, blockchain facilitates collaboration among diverse stakeholders, including suppliers, manufacturers, logistics providers, and retailers, by providing a single source of truth. This improves operational efficiency and strengthens trust and accountability in business relationships (Oriekhoe, Ashiwaju, Ihemereze, Ikwue, & Udeh, 2024).

1.3 Objectives and Scope of the Paper

This paper explores how blockchain technology is transforming supply chain management by addressing challenges related to transparency and sustainability. It highlights the benefits of blockchain adoption, particularly in promoting ethical practices, reducing inefficiencies, and enhancing stakeholder trust. The paper will also examine the barriers to blockchain implementation and propose strategies to overcome these challenges.

The scope of this discussion focuses on theoretical and practical applications of blockchain in SCM, emphasizing its role in advancing sustainability and transparency. While acknowledging the contributions of complementary technologies like AI and IoT, the primary focus remains on blockchain as the central enabler of change. Through this exploration, the paper aspires to provide valuable insights for businesses, policymakers, and researchers seeking to leverage blockchain for a more efficient, transparent, and sustainable supply chain.

II. BLOCKCHAIN TECHNOLOGY IN SUPPLY CHAIN MANAGEMENT

2.1 Overview of Blockchain Technology

Blockchain technology is a distributed ledger system designed to securely record transactions in a decentralized and immutable manner. It operates as a shared database maintained across multiple nodes or participants within a network. Each transaction is grouped into a "block" and appended to a chronological chain, creating an unalterable record (Antal, Cioara, Anghel, Antal, & Salomie, 2021). The system relies on cryptographic techniques to ensure data integrity and security, with every block linked to the previous one via a cryptographic hash. This design makes tampering nearly impossible, as altering one block would require modifying all subsequent blocks, a computationally unfeasible task (Habib et al., 2022).
Key features of blockchain include decentralization, transparency, immutability, and security. Decentralization ensures that no single entity controls the ledger, promoting participant trust. Transparency

allows all authorized parties to access the same version of the truth, minimizing disputes and errors. Immutability guarantees that it cannot be changed or deleted once data is recorded, providing a reliable audit trail. Security is bolstered by cryptographic protocols, which protect sensitive information and prevent unauthorized access (Kumar & Sharma, 2022).

In addition to its core functionality, blockchain supports programmable scripts known as "smart contracts." These are self-executing agreements with terms directly written into code. When predefined conditions are met, the smart contract automatically triggers actions such as payments, notifications, or approvals. This automation reduces the need for intermediaries and accelerates processes, making blockchain highly applicable to complex systems like supply chain management (SCM) (Singh, Parizi, Zhang, Choo, & Dehghantanha, 2020).

2.2 Specific Applications of Blockchain in SCM

Blockchain technology has transformative potential in addressing various challenges within supply chain management. Key applications include traceability, smart contracts, and provenance tracking.

i. Traceability

Traceability refers to the ability to track a product's journey throughout the supply chain, from raw material extraction to final delivery. Blockchain provides a transparent and tamper-proof record of every transaction and movement of goods. For example, in the food industry, blockchain can record data on farming, processing, transportation, and storage, ensuring that consumers and stakeholders have access to verifiable information about the product's origin and handling (Brandín & Abrishami, 2024).

This application is especially crucial for industries with stringent regulatory requirements, such as pharmaceuticals, where counterfeit drugs pose serious risks. By integrating blockchain, supply chains can verify the authenticity and quality of products, ensuring compliance and safeguarding public health.

ii. Smart Contracts

Smart contracts automate and enforce contractual agreements between supply chain participants. For instance, a smart contract could trigger payment to a supplier once goods are delivered and verified. This reduces manual intervention, minimizes delays, and eliminates disputes over terms (De Giovanni, 2020).

Smart contracts also enhance efficiency in logistics and inventory management. For example, they can automatically notify stakeholders when stock levels reach a certain threshold, enabling timely replenishment. By reducing reliance on intermediaries and manual processes, smart contracts streamline operations and reduce costs (Omar et al., 2021).

iii. Provenance Tracking

Provenance tracking ensures that products are sourced ethically and sustainably. Blockchain enables companies to certify the origins of raw materials, verify compliance with labor and environmental standards, and demonstrate adherence to ethical practices. This capability is vital for fashion, electronics, and agriculture industries, where consumers are increasingly concerned about sustainability and corporate responsibility (Vazquez Melendez, Bergey, & Smith, 2024). For instance, a blockchain-based system can trace the journey of coffee beans from farm to cup, documenting every stage of the process. This transparency builds consumer trust and supports fair trade initiatives. Similarly, blockchain can verify that minerals are conflict-free in the mining industry, ensuring ethical sourcing practices (Calvão & Archer, 2021).

2.3 Benefits of Blockchain in Addressing SCM Challenges

Blockchain technology addresses several persistent challenges in supply chain management, including inefficiencies, lack of transparency, and vulnerability to fraud. Traditional supply chains often suffer from fragmented systems and siloed data, making it difficult to achieve end-to-end visibility (Laroiya, Saxena, & Komalavalli, 2020). Blockchain consolidates information into a shared ledger accessible to all authorized participants. This transparency eliminates information asymmetry, reduces disputes, and builds stakeholder trust. For instance, in global trade, blockchain can provide real-time updates on shipping status, customs clearance, and delivery schedules. This level of visibility enables better decision-making and fosters stronger collaboration among supply chain partners (Rejeb, Keogh, Simske, Stafford, & Treiblmaier, 2021).

Supply chains are susceptible to fraud, counterfeiting, and data breaches. Blockchain's immutable ledger and cryptographic security features mitigate these risks by ensuring data accuracy and integrity. Unauthorized changes to records are virtually impossible, protecting the supply chain from fraudulent activities. Additionally, blockchain's ability to verify the authenticity of products and documents helps combat counterfeit goods. For example, luxury brands can use blockchain to certify the origin and authenticity of high-value items, protecting their reputation and revenue (Agarwal et al., 2022).

Blockchain streamlines supply chain operations by automating processes and reducing reliance on intermediaries. Smart contracts eliminate manual paperwork, accelerate transactions, and minimize human errors. This saves time and costs and allows businesses to focus on strategic initiatives rather than administrative tasks. Moreover, blockchain enables efficient dispute resolution by providing a clear and immutable record of transactions. This reduces delays in addressing issues such as payment discrepancies or delivery disputes, enhancing overall supply chain resilience (Esmaeilian et al., 2020).

Blockchain promotes sustainability by facilitating responsible sourcing, reducing waste, and optimizing resource utilization. It allows companies to track carbon footprints, monitor environmental impact, and verify adherence to sustainability standard (Rani, Sharma, & Gupta, 2024) s. This capability is crucial for meeting regulatory requirements and addressing growing consumer demand for eco-friendly practices. For example, blockchain can help reduce food waste by enabling real-time monitoring of expiration dates and storage conditions. Similarly, it can support circular economy initiatives by tracking recycled materials throughout their lifecycle (Asante et al., 2021).

III. IMPACT ON TRANSPARENCY AND SUSTAINABILITY

3.1 How Blockchain Enhances Supply Chain Transparency

Transparency in supply chain management (SCM) has traditionally been a challenge due to global trade's complex and fragmented nature. Supply chains often involve multiple stakeholders, including manufacturers, suppliers, logistics providers, and retailers, each operating within their own systems and processes (Chang, Iakovou, & Shi, 2020). This lack of interoperability results in silos of information, making it difficult to achieve a comprehensive view of the supply chain. Blockchain technology offers a transformative solution by providing an immutable, decentralized, and transparent ledger that records every transaction and interaction across the supply chain (Brun, Karaosman, & Barresi, 2020).

One of blockchain's most significant contributions to transparency is its ability to create immutable records. Every transaction entered into the blockchain is time-stamped, encrypted, and linked to the previous transaction, forming a chronological chain of events. These records are virtually tamper-proof, ensuring that all data remains accurate and trustworthy. This immutability is particularly important in pharmaceutical industries, where counterfeit drugs can pose significant risks. With blockchain, companies can verify the authenticity of products at every stage, ensuring that only genuine items reach consumers (Dong, Abbas, Li, & Kamruzzaman, 2023).

Real-time tracking is another way blockchain enhances transparency. By integrating blockchain with other technologies such as the Internet of Things (IoT), supply chain participants can monitor the location and condition of goods as they move through the supply chain. For example, IoT sensors can capture data on temperature, humidity, and handling conditions for perishable goods like food or vaccines, while blockchain ensures that this data is securely recorded and accessible. This level of visibility reduces the risk of spoilage or loss and allows stakeholders to proactively address potential issues.

Blockchain also facilitates transparency by providing a single source of truth for all participants. Traditional supply chains often suffer from discrepancies in records due to human error or inconsistent reporting practices. Blockchain eliminates these inconsistencies by maintaining a shared, synchronized ledger accessible to all authorized parties. This ensures everyone has access to the same accurate and up-to-date information, reducing disputes and fostering trust (Adewumi, Dada, Azai, & Oware, 2024; Dada, Okonkwo, & Cudjoe-Mensah, 2024).

In global trade, where compliance with customs regulations and trade agreements is critical, blockchain can streamline processes by providing clear documentation of product origins, certifications, and tariffs. This transparency simplifies audits, reduces administrative burdens, and helps companies comply with increasingly stringent regulatory requirements.

By addressing these transparency challenges, blockchain improves operational efficiency and enhances trust between businesses and their customers. Consumers increasingly demand visibility into how products are sourced and produced, and they can use blockchain-enabled systems to verify claims about a product's origin, quality, and authenticity. This transparency strengthens brand loyalty and differentiates companies in competitive markets (Attah, Garba, Gil-Ozoudeh, & Iwuanyanwu, 2024b).

3.2 Role in Promoting Sustainability

Sustainability has become a cornerstone of modern supply chain management, driven by growing environmental concerns, regulatory pressures, and consumer demand for ethical practices. Blockchain technology is critical in promoting sustainability by enabling responsible sourcing, reducing waste, and fostering accountability across the supply chain. One of blockchain's primary contributions to sustainability is its ability to ensure ethical sourcing. Consumers and businesses alike are increasingly concerned about the origins of raw materials and the conditions under which products are made (SA, Korang, Umoren, & Donkor, 2024). Blockchain provides a transparent record of a product's journey from its source to its final destination, allowing stakeholders to verify that materials are sourced ethically and sustainably. For example, in the fashion industry, blockchain can trace the origin of textiles to ensure they are produced in compliance with fair labor practices. Similarly, in the food industry, blockchain can certify that products are organic or sourced from fair trade farms (AD Adekola & SA Dada, 2024b; Attah, Garba, Gil-Ozoudeh, & Iwuanyanwu, 2024a).

Reducing waste is another critical area where blockchain contributes to sustainability. In industries like agriculture and retail, significant amounts of food and products are wasted due to inefficiencies in inventory management and supply chain coordination. Blockchain addresses these issues by providing real-time visibility into stock levels, expiration dates, and storage conditions. For example, blockchain-enabled systems can alert stakeholders when perishable goods are nearing their expiration dates, allowing them to redistribute or discount these items before they are wasted.

Blockchain also supports the circular economy by enabling the tracking and recycling of materials. For instance, blockchain can monitor the lifecycle of electronic components, ensuring that they are properly recycled or refurbished rather than ending up in landfills. This capability aligns with global efforts to reduce e-waste and promote sustainable consumption. In addition to reducing waste and enabling ethical sourcing, blockchain enhances sustainability by improving supply chain efficiency. Blockchain reduces energy consumption and resource waste associated with traditional systems by eliminating intermediaries and automating processes through smart contracts. For example, smart contracts can automate payment processing and reduce delays, minimizing the environmental impact of prolonged shipping and storage (Attah, Garba, Gil-Ozoudeh, & Iwuanyanwu, 2024c; Banji, Adekola, & Dada, 2024).

Blockchain also empowers consumers to make informed decisions about sustainability. By providing transparent and verifiable information about a product's environmental and social impact, blockchain enables consumers to choose brands and products that align with their values. For instance, a blockchain-enabled label on a coffee package could show its carbon footprint, the farmer who produced it, and the certifications it holds, giving consumers confidence in their purchases.

From a regulatory perspective, blockchain facilitates compliance with environmental and labor standards. Governments and international organizations increasingly require businesses to disclose their environmental and social impact. Blockchain simplifies this process by providing a reliable and easily accessible compliance record. This helps companies avoid penalties and demonstrates their commitment to sustainability (Dada & Adekola, 2024).

IV. CHALLENGES AND FUTURE DIRECTIONS

4.1 Key Barriers to Blockchain Adoption in SCM

While blockchain technology offers transformative potential for supply chain management (SCM), its widespread adoption is hindered by several challenges. One significant barrier is the cost of implementation. Deploying a blockchain system involves substantial upfront investment in infrastructure, software development, and training. These costs can be prohibitive for small and medium-sized enterprises, especially compared to traditional supply chain systems. Additionally, ongoing expenses, such as energy consumption for blockchain networks, particularly in proof-of-work systems, add to the financial burden.

Another critical challenge is scalability. As the number of transactions increases, blockchain networks can become congested, leading to slower processing times and higher costs. This limitation is particularly problematic for global supply chains that process thousands of transactions daily. Current blockchain systems, such as Bitcoin and Ethereum, struggle to handle high transaction volumes efficiently, prompting concerns about their suitability for large-scale SCM applications (AD Adekola & SA Dada, 2024).

Interoperability is also a significant hurdle. Modern supply chains involve multiple stakeholders using diverse systems and platforms. Integrating blockchain with these existing systems can be complex and time-consuming. The lack of standardization in blockchain protocols further complicates this process, as different blockchains may not communicate seamlessly.

Regulatory concerns represent another obstacle to adoption. Blockchain's decentralized and borderless nature poses challenges for regulatory frameworks, which are often jurisdiction-specific. Data privacy, intellectual property, and compliance with industry standards require careful consideration. For example, the General Data Protection Regulation (GDPR) in the European Union imposes strict rules on data storage and sharing, which may conflict with blockchain's immutable nature. Furthermore, the absence of clear regulations for blockchain technology creates uncertainty for businesses, discouraging investment. Finally, resistance to change can impede blockchain adoption. Many organizations are hesitant to transition from traditional supply chain systems to blockchain-based solutions due to complexity, reliability, and employee adaptation concerns. Overcoming these cultural and organizational barriers requires significant effort and commitment from all stakeholders (AD Adekola & SA Dada, 2024a; Iwuanyanwu, 2024).

4.2 Emerging Trends and Technologies Complementing Blockchain

Despite these challenges, emerging trends and complementary technologies are enhancing the utility and feasibility of blockchain in SCM. One notable trend is the integration of Artificial Intelligence with blockchain. AI algorithms can analyze vast amounts of data stored on the blockchain, identifying patterns, predicting demand, and optimizing supply chain operations. For example, AI can enhance fraud detection by identifying anomalies in blockchain transactions, further improving security and efficiency.

The Internet of Things is another technology that complements blockchain in SCM. IoT devices, such as sensors and RFID tags, collect real-time data on the condition and location of goods. This data can be securely recorded on the blockchain, creating an end-to-end traceability system. For instance, IoT-enabled temperature sensors can monitor perishable goods during transit, ensuring compliance with storage requirements. Combined with blockchain, this ensures a tamper-proof record of the product's journey, enhancing transparency and accountability.

Smart contracts, an inherent feature of blockchain, are also gaining traction as a tool for automating processes within the supply chain. Organizations can create highly efficient, self-regulating supply chains by integrating these self-executing contracts with AI and IoT. For example, a smart contract could automatically release payment once IoT sensors confirm the delivery of goods in acceptable conditions (Attah, Garba, Gil-

Ozoudeh, & Iwuanyanwu; Attah, Garba, Gil-Ozoudeh, & Iwuanyanwu, 2024b).

Another trend is the development of scalable blockchain solutions, such as proof-of-stake (PoS) consensus mechanisms and Layer 2 protocols. These advancements aim to address the scalability issues of traditional blockchains, enabling them to handle larger transaction volumes while reducing energy consumption and costs. Platforms like Ethereum 2.0 are leading the way, making blockchain more accessible and practical for SCM. Finally, collaboration among industry players is emerging as a key enabler of blockchain adoption. Initiatives like the Blockchain in Transport Alliance (BiTA) and IBM's Food Trust bring together stakeholders to establish standards, share best practices, and promote interoperability. These collaborations foster a unified approach to blockchain implementation, reducing barriers and accelerating adoption.

4.3 Potential Strategies for Overcoming Implementation Challenges

Organizations must adopt a strategic approach to overcome the barriers to blockchain adoption in SCM. One critical step is to invest in education and training. Stakeholders, including employees, suppliers, and partners, need to understand the benefits and functionality of blockchain. Providing comprehensive training programs and resources can help build confidence and reduce resistance to change.

Another strategy is to leverage consortium blockchains. Unlike public blockchains, which are open to everyone, consortium blockchains are governed by trusted entities. This approach offers greater control, privacy, and scalability while maintaining the benefits of transparency and immutability. For example, manufacturers and retailers could use a consortium blockchain to share data securely and efficiently. Standardization and interoperability are also critical for successful implementation. Industry-wide standards for blockchain protocols, data formats, and communication interfaces can simplify integration with existing systems and promote stakeholder collaboration. Organizations like the International Organization for Standardization (ISO) are working to develop such standards, providing a framework for blockchain adoption (Attah, Garba, Gil-Ozoudeh, & Iwuanyanwu, 2024d).

Addressing regulatory challenges requires proactive engagement with policymakers and regulators. Businesses should collaborate with governments to shape regulations that balance innovation with compliance. By participating in regulatory discussions and pilots, companies can help create an environment that supports blockchain adoption while addressing concerns about privacy and security.

To mitigate the cost barrier, organizations can explore incremental implementation. Instead of overhauling the entire supply chain simultaneously, companies can start with pilot projects targeting specific pain points. For example, a business could implement blockchain for traceability in a single product line before scaling up to other areas. This approach reduces risk and allows organizations to demonstrate tangible benefits before committing to larger investments. Finally, collaborative ecosystems can drive adoption by sharing resources and expertise. Partnerships between technology providers, industry leaders, and academic institutions can accelerate innovation and reduce the cost of development. By pooling resources, organizations can overcome challenges more effectively and unlock the full potential of blockchain in SCM (Anozie et al., 2024; Attah, Garba, Gil-Ozoudeh, & Iwuanyanwu, 2024a).

In conclusion, while blockchain adoption in supply chain management faces significant challenges, emerging trends and strategic approaches offer a path forward. By addressing barriers such as cost, scalability, and regulatory concerns and leveraging complementary technologies like AI and IoT, blockchain can revolutionize SCM. Collaborative efforts and innovative solutions will be essential for unlocking the transformative potential of blockchain, paving the way for a more transparent, efficient, and sustainable future.

CONCLUSION

Blockchain technology has proven to be a transformative tool in supply chain management (SCM), addressing challenges such as transparency, trust, and accountability. Its core features—

immutability, decentralization, and secure data storage—enhance visibility and facilitate traceability, ethical sourcing, and provenance tracking. These capabilities are essential in meeting growing consumer demands for transparency and ensuring compliance with regulatory standards. Furthermore, blockchain plays a pivotal role in sustainability by reducing waste, optimizing resource utilization, and supporting environmentally and socially responsible practices. Integrating complementary technologies like Artificial Intelligence and the Internet of Things further expands blockchain's utility, creating innovative solutions for complex supply chain networks. However, adoption is hindered by barriers such as high costs, scalability issues, regulatory uncertainties, and organizational resistance, requiring strategic interventions to unlock its full potential.

To harness blockchain's benefits, stakeholders must adopt tailored strategies. Businesses should start with pilot projects demonstrating the technology's feasibility and gradually scaling up implementation. Investment in training and education is critical to equipping employees and partners with the skills necessary to leverage blockchain effectively. Collaborating within industry consortia and forming strategic partnerships can foster knowledge sharing, standardization, and cost reduction, accelerating adoption. On the other hand, policymakers should focus on creating supportive regulatory frameworks that address data privacy and interoperability while incentivizing innovation through funding and research initiatives. Engaging with industry leaders to understand challenges and conducting regulatory sandbox trials can ensure balanced and practical governance.

For technologists, addressing scalability and interoperability through innovations like proof-of-stake mechanisms and hybrid blockchain models is vital. Integrating blockchain with AI and IoT will enable more efficient, transparent, and secure supply chains. Developers should also prioritize user-friendly designs to simplify implementation for businesses with limited technical expertise. By combining these efforts, businesses, governments, and technologists can overcome the existing barriers, paving the way for blockchain to revolutionize SCM. This collaborative approach will enhance operational efficiency and transparency and contribute to building sustainable, resilient supply chains for the future.

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