GENERATE

Start-up and Financial Technology

e-ISSN: 3090-661X
Vol 01 (2) 2025 p. 138-159

Corresponding author:
Kiruthika Dhanapal
Email : kiruthikaadv@gmail.com

Received 28 November 2025;
Accepted 24 December 2025;
Published 29 December 2025.

Conflict of interest statement:
Author(s) reported no conflict of interest

DOI: http://doi.org/10.70764/gdpu-sft.2025.1(2)-10

TOKENIZATION OF MSME ASSETS IN DEFI: OPPORTUNITIES, RISKS, AND HYBRID GOVERNANCE ARCHITECTURE

Kiruthika Dhanapal[1], Peter Waher[2]

[1] Chennai Dr. Ambedkar Government Law College, India
[2] Trust Anchor Group AB

ABSTRACT

Objective: This study aims to comprehensively analyze the transformative potential of asset tokenization for Micro, Small, and Medium Enterprises (MSMEs) within the Decentralized Finance (DeFi) ecosystem, with a focus on opportunities, risks, and the hybrid governance architecture required.

Research Design & Methods: This study uses a qualitative approach, combining a systematic literature review and case studies with thematic content analysis of secondary data from credible sources to identify patterns and key themes.

Findings: Findings show that tokenization of MSME assets offers significant opportunities, such as broader and faster access to funding through fractionalization of ownership, increased asset liquidity, operational efficiency, and enhanced transparency and security. However, this implementation is accompanied by various risks, including smart contract vulnerabilities, cyber attacks, blockchain scalability challenges, regulatory uncertainty, market volatility, and operational risks related to reliance on off-chain third parties. A hybrid governance architecture that integrates on-chain and off-chain elements is essential to mitigate these risks.

Implications & Recommendations: This study indicates that tokenization can be an essential bridge for MSMEs to enter the global digital economy, but it requires improved digital literacy and technological readiness. For investors, it offers new diversification opportunities with inherent risks. Policy recommendations include adaptive regulation, simplified compliance, digital education, infrastructure strengthening, utilization of regulatory sandboxes, and cross-sector collaboration and standardization.

Contribution & Value Added: This study presents a comprehensive framework for tokenizing MSME assets, offering practical guidance for various stakeholders to promote financial inclusion and equitable economic growth.

Keywords: Asset Tokenization, MSMEs, DeFi, Hybrid Governance, Regulation.

JEL codes: E42, G21, G28.
Article type: research paper

INTRODUCTION

Global financial landscapes are undergoing a fundamental transformation, driven by advances in digital technology. At the front lines of this revolution are the concepts of asset tokenization and decentralized finance (DeFi), which collectively promise unprecedented efficiency,

transparency, and accessibility in the management and exchange of value (Treleaven et al., 2022). Micro, small, and medium enterprises (MSMEs) in Indonesia, which are the backbone of the national economy, have a great opportunity to take advantage of this innovation to overcome the challenges of access to capital and digitization that they have been facing (Tarhini, 2021). Although MSMEs in Indonesia are a vital pillar of the economy, contributing significantly to gross domestic product (GDP) and employment, the sector consistently faces substantial obstacles that hinder its growth and potential (Kumar et al., 2023).

One of the most pressing issues is limited access to financing from traditional financial institutions (Ikponmwoba et al., 2022). MSMEs are often hampered by lengthy bureaucracy, strict collateral requirements, and complicated application processes, which effectively exclude most of them from the formal credit system (Chen, 2023). These limitations not only restrict MSMEs' capacity to expand and innovate but also perpetuate a significant financing gap, estimated to reach $5 trillion globally (Ikponmwoba et al., 2022). Traditional financial systems often lack efficient mechanisms for accurately assessing the risk of MSMEs, especially those without formal credit histories or adequate collateral, resulting in loan rejections or onerous interest rates (Chen, 2023). Additionally, the slow clearing and settlement process in conventional systems adds to costs and time, a significant burden for MSMEs with tight profit margins (Polikarpova, 2018).

Besides funding challenges, MSMEs also face a noticeable digital divide. Many business owners and employees of MSMEs don't have the digital literacy and technical skills needed to use different technologies efficiently (Wahida, 2025). There are times when it is difficult to adapt to changes in business processes that are now digital-based, as well as a lack of awareness of the full potential of various digital tools available. Budget constraints and financial resources are also major obstacles to initial investment in technology, such as purchasing software, hardware, or digital platform subscription fees. This lack of technological readiness makes SMEs vulnerable to cyberattacks and data breaches, and hinders their ability to fully leverage the potential of available digital tools. Cyber threats, such as data breaches, malware attacks, phishing, and online fraud, pose real risks that can financially harm SMEs and damage their reputation (Eko, 2025). Consequently, MSMEs find improving their marketing, capital, business operations, innovation, and competitiveness difficult in an increasingly competitive digital era (Schafer et al., 2023). Without innovative solutions, MSMEs risk being left behind in the global economic transformation, which could hamper overall national economic growth (Lewandowska et al., 2023).

Responding to the critical challenges MSMEs face, asset tokenization in the Decentralized Finance (DeFi) ecosystem has emerged as a promising, transformative solution. Tokenization is the process of converting ownership rights to physical or digital assets into digital tokens on the blockchain, which function as transparent and secure digital ownership certificates (Treleaven et al., 2022). This concept enables asset fractionalization, where high-value assets can be broken down into smaller, more affordable units (Zhitomirskiy et al., 2023). Fundamentally democratizing investment access opens the door for retail or individual investors with limited capital to participate in investments that were previously only accessible to large or institutional investors (Pramudya et al., 2024). Thus, MSMEs can tokenize various assets, ranging from properties such as boarding houses, business shares or equities, music royalties, to receivables or crop yields, to gain wider and faster access to financing.

In DeFi ecosystems, tokenized assets can be traded 24/7 on global platforms, significantly increasing liquidity compared to physical assets that may be difficult to liquidate. This increased liquidity not only benefits MSMEs in obtaining capital but also provides greater flexibility in managing their assets, allowing them to quickly liquidate assets when needed (Nadya, 2022). The blockchain technology underlying DeFi ensures transparency in asset ownership and transactions, creating an immutable transaction trail that anyone can audit, thus minimizing the risk of fraud and increasing trust (Rozario and Thomas, 2019). Additionally, smart contracts automate processes, reduce administrative costs and completion times, and eliminate traditional intermediaries, significantly reducing transaction costs (Yaramolu, 2025). Thus, tokenization can bring MSMEs that

previously did not have access to formal financial systems into the global ecosystem, promoting broader financial inclusion.

This study analyzes the transformative potential of SME asset tokenization in the DeFi ecosystem by highlighting opportunities, risks, and hybrid governance needs. Its contributions include: (1) developing a holistic framework that integrates technical, economic, regulatory, and operational aspects; (2) identifying unique challenges and risks for SMEs; (3) proposing a governance architecture that combines decentralization and regulatory compliance; (4) reviewing digital asset regulations in Indonesia and their implications; (5) relevant global case studies for the local context; and (6) policy recommendations and directions for further research. The results of this study are intended for SMEs, investors, regulators, and academics who wish to understand and implement asset tokenization safely and sustainably.

This report is structured systematically to discuss MSME asset tokenization in the DeFi ecosystem. The literature reviews related to concepts, theories, and previous findings follow the introduction. The research methods section explains the qualitative methodology, including a systematic review and case studies. The research findings present key findings related to the opportunities and risks of asset tokenization for MSMEs. The discussion section discusses hybrid governance architecture, regulatory dynamics in Indonesia, and global case studies and their potential for local implementation. Finally, the conclusion summarizes prospects, policy recommendations, and further research directions. This structure is designed to provide a comprehensive understanding for all stakeholders.

LITERATURE REVIEW

Asset Tokenization and Blockchain

Asset tokenization is the process of representing ownership rights to physical or digital assets as digital tokens on a blockchain (Awasthi, 2024). This process enables fractional ownership, where high-value assets can be broken down into smaller, more affordable units, thereby increasing liquidity and broader market access (Gupta et al., 2020). Blockchain technology is the backbone of tokenization, providing a decentralized, transparent, and immutable system for recording transactions. Each transaction is permanently recorded and can be verified by all parties, reducing the risk of fraud and increasing trust (Chambefort and Chaudey, 2024). Additionally, smart contracts running on the blockchain automate the execution of agreements and transactions, reducing the need for intermediaries and operational costs. Tokenization can be applied to protect various types of sensitive information, ranging from account numbers to medical records and payment data, making it a versatile data security solution (Hasan and Salah, 2018).

DeFi and MSME Financing

DeFi is a financial ecosystem built on blockchain technology, enabling peer-to-peer transactions and automated financial services through smart contracts without the need for traditional intermediaries such as banks (Kadir, 2023). DeFi addresses the limitations of public access to financial services and reduces transaction costs often imposed by conventional institutions. Research shows that blockchain can significantly reduce information asymmetry between SMEs and financing providers, improve the credibility of SMEs, and reduce the costs of equity and bond financing (Chen, 2023). Decentralized lending platforms, such as Aave and MakerDAO, enable MSMEs to borrow against crypto assets, bypassing traditional lending processes. Studies show that decentralized digital lending frameworks can increase loan approval rates by up to 40%, reduce interest rates by 30%, and cut processing times by up to 50% for MSMEs (Ikponmwoba et al., 2022). Additionally, DeFi offers the potential for portfolio diversification for investors, enabling them to fund various SME ventures with smaller capital, and potentially earn attractive returns through passive income (Amyulianthy et al., 2025).

Risks and Challenges of Tokenization

Although promising, asset tokenization in DeFi comes with various risks. Technical risks include smart contract vulnerabilities that can be exploited, causing significant financial losses (Corey et al., 2025). These exploits may include reentrancy attacks, oracle manipulation, or flash loan exploits (Lubis et al., 2025). Cyberattacks and data breaches also pose a serious threat to token asset security. In addition, the scalability of certain blockchains remains a challenge, affecting transaction speed and costs. Regulatory risks arise from the evolving legal landscape. The lack of common standards and legal uncertainty can lead to market fragmentation and compliance challenges. Compliance with Anti-Money Laundering (AML) and Know Your Customer (KYC) requirements also represents a significant operational and financial burden (Faruk et al., 2024). The shift in the classification of crypto assets from commodities to securities, as has happened in Indonesia, could drastically change regulatory requirements (Wicaksono, 2023). Market risk includes the volatility of the crypto market, which can affect the value of tokenized assets. The secondary market liquidity for certain tokenized assets may not be deep enough, especially for more niche MSME assets, making it difficult to sell quickly without significant price impact (Amyulianthy et al., 2025). Centralization of tokenization platforms also poses risks of single points of failure and a lack of transparency. Operational risks arise from dependence on off-chain third parties such as custodians, who store and manage the physical assets underlying the tokens. Failure of these third parties could result in financial losses. Coordination with off-chain third parties could lead to delays or data inconsistencies (Lubis et al., 2025).

Hybrid Governance

To balance DeFi innovation with the need for stability and compliance, a hybrid governance architecture is a promising approach. This model deliberately combines the power of decentralization, transparency, and automation offered by blockchain (on-chain) with the essential need for regulatory compliance, law enforcement, and physical asset management in the real world (off-chain) (Patil et al., 2025). On-chain components include smart contracts that automate agreements, Decentralized Autonomous Organizations (DAOs) governed by smart contracts and collective decisions of governance token holders, as well as blockchain validators and security nodes that verify transactions and secure the network (Lubis et al., 2025).

Meanwhile, off-chain components provide a layer of legal, physical, and compliance that cannot be fully replicated on the blockchain (Fox, 2021). A legal and regulatory framework that ensures compliance with local and international laws, a custodian responsible for storing and managing the physical assets underlying the tokens, independent auditors who verify the existence and value of off-chain assets, legal entities such as Special Purpose Vehicles (SPVs) to facilitate tokenization, and identity management and KYC/AML, which are often conducted off-chain (Osho et al., 2024). This hybrid model addresses the limitations of pure on-chain governance, which may not be compatible with traditional legal frameworks or complex physical asset management requirements.

METHODS

This study adopts a qualitative approach to deeply analyze the complex phenomenon of asset tokenization for Micro, Small, and Medium Enterprises (MSMEs) in the Decentralized Finance (DeFi) ecosystem. The qualitative approach was chosen because it allows for exploring nuances, contexts, and complex interactions between blockchain technology, regulatory frameworks, and MSME business practices, which cannot be fully captured by quantitative methods. The research design uses a combination of systematic literature review and case studies. The systematic literature review involves the systematic collection, synthesis, and evaluation of relevant literature from peer-reviewed journal articles, industry reports, conference papers, and publications from leading financial institutions and research organizations. The purpose of this literature review is to build a comprehensive understanding of the basic concepts of asset tokenization, including the mechanisms and types of assets that can be tokenized, the definition and characteristics of the DeFi

ecosystem and its role in financial innovation, the financing challenges faced by SMEs and how blockchain and DeFi can serve as solutions, the various risks (technical, regulatory, market, operational) associated with asset tokenization in DeFi, the concepts and components of hybrid governance architecture in the context of asset tokenization, the regulatory landscape for digital assets in Indonesia, and case studies and pilot projects of real-world asset tokenization. Case study analysis is used to test and illustrate the concepts identified in the literature review, focusing on successful implementations of real-world asset (RWA) tokenization, both globally and in Indonesia, to identify best practices, challenges encountered in real-world scenarios, and lessons learned for the development of effective and sustainable MSME asset tokenization models.

The data for this study were collected from credible and indexed secondary sources, with the selection of data sources based on relevance, authority, and recency of information. The main sources include academic journals and research papers that discuss in depth the technical, economic, legal, and social aspects of blockchain, tokenization, and DeFi, as well as their impact on MSME financing, industry and consultant reports that provide market analysis, projections, and case studies on asset tokenization implementation, regulatory documents and policies from financial supervisory authorities such as the Financial Services Authority (OJK) and the Commodity Futures Trading Supervisory Agency (BAPPEBTI) in Indonesia, as well as international regulatory bodies, to understand the applicable legal framework and its developments, and case studies of tokenization projects that have been implemented, including details about the business model, technology used, challenges, and results achieved. Qualitative data collected from various sources were analyzed using thematic content analysis, which involved familiarizing the data, initial coding, theme searching, theme review, theme definition and naming, and report writing. Through this approach, this study aims to present a comprehensive and structured analysis of the tokenization of MSME assets in the DeFi ecosystem, providing relevant insights for various stakeholders.

RESULT

Basic Mechanism of Asset Tokenization

Asset tokenization is a fundamental process that converts asset ownership rights into digital representations that can be stored and traded on the blockchain. These tokens function like digital ownership certificates, providing transaction clarity and security.

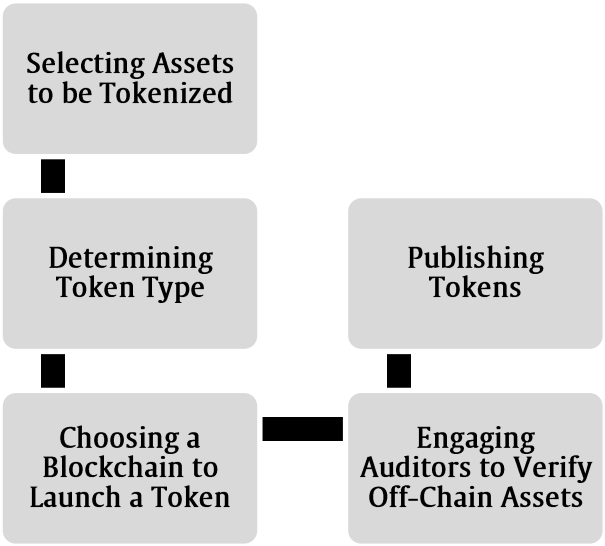

Figure 1. Asset Tokenization Process

The asset tokenization process is a series of structured steps designed to ensure the validity, security, and representation of physical or conventional assets in digital form on the blockchain network (Ferrara et al., 2022). The first step begins with identifying and selecting assets to be

tokenized. These assets include company shares, commodities, currencies, securities, property, and intellectual property. This diversity creates significant opportunities for SMEs to transform their assets into a digital format that can be traded or used as collateral. Once the asset has been determined, the next step is to design the token's characteristics, including determining whether the token is fungible (exchangeable like digital currency) or non-fungible (NFT), unique like a certificate of ownership or digital artwork. This determination also includes selecting technical standards such as ERC-20 or ERC-721, the token creation mechanism, token allocation, and governance aspects that regulate its use.

The next step is to select the blockchain network that will be used to launch the token. This selection is based on technical and regulatory requirements like scalability, transaction costs, and access control. Public blockchains such as Ethereum are widely used due to their extensive ecosystem support, while Layer 2 solutions such as Polygon offer low costs and high compatibility. On the other hand, for projects with high throughput requirements and strict oversight, blockchains such as Avalanche or Hyperledger Fabric are more suitable options. To bridge the physical and digital worlds, the involvement of independent auditors is essential to verify the existence and validity of tokenized physical assets. This stage is critical because although blockchain guarantees transparency and immutability of on-chain data, the overall reliability of the system remains highly dependent on the off-chain asset verification process. Reliance on third parties such as auditors or custodians introduces operational and counterparty risks, which can negatively impact investor confidence if not managed properly–especially for MSMEs, which often have small-value and informally documented assets.

Once the entire validation and technical configuration process is complete, the token is issued and recorded on the blockchain. The token can then be distributed, exchanged, or traded through decentralized finance (DeFi) platforms or other secondary markets, with the main benefits being increased liquidity and transaction efficiency. This final stage will determine whether tokenization can promote financial inclusion and viable alternative financing, especially for the MSME sector, which has previously been underserved by the traditional financial system.

Types of MSME Assets that Can Be Tokenized

Principally, any asset with value can be tokenized, whether tangible, digital, fungible, or non-fungible. For MSMEs, the spectrum of assets that can be tokenized is very broad, opening up new opportunities for financing and growth.

Asset Type	Definition	Scientific References
Property	Properties such as boarding houses or lodgings can be tokenized into fractional ownership, allowing small investors to participate.	(Kreppmeier et al., 2023; Rudzeyt et al., 2020)
Business Shares/Equity	SMEs can sell shares of business ownership in the form of tokens to access financing from public investors.	(OECD, 2020)
Music Royalties/ Intellectual Property	Future income from music, art, or patents can be tokenized to obtain initial funding.	(Bamakan et al., 2022; Moreaux and Mitrea, 2023)
Collectibles/Limited Edition Products	Unique products or high-value collections can be tokenized to be owned fractionally or traded on digital markets.	(Bamakan et al., 2022; Rudzeyt et al., 2020)
Digital Loyalty Systems	Tokens can be used as customer loyalty points redeemed for products or services, enhancing retention and engagement.	(Lukas, 2020)
Receivables/Harvest Yields	Trade receivables or projected harvest yields can be tokenized to fund operations more quickly.	(Ponniah, 2014)
Capital Assets	Production equipment or machinery can be tokenized so that SMEs can access funds by selling fractional ownership rights.	(Rudzeyt et al., 2020)

Asset Type	Definition	Scientific References
Vouchers/Tickets/Gifts	Tokens can replace event tickets, shopping coupons, or exclusive gifts that can be resold or collected by customers.	(Lukas, 2020)
Aset Negara Idle	The government can lease or tokenize the rights to use unproductive state-owned land or assets for MSMEs.	(Fox, 2021)

The concept of fractional ownership is key to the tokenization of MSME assets. MSMEs often have assets that are relatively small in value or illiquid in traditional markets. With tokenization, these assets can be broken down into smaller, more affordable units. This opens the door for retail investors or individuals with limited capital to participate in investments that were previously only accessible to large investors (Kreppmeier et al., 2023). This process not only provides MSMEs with access to larger and more diverse pools of capital but also democratizes investment (Ahmed, 2024). Individuals can now own a small portion of property, royalties, or even MSME businesses, which were previously beyond their reach (Liu and Chen, 2025). This has the potential to accelerate the growth of MSMEs and significantly improve financial inclusion in society.

Opportunities for Tokenizing MSME Assets in DeFi Ecosystems

The tokenization of Micro, Small, and Medium Enterprises (MSME) assets within the Decentralized Finance (DeFi) ecosystem offers significant transformational opportunities for both businesses and investors. Integrating MSME financing needs and investor interest in alternative investment instruments creates a mutually beneficial synergy within a more inclusive, efficient, and transparent financial framework. By leveraging blockchain technology, tokenization provides innovative solutions that address classic challenges in MSME financing while expanding access to global markets and financial resources.

For MSMEs, tokenization provides a broader, faster, and more flexible financing alternative compared to conventional financing schemes. Through asset digitization and the use of DeFi protocols, MSME players can gain direct access to blockchain-based financing platforms without having to go through complex bureaucratic processes, strict collateral requirements, or administrative barriers commonly found in traditional financial institutions (Permana et al., 2019). Studies show that using decentralized digital platforms can really boost loan approval rates, lower interest rates, and speed up the process of getting funds (Gudgeon et al., 2020). Additionally, tokenization improves the liquidity of MSME assets previously considered illiquid, such as property, royalties, or receivables, by enabling global and continuous trading of tokens 24 hours a day through secondary markets (Ante, 2022).

From an operational efficiency standpoint, tokenization supported by smart contracts enables the automation of various important business processes, including payment execution, profit distribution, and ownership rights management (Fitriani et al., 2024). This directly impacts reducing transaction costs and increasing the efficiency of internal resource utilization. Another advantage lies in the system's transparency, where every transaction is permanently recorded on the blockchain and can be publicly audited, creating stronger trust between MSMEs and investors (Arwani and Priyadi, 2024). Data security is also an added value, considering that tokenization protects sensitive customer information, which in turn strengthens consumer loyalty and trust (Felicia et al., 2024). Furthermore, the flexible and scalable nature of tokenization technology allows for its application across various industry sectors and business scenarios, making it an adaptive solution for the diverse needs of MSMEs (Humas Tel-U Surabaya, 2024).

Meanwhile, for investors, the tokenization of MSME assets expands access to investment opportunities that were previously unavailable or difficult to access. Through the concept of fractional ownership, investors can participate in financing various MSME projects with relatively small capital, enabling broader portfolio diversification and more optimal risk management (Golberg and Palladini, 2011). Access to high-value assets such as real estate, commodities, or intellectual property has become more democratic and inclusive. In addition to competitive

potential returns, investors also benefit from passive income derived from dividends, profit-sharing, or the growth in value of tokenized assets. Liquidity is another key advantage, with the availability of a secondary market enabling real-time token transactions, providing greater flexibility in exit strategies (Amyulianthy et al., 2025). On the other hand, blockchains' transparency and security boost investor confidence in the integrity and accountability of transactions, making tokenization a key pillar in the development of the future digital investment ecosystem (Herman et al., 2024).

The combination of fractional ownership, increased liquidity, and global accessibility creates a powerful and decentralized crowdfunding model for MSMEs (Hutabarat et al., 2025). Investors from around the world can purchase tokens representing small portions of MSME assets or projects, giving MSMEs access to much larger and more diverse capital than they could obtain locally. This is not only about funding, but also about global market validation for MSME assets, which can drive exponential growth and competitiveness in broader markets. The consequence is the accelerated upgrading of MSMEs through direct integration into decentralized global capital markets.

Table 1. Comparison of Key Opportunities for MSMEs and Investors

Opportunities	Opportunities for MSME	Opportunities for Investors
Funding Access	Utilizing blockchain-based financing, such as DeFi, overcoming the bureaucracy and difficult requirements of traditional institutions, and obtaining funds without bank loans	Access to investment opportunities that were previously unavailable or difficult to access, participation in decentralized crowdfunding
Asset Liquidity	Assets that were previously illiquid (e.g., property, royalties) can be traded 24/7 on the global market.	Increased liquidity enables easier exit strategies through trading on secondary markets.
Operational Efficiency	Reduction of operational costs and acceleration of workflows through smart contract automation and the elimination of intermediaries.	Reduced transaction costs and settlement times.
Transparency	Transaction records that cannot be altered on the blockchain enhance trust and minimize fraud.	Increased investment confidence and security through immutable blockchain records.
Portfolio Diversification	-	The ability to fund a variety of different SME businesses or projects, spreading risk and increasing profit opportunities.
Access to High-Value Assets	-	Access to fractional ownership of high-value assets (e.g., real estate, art) that were previously exclusive to large investors.
Return Potential	-	Potential for higher returns compared to traditional fixed-income investments; opportunities for passive income from dividends or profit-sharing.

Risks of SME Asset Tokenization in DeFi Ecosystems

Although blockchain-based asset tokenization promises great opportunities for financial inclusion for MSMEs, especially through integration into the decentralized finance (DeFi) ecosystem, its implementation is not without various challenges and risks. A thorough understanding of these potential risks is crucial for policymakers, platform developers, investors, and MSME players themselves. The following infographic summarizes the four main categories of

risks in MSME asset tokenization: technical, regulatory, market, and operational. Each category is accompanied by data and real-life examples that reflect the current conditions in Indonesia and globally. This visualization aims to provide a concise yet comprehensive overview of the risk landscape that needs to be anticipated before widely adopting asset tokenization solutions.

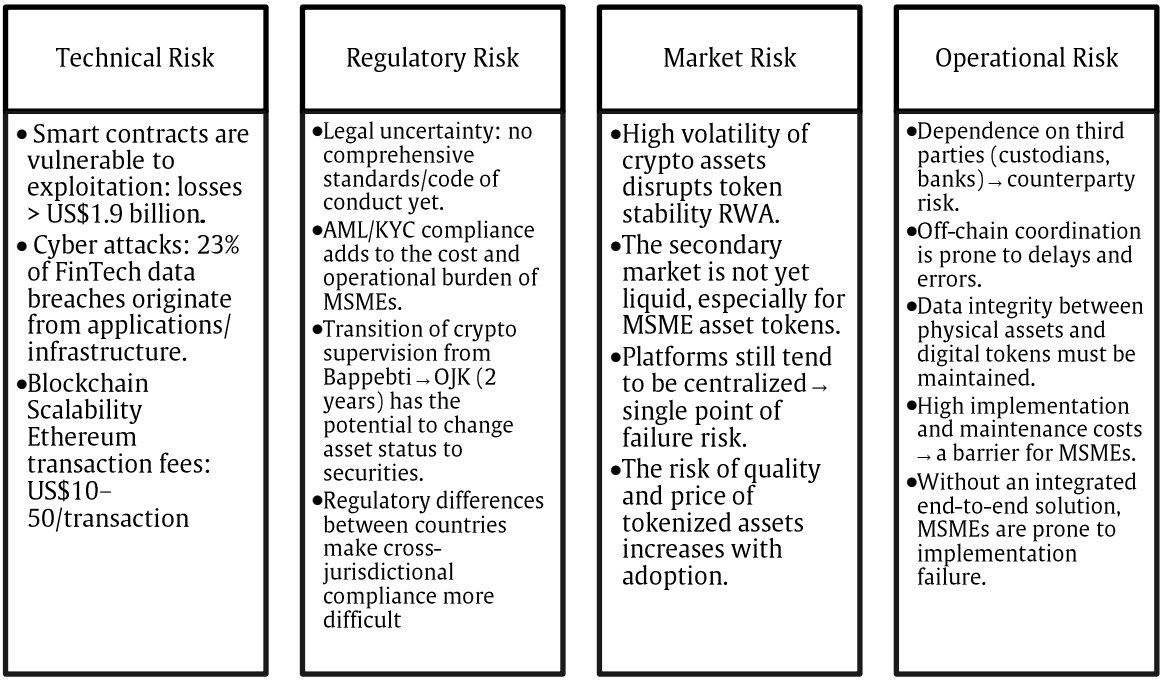

Table 2. Risk Matrix for SME Asset Tokenization in DeFi

Risk Category	Specific Risk Description	Potential Impact on MSMEs/Investors	Initial Mitigation Strategy
Technical (Corey et al., 2025; Saqib and AL-Talla, 2023; Wahida, 2025)	Smart Contract Vulnerabilities	Financial losses due to code exploitation	Strict code security audits use proven token standards.
	Cyber Attacks	Data breaches, theft of token assets.	Advanced security protocols, cyber education, and firewalls.
	Blockchain Scalability	Slow transaction times, high fees during high-volume periods.	Use of Layer 2 solutions (e.g., Polygon, Avalanche).
Regulations (Bolar, 2025; Corey et al., 2025; Kobrata, 2025; Soni et al., 2025).	Legal uncertainty	Market fragmentation, undesirable practices, and legal sanctions.	Clear regulatory framework, regulator-industry collaboration
	AML/KYC compliance	Operational burdens, transaction rejections, penalties.	Automation of KYC/AML processes, partnerships with compliance providers.
	Asset classification	Changing regulatory requirements, unexpected compliance costs.	Active regulatory monitoring, legal consultation, and business model adaptation.
Pasar	Crypto Market Volatility	Fluctuations in the value of underlying RWA assets.	Portfolio diversification, hedging strategies, and long-term investments.

Risk Category	Specific Risk Description	Potential Impact on MSMEs/Investors	Initial Mitigation Strategy
(Amartha, 2024; Ekwealor, 2025; Haq, 2021).	Secondary Market Liquidity	Difficulty selling tokens, asset value trapped.	Deep secondary market development, partnerships with exchanges.
	Platform Centralization	Single point of failure risk, lack of transparency.	Selection of platforms with strong decentralized governance and independent audits.
Operational (Chen, 2023; Wahida, 2025)	Off-Chain Custodian Dependency	Counterparty risk (bankruptcy, mismanagement).	Selection of reputable custodians, independent audits, and insurance.
	Off-Chain Coordination	Delays, errors, data discrepancies.	Integrated systems, standard communication protocols, process automation
	Implementation & Maintenance Costs	Financial burden on MSMEs	Affordable subscription model, gradual digitization, and government support.

DISCUSSION

Hybrid Governance Architecture

To realize the full potential of real-world asset (RWA) tokenization, especially for MSMEs, a governance architecture is needed that can bridge the decentralized world of blockchain with the legal and operational realities of physical assets. This approach is known as hybrid governance. Hybrid governance is a strategy that deliberately combines the strengths of decentralization, transparency, and automation offered by blockchain (on-chain) with the essential need for regulatory compliance, law enforcement, and physical asset management in the real world (off-chain). This model is a realistic and pragmatic approach to RWA tokenization, given that not all aspects of real-world assets can be fully regulated or replicated on-chain. Its main objective is to achieve an optimal balance between the efficiency and transparency inherent in blockchain technology and the need for trust, legality, and accountability regulated by traditional legal and financial systems. Hybrid models recognize that, although blockchain can record token ownership and transactions immutably, the legal validity and physical existence of the assets they represent still require trusted off-chain structures and entities.

On-Chain Governance Components

On-chain components play a strategic role in the use of blockchain technology to build automated, transparent, and decentralized systems. One of the fundamental components in this architecture is smart contracts, which are programs that run automatically on the blockchain network to execute agreements, transfer ownership rights, set payment schedules, and apply a set of predefined rules without human intervention. The implementation of smart contracts has proven to reduce the need for manual intervention and lower operational costs, given that every transaction is deterministic and permanently documented in a digital ledger (Rudzeyt et al., 2020).

Along with the development of the blockchain ecosystem, a new form of governance has emerged through the Decentralized Autonomous Organizations (DAO) model. DAO is an organizational entity controlled by a set of smart contracts and collective decisions from members who own governance tokens. This model presents an inclusive and transparent decision-making mechanism, in which the entire voting process and its implementation are recorded on the

blockchain and can be audited by the public, thereby eliminating the need for a central authority or conventional hierarchical structure (Fox, 2021).

In terms of platform governance, governance tokens play a crucial role because they give their owners the right to participate in determining policy direction, technical development, and strategic protocol changes. This creates a more democratic and community-based ecosystem, where users have direct control over the evolution of the platform they use (Lukas, 2020). To ensure transaction integrity and network infrastructure security, on-chain systems also rely on the role of blockchain validators and security nodes. These entities are tasked with verifying transactions, maintaining data consistency within the network, and securing the system from potential attacks or manipulation. As an incentive, validators typically receive rewards in the form of tokens or transaction fees, which in turn encourages active participation in maintaining network stability and sustainability (Ferrara et al., 2022).

Legal and Regulatory Framework

- Compliance with local and international laws is essential for the legality and enforcement of asset tokenization . This includes securities registration requirements, anti-fraud provisions, broker-dealer regulations, and custody rules applicable in the relevant jurisdiction (Lavayssière, 2025)

Kustodian

- A trusted entity responsible for storing and managing the digital and/or physical assets underlying a token. Custodians ensure the security of tokenized assets and foster trust among investors, especially for physical assets that require storage and maintenance (Teis & Clarke, 2024).

Auditor

- An independent party that verifies the existence, value, and ownership of tokenized off-chain assets. This audit provides investors with assurance that the tokens they hold are truly backed by real assets(Bhattacharjee et al., 2005)

Entitas Hukum

- Legal structures such as SPVs can be developed to facilitate tokenization while remaining compliant with applicable regulations . SPVs can serve as entities that legally own and manage physical assets, mitigate risk, and facilitate investment (Riabokin et al., 2025)

Manajemen Identitas dan KYC/AML

- Verification of investor identity (Know Your Customer - KYC) and transaction monitoring to prevent money laundering (Anti-Money Laundering - AML) or terrorist financing. This process is often carried out off-chain by regulated service providers (Tan et al., 2023)

Sumber : (Bhattacharjee et al., 2005; Lavayssière, 2025; Riabokin et al., 2025; Tan et al., 2023; Teis and Clarke, 2024).

Figure 2. Off-Chain Governance Components

Rationalization of Hybrid Governance: Balancing Decentralization with Compliance and Security

The hybrid governance model addresses the limitations of pure on-chain governance, which may not be fully compatible with traditional legal frameworks or the complexities of managing physical assets. This approach allows for greater flexibility in managing underlying assets and complying with existing regulations, which is critical for mass adoption by institutions and SMEs (World Economic Forum, 2025). Additionally, hybrid models can also improve efficiency by combining claims on platform services and profits, creating aligned incentives for all stakeholders (Abadi and Brunnermeier, 2024).

The success of hybrid governance depends heavily on the ability of on-chain and off-chain systems to interact seamlessly. This includes the ability of tokens to be enriched with real-world

information, transferred securely across chains, and connected to off-chain data (Wibowo, 2023). The lack of interoperability between different ledger systems can hinder the full potential of tokenization and cause market fragmentation. Solutions such as Chainlink, which provides oracle services to connect smart contracts with real-world data, and Quant, which develops blockchain interoperability technology, are working to bridge this gap (Kristanto et al., 2014). Therefore, the development of universal message standards and uniform ledger protocols is a critical prerequisite for realizing the full benefits of MSME asset tokenization on a large scale, ensuring that the legal and physical aspects of assets can be efficiently synchronized with their digital representations.

Table 3. Governance Components and Functions in On-Chain and Off-Chain Systems

Governance Aspects	On-Chain Components	Main On-Chain Functions	Off-Chain Components	Main Off-Chain Functions
Automation and Execution	*Smart Contracts*	Automatic contract execution, transfer of rights, and payments without intermediaries	Traditional Legal Agreement	Establish a binding legal framework outside the blockchain, with enforcement through judicial systems.
Verification and Audit	*Blockchain Validators*	Validates and verifies on-chain transactions, ensuring the integrity of blockchain data.	Independent Auditor	Verify the existence, value, and ownership of tokenized physical assets.
Compliance & Legality	Protocol Rules (code)	Ensuring compliance with the rules programmed into the smart contract.	Legal and Regulatory Framework	Ensuring compliance with securities laws, AML/KYC, and other regulations in relevant jurisdictions.
Asset Storage (OJK, 2023)	*Digital Wallet*	Storing digital tokens that represent asset ownership.	Custodian	Storing and managing the physical assets underlying the tokens, ensuring physical security.
Decision Making	DAO and Token *Governance*	Collective and transparent decision-making by token holders.	Legal Entity (e.g., SPV)	Manage assets and operations under the legal framework in accordance with decisions made by shareholders/token holders.

Risks of SME Asset Tokenization in the DeFi Ecosystem

Although tokenization of MSME assets in DeFi offers great opportunities, its implementation also comes with various risks that need to be carefully identified and mitigated. These risks can be categorized into technical, regulatory, market, and operational risks.

1. Technical Risk

Technical risks in SME asset tokenization are closely related to the underlying blockchain infrastructure and smart contracts. One of the main risks is smart contract vulnerability. According to a 2023 report by Chainalysis, more than US$1.9 billion in crypto assets were lost due to smart contract exploitation, including re-entrancy attacks, oracle manipulation, and flash loan exploits (Chainalysis, 2024). This highlights the importance of regular security audits, given that most MSMEs do not have the internal capacity to assess the security of code used.

On the other hand, the challenge of scalability in blockchain infrastructure is also a concern, given that some networks are unable to process high transaction volumes efficiently, resulting in transaction delays and increased costs (Dewi, 2024). Although Layer 2 solutions such as Polygon and Avalanche have been developed to address these challenges, their adoption rate remains

limited and uneven (Calibraint, 2025). The problem is exacerbated by the gap between the complexity of the DeFi technology ecosystem and the digital readiness of MSMEs. Many MSME players in Indonesia still face significant obstacles, such as budget constraints, low digital literacy, and a lack of human resource capacity to optimally adopt and manage blockchain-based technology (Tarhini, 2021; Wahida, 2025). This gap risks hindering the adoption of tokenization or even causing losses if it is not accompanied by inclusive infrastructure support and adequate literacy and technical assistance programs. Therefore, a user-friendly tokenization platform design is needed, as well as policy and institutional support specifically aimed at strengthening the digital readiness of MSMEs in facing this transformation.

2. Regulatory Risk

The regulatory landscape for digital assets, including asset tokenization, is still in a dynamic and evolving phase, creating legal uncertainty and complex compliance challenges for market participants, particularly MSMEs (Wibowo, 2023). The absence of comprehensive standards and codes of conduct leads to market fragmentation and opens opportunities for manipulation or misuse of tokenized assets. These conditions underscore the urgent need for a clear, consistent, and coordinated regulatory framework that can provide legal certainty and support responsible innovation.

Compliance with Anti-Money Laundering (AML) and Know Your Customer (KYC) regulations further intensifies the regulatory burden. Strict identity verification and transaction-monitoring requirements impose operational and cost pressures on MSMEs, many of which are unfamiliar with digital compliance systems (Moreno et al., 2020). This complexity is compounded by shifting asset classifications: in Indonesia, crypto assets currently categorized as commodities under BAPPEBTI are transitioning to the Financial Services Authority (OJK). This move may lead to their reclassification as securities, which would entail more stringent registration, disclosure, and trading obligations (Alfiani, 2024; Kusnadi et al., 2023). Adaptive and balanced regulations are needed to support innovation while ensuring consumer protection and financial stability (Soni et al., 2025). However, regulatory processes tend to be slower than the pace of technological innovation. The shift in crypto oversight in Indonesia from BAPPEBTI to OJK and the potential change in classification from commodities to securities are concrete examples of this uncertainty (Kobrata, 2025).

Regulatory complexity is further heightened by divergent international standards. Since tokenized assets can be traded seamlessly across borders, businesses face inconsistent rules between jurisdictions, creating substantial cross-border compliance burdens for platforms and investors. These challenges can hinder the global expansion of MSMEs and startups, emphasizing the need for policy harmonization at both national and international levels, as well as regulatory frameworks that promote innovation while preserving financial stability.

In parallel, Data governance and cybersecurity responsibilities are another new regulatory issue. Data protection rules apply to tokenization systems since they handle sensitive financial and personal data. Operational complexity is increased by ensuring safe data storage, breach reporting procedures, and adherence to data localization regulations. MSMEs, which usually lack technical capacity, may be more vulnerable to compliance issues, especially as financial technology companies are subject to stricter cybersecurity regulations. Another source of uncertainty is taxation. Businesses reporting obligations and transaction expenses are directly impacted by the tax classification of tokenized assets. Regular policy changes run the danger of producing uneven tax costs that can deter adoption.

Consumer and investor protection is another area of regulatory concern. Regulators must decide on suitable disclosure rules, risk warnings, dispute resolution procedures, and protections against market abuse because tokenization can make it difficult to distinguish between traditional and digital financial products. Technical know-how and regulatory capability are additional fundamental problems. The technological knowledge required to adequately oversee tokenization

markets is still being developed by many regulators. Delays in policy responses, uneven enforcement, or too cautious regulatory measures could result from this capability gap.

3. Market Risk

Market risk is one of the crucial aspects that must be considered in the implementation of asset tokenization, particularly in the context of real-world assets (RWA) integrated into the decentralized finance (DeFi) ecosystem. One of the main challenges is the volatility of the crypto market, where the value of digital assets can experience extreme fluctuations in a short period of time. Although RWA tokenization aims to bring stability to the DeFi ecosystem, the value of tokens pegged to real-world assets can still be affected by overall crypto market volatility, creating uncertainty for investors and asset owners (Financial Stability Board, 2024).

On the other hand, although tokenization is intended to increase liquidity, the reality in the secondary market shows that not all tokenized assets have adequate liquidity. Especially for niche or lesser-known MSME assets, the secondary market often lacks sufficient transaction depth, making it difficult for investors to resell their tokens. The inability to exit investments easily can reduce investor interest in such assets and hinder broader participation in token-based financing. Therefore, the development of strong secondary market infrastructure, including integration with decentralized exchanges or digital trading desks, is a strategic necessity to support the sustainability of the MSME tokenization ecosystem (OECD, 2020).

Furthermore, although the basic principle of DeFi is decentralization, in reality many tokenization platforms still operate in a centralized manner. This dependence on central entities creates a single point of failure risk and raises concerns about the transparency and integrity of operational processes. If the infrastructure is not openly audited or depends on certain parties, technical and governance risks increase significantly, which can ultimately affect market confidence.

Finally, the Financial Stability Board (FSB) also highlighted the importance of the quality and pricing of tokenized assets. As the adoption of tokenization technology increases, there is a potential for the emergence of tokens that represent assets of low quality or with insufficient information. The lack of standards in asset valuation and data verification can lead to price distortions, misallocation of capital, and increased systemic risk. Therefore, stricter regulatory frameworks and asset evaluation mechanisms are needed to ensure that tokenization truly reflects the real economic value of the assets it represents.

4. Operational Risk

Operational risk in real-world asset (RWA) tokenization ecosystems is an important aspect that can affect the success of implementation and the sustainability of the system as a whole (Chen et al., 2024). One of the main risks arises from dependence on off-chain third parties, such as custodians, trustees, or financial institutions tasked with storing and managing the physical assets underlying the tokens. This dependence opens up the potential for counterparty risk, whereby if the third party experiences operational failure, bankruptcy, or refuses to fulfill its asset redemption obligations, on-chain token holders risk incurring losses (Robertson, 2016). This poses a serious challenge in reliably and securely bridging physical assets with their digital representations.

Additionally, the coordination process between on-chain systems and off-chain entities is often complex and prone to errors. Failure to synchronize information or processing times can result in transaction delays, recording errors, and discrepancies between the actual condition of physical assets and the tokens circulating on the blockchain network. This risk is exacerbated if there are no strict verification and audit mechanisms in place to maintain data integrity. Without clear and well-documented links between tokens and physical assets, the value and trust in RWA tokens can be significantly degraded.

On the other hand, cost is also an operational consideration that cannot be ignored, especially for MSME players. The implementation of tokenization technology requires a significant initial investment, including development costs, digital infrastructure, and integration with

blockchain systems. Additionally, a sustainable budget allocation is required for platform maintenance, periodic audits, and security system management. For SMEs with limited budgets, these cost burdens can act as barriers to fully and sustainably adopting tokenization solutions. Therefore, mitigating operational risks must be an integral part of the tokenization system design, through strengthened governance, transparency of off-chain partners, and cost efficiency in technology implementation.

Although blockchain simplifies on-chain transactions, the biggest operational challenge lies in bridging the gap between SME physical assets and their digital representations. Reliance on off-chain custodians and the need for ongoing verification and auditing add layers of complexity and cost. For SMEs, which may lack the infrastructure or expertise to manage these on-chain and off-chain interactions, operational risks can become extremely high. Therefore, an end-to-end solution is needed to simplify this process, potentially through a comprehensive tokenization service provider that manages both on-chain and off-chain aspects in an integrated manner.

Relevant Asset Tokenization (RWA) Case Studies and Pilot Projects

The implementation of real-world asset (RWA) tokenization is now entering a more mature phase, shifting from experimentation to real-world application in various countries. Institutional case studies show that tokenization is technically feasible and can be adapted to regulations without disrupting financial stability. This technology has proven capable of increasing investment access, improving the liquidity of illiquid assets, and opening up more inclusive economic participation. Although its implementation is currently dominated by the corporate sector and large institutions, existing models and infrastructure offer valuable lessons that can be adapted for MSMEs in emerging markets

One of the most relevant examples is an initiative from Franklin Templeton, which launched the Franklin on Chain U.S. Government Money Fund—the first government mutual fund to be fully managed and recorded through a public blockchain network. This project not only demonstrates that traditional assets such as government bonds can be tokenized, but also proves that the process can remain compliant with US capital market regulations (OECD, 2020). Such an approach opens up the possibility of managing public assets or SME-based investment funds in a more transparent and efficient manner through tokenization.

The Dubai Land Department, in collaboration with the Prypco Mint platform, has launched the first real estate tokenization project in the MENA region. Through this initiative, people can purchase fractional ownership of real estate properties with a minimum investment of AED 2,000 (approximately USD 545), making it more affordable and democratic. Interestingly, during the initial phase, all transactions are facilitated using the local currency, the UAE Dirham, rather than cryptocurrency, signalling careful integration with the conventional financial system and a more user-friendly approach toward regulators and the general public (Ferrara et al., 2022). JPMorgan, as a representative of established financial institutions, has developed the Onyx Digital Assets platform to manage securities transactions and intraday interbank payments using blockchain-based token technology. This project significantly reduces counterparty risk and improves operational efficiency, marking an important shift in how large financial institutions settle high-value transactions in real time (Rudzeyt et al., 2020).

In addition, research on Neuro-Ledger shows that this technology offers an alternative DLT approach that overcomes a number of fundamental limitations of traditional blockchains. Neuro-Ledger is designed to provide distributed storage that is tamper-proof and auditable, while maintaining privacy and compliance with regulations such as GDPR (Waher, 2019). Unlike proof-of-work-based blockchains that require intensive computation, Neuro-Ledger adopts a trust-based architecture through cryptographic identities, XMPP communication, and the IEEE P1451.99 proposed standard, enabling secure and efficient cross-domain interoperability. Its no-chain architecture allows for the deletion of irrelevant data in line with the principle of data minimization and prevents the information waste that commonly occurs on immutable blockchains. These characteristics are particularly significant in the application of RWA tokenization, which involves

sensitive data and physical asset administration updates (Waher, 2021). Additionally, support for heterogeneous nodes, including low-power devices, makes Neuro-Ledger relevant for the SME ecosystem and smart-city implementations that require energy efficiency, scalability, and long-term compatibility.

In line with these advantages, sustainable real estate tokenization demonstrates that real-world asset (RWA) tokenization provides significant legal benefits through the digitization of the legal framework into IEEE P1451.99 proposed standard based smart contracts (Waher et al., 2022). This model allows contracts to contain human-readable legal text as well as machine-executable instructions, so that each token carries legally valid rights and obligations because it is validated by a Trust Provider before use. Thus, these smart contracts have stronger legal integrity than public blockchain-based smart contracts, which are non-auditable and non-revisable.

From an investor protection perspective, the PropiToken project demonstrates that tokenization enables unique proof of ownership, full auditability throughout the asset lifecycle, and automatic revenue distribution based on legal provisions documented in the ledger. Token owners are treated as shareholders who receive rental income transparently, thereby reducing information asymmetry and providing a dispute resolution mechanism based on an immutable digital trail.

Regulatory-wise, the integration of KYC mechanisms, digital identity-based access control, privacy contracts, and granular authorization in the IEEE P1451.99 proposed standard reinforces the principle of compliance by design. Legal contracts can incorporate sectoral provisions–such as real estate regulations, environmental obligations, and data protection–directly into the technology architecture, facilitating cross-domain policy harmonization in multi-actor ecosystems such as smart cities and MSME financing.

CONCLUSION

This study comprehensively examines the transformative potential of asset tokenization for Micro, Small, and Medium Enterprises (MSMEs) within the Decentralized Finance (DeFi) ecosystem, identifying significant opportunities, inherent risks, and the need for an innovative hybrid governance architecture. MSMEs in Indonesia face chronic challenges in accessing traditional financing and adopting digital technologies, which hinder their growth and competitiveness. Asset tokenization has emerged as a promising solution, enabling fractional ownership, increased asset liquidity through 24/7 trading, higher operational efficiency through smart contracts, and enhanced transparency and security thanks to blockchain technology. For SMEs, this means broader and faster access to global funding sources, while for investors, tokenization opens the door to portfolio diversification into high-value assets with minimal investment and attractive potential returns. However, this implementation is not without risks, including smart contract vulnerabilities, cyberattacks, blockchain scalability challenges, regulatory uncertainty, crypto market volatility, and operational risks related to reliance on off-chain third parties.

To navigate this complexity and maximize benefits while mitigating risks, this research emphasizes the importance of a hybrid governance architecture. This model intelligently integrates on-chain elements such as smart contracts and DAOs for automation and decentralization, with off-chain components such as legal frameworks, custodians, and auditors to ensure regulatory compliance, legality, and physical asset management. A hybrid approach is essential given Indonesia's evolving regulatory landscape, particularly with the transition of crypto asset oversight from BAPPEBTI to OJK and the potential reclassification of crypto assets as securities. Global case studies demonstrate the technical and commercial viability of RWA tokenization at an institutional scale, providing a valuable blueprint for implementation in Indonesian SMEs, albeit with relevant adjustments.

The implications of these findings are significant for various stakeholders. For MSMEs, tokenization offers an untapped avenue to address financing gaps and improve competitiveness in global markets, but requires improved digital literacy and technological readiness. For investors, it opens up unprecedented diversification opportunities and attractive potential returns, albeit with

a new risk profile that needs to be understood. For policymakers and regulators, there is an urgent need to develop a clear, adaptive, and balanced regulatory framework that supports innovation while protecting consumers and maintaining financial stability. The use of regulatory sandboxes and cross-sector collaboration will be key to creating a conducive ecosystem. Overall, the tokenization of SME assets within the DeFi ecosystem holds extraordinary transformative potential to drive financial inclusion and more equitable economic growth in Indonesia, provided that existing risks are proactively managed and supported by a robust governance framework and visionary policies.

REFERENCES

Abadi, J., & Brunnermeier, M. (2024). Token-based platform governance. *Journal of Financial Economics*, 162. https://doi.org/10.1016/j.jfineco.2024.103951

Ahmed, H. (2024). Security tokens, ecosystems and financial inclusion: Islamic perspectives. *International Journal of Islamic and Middle Eastern Finance and Management, 17*(4), 730–745. https://doi.org/10.1108/IMEFM-04-2024-0195

Alfiani, F. R. N. (2024). The Urgency of Comprehensive and Integrated Digital Asset Regulation. *Journal of Social Science, 5*(1), 90–102. https://doi.org/10.46799/jss.v5i1.764

Amartha. (2024). Securities Crowdfunding, Alternatif Pendanaan untuk UMKM. *Amartha*. https://amartha.com/blog/pendana/money-plus/securities-crowdfunding-alternatif-pendanaan-umkm/

Amyulianthy, R., Shalihah, M., Haryanti, T., Apriyanto, A., & Hakim, C. A. (2025). Kecerdasan Finansial : Mengelola Keuangan Bisnis untuk Pertumbuhan Berkelanjutan. *PT. Sonpedia Publishing Indonesia*. https://books.google.co.id/books?hl=en&lr=&id=znw9EQAAQBAJ&oi=fnd&pg=PA1&dq=DeFi+juga+menawarkan+potensi+untuk+diversifikasi+portofolio+bagi+investor,+memungkinkan+mereka+mendanai+berbagai+usaha+UMKM+dengan+modal+yang+lebih+kecil,+serta+berpotensi+mendapa

Ante, L. (2022). Liquidity Shocks, Token Returns and Market Capitalization in Decentralized Finance (DeFi) Markets. *SSRN Electronic Journal, August* 6, https://doi.org/10.2139/ssrn.4183105

Arwani, A., & Priyadi, U. (2024). Eksplorasi Peran Teknologi Blockchain dalam Meningkatkan Transparansi dan Akuntabilitas dalam Keuangan Islam: Tinjauan Sistematis. *Jurnal Ekonomi Bisnis & Manajemen, 2*(2), 23–37. https://doi.org/10.59024/jise.v2i2.653

Awasthi, V. (2024). Blockchain Revolution in Asset Management: A Comprehensive Analysis and Implementation Framework. *International Journal of Scientific Research in Engineering and Management, 08*(05), 1–5. https://doi.org/10.55041/IJSREM35343

Bamakan, S. M. H., Nezhadsistani, N., Bodaghi, O., & Qu, Q. (2022). Patents and intellectual property assets as non-fungible tokens; key technologies and challenges. Scientific Reports, 12(1), 2178. https://doi.org/10.1038/s41598-022-05920-6

Bhattacharjee, S., Moreno, K., & Yardley, J. (2005). Auditors as Underwriters: An Alternative Framework. *International Journal of Auditing, 9*(1), 1–19. https://doi.org/10.1111/j.1099-1123.2005.00099.x

Bolar, T. V. (2025, July 1). Tokenized Securities Unveiled: Navigating U.S. Securities Laws with Robinhood and Ondo. *medium.com*. https://medium.com/@trentice.bolar/tokenized-securities-unveiled-navigating-u-s-securities-laws-with-robinhood-and-ondo-d57f8fe194e7

Calibraint. (2025, July 21). RWA Tokenization Platform Development: Choosing the Right Blockchain for Real-World Asset Transformation. *Calibraint*. https://www.calibraint.com/blog/rwa-tokenization-platform-development

Chainalysis. (2024, January 24). Funds Stolen from Crypto Platforms Fall More Than 50% in 2023, but Hacking Remains a Significant Threat as Number of Incidents Rises. *Chainalysis*. https://www.chainalysis.com/blog/crypto-hacking-stolen-funds-2024/?utm_source=chatgpt.com

Chambefort, C., & Chaudey, M. (2024). Blockchain, tokens, smart contracts, and "decentralized autonomous organization": Expanding and renewing the mechanisms of governance? *European Management Review, 21*(3), 511–515. https://doi.org/10.1111/emre.12677

Chen, H. (2023). Blockchain Technology and Small and Medium Enterprises Access to Finance. *Advances in Economics, Management and Political Sciences, 8*(1), 138–144. https://doi.org/10.54254/2754-1169/8/20230297

Chen, S., Jiang, M., & Luo, X. (2024). Exploring the Security Issues of Real World Assets (RWA). *Proceedings of the Workshop on Decentralized Finance and Security*, 31–40. https://doi.org/10.1145/3689931.3694913

Corey, E., Koffler, M., Garcia, C., & Sutherland, E. (2025, July 7). Tokenization: Benefits, risks, and its impact on fund business. *Fund Board Views*. https://fundboardviews.com/Content_Free/Viewpoints-tokenization-Corey-Eversheds.aspx

Dewi, H. (2024, September 13). Tokenisasi Aset: Pengertian, Jenis, Manfaat, dan Peran dalam Dunia Keuangan. *Be in Crypto*. https://id.beincrypto.com/belajar/tokenisasi-aset/

Eko. (2025). Decentralized Finance (DeFi): Masa Depan Keuangan Tanpa Bank dan Peluang Investasi di Era Digital. *Universitas Gadjah Mada Fakultas Ekonomika Dan Bisnis Magister Sains Dan Doktor*. https://mscdoctor.feb.ugm.ac.id/id/decentralized-finance-defi-masa-depan-keuangan-tanpa-bank-dan-peluang-investasi-di-era-digital/

Ekwealor, B. (2025). Tokenization and Decentralized Autonomous Organizations: Revolutionizing Digital Governance and Asset Management: Vol. July. https://www.researchgate.net/publication/393228085_Tokenization_and_Decentralized_Autonomous_Organizations_Revolutionizing_Digital_Governance_and_Asset_Management

Faruk, M. J. H., Raya, P., Siam, M. K., Cheng, J. Q., Shahriar, H., Cuzzocrea, A., & Bringas, P. G. (2024). A Systematic Literature Review of Decentralized Applications in Web3: Identifying Challenges and Opportunities for Blockchain Developers. *2024 IEEE International Conference on Big Data (BigData)*, 6240–6249. https://doi.org/10.1109/BigData62323.2024.10826066

Felicia, F., Elvilie, E., Calista, C., Chic, S. A., Bilqisthi, M. F., & Joosten, J. (2024). Tantangan dan Peluang Blockchain di Era Digital dalam Bidang Keamanan Data dan Transaksi Digital. *Journal of Comprehensive Science (JCS), 3*(11), 5131–5147. https://doi.org/10.59188/jcs.v3i11.2887

Ferrara, G., Messina, F., De Benedetti, M., & Santoro, C. (2022). Physical Assets Tokenization for Blockchain Market. *International Symposium on Intelligent and Distributed Computing*, 273–282. https://doi.org/10.1007/978-3-030-96627-0_25

Financial Stability Board. (2024). The Financial Stability Implications of Tokenisation (Issue October). www.fsb.org/emailalert

Fitriani, Purnamasari, E., & Hapsari, A. A. (2024). Perbankan dan revolusi blockchain: Membangun keuangan berbasis DLT (Distributed Ledger Technology). *Takaza Innovatix Labs*. https://books.google.co.id/books?hl=en&lr=&id=iyQyEQAAQBAJ&oi=fnd&pg=PR6&dq=Dari+sisi+efisiensi+operasional,+tokenisasi+yang+didukung+oleh+smart+contract+memungkinkan+otomatisasi+berbagai+proses+bisnis+penting,+termasuk+eksekusi+pembayaran,+distribusi+keu

Fox, D. (2021). Tokenised Assets in Private Law. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3807858

Golberg, M., & Palladini, E. (2011). Pengelolaan Risiko Dan Penciptaan Nilai Melalui Pendanaan

Usaha Mikro.

Gudgeon, L., Werner, S., Perez, D., & Knottenbelt, W. J. (2020). DeFi Protocols for Loanable Funds. *Proceedings of the 2nd ACM Conference on Advances in Financial Technologies*, 92–112. https://doi.org/10.1145/3419614.3423254

Gupta, A., Rathod, J., Patel, D., Bothra, J., Shanbhag, S., & Bhalerao, T. (2020). Tokenization of Real Estate Using Blockchain Technology. *International Conference on Applied Cryptography and Network Security*, 77–90. https://doi.org/10.1007/978-3-030-61638-0_5

Haq, F. N. (2021). Mengapa Teknologi DeFi Akan Menjadi Masa Depan Jasa Keuangan? *Pluang*. https://pluang.com/blog/resource/decentralized-finance-masa-depan

Hasan, H. R., & Salah, K. (2018). Proof of Delivery of Digital Assets Using Blockchain and Smart Contracts. *IEEE Access*, 6, 65439–65448. https://doi.org/10.1109/ACCESS.2018.2876971

Herman, H., Husna, J., Biddinika, M. K., Yulianto, D., Fitriah, F., & Suwanti, S. (2024). Kerangka Sistem Aset Digital pada Infrastruktur Blockchain yang Sejalan dengan Syariah Islam. *JIPI (Jurnal Ilmiah Penelitian Dan Pembelajaran Informatika), 9*(2), 768–781. https://doi.org/10.29100/jipi.v9i2.5431

Humas Tel-U Surabaya. (2024). Tokenisasi: Pengertian, Manfaat, dan Peran Profesional IT. *Telkom University Surabaya*. https://surabaya.telkomuniversity.ac.id/tokenisasi-pengertian-manfaat-dan-peran-profesional-it/

Hutabarat, M. R. E., Lathiefllhamy Nst, M., & Harahap, M. I. (2025). Analisis Kontribusi Crowdfunding Syariah Dalam Pengembangan UMKM di Sumatera Utara. *Kamaya: Jurnal Ilmu Agama, 8*(1), 105–119. https://doi.org/10.37329/kamaya.v8i1.4025

Ikponmwoba, S. O., Chima, O. K., & Ezeilo, O. J. (2022). Conceptual Framework for Access to Finance in SMEs Using Decentralized Conceptual Framework for Access to Finance in SMEs Using Decentralized Digital Lending Platforms. *International Scientific Refereed Research Journal, 5*(2), 164–174.

Kadir, S. (2023). Keuangan Terdesentralisasi (DeFi) Dan Fintech Syariah dalam Sistem Keuangan Abad 21. *Journal of Accounting and Finance (JACFIN), 5*(2), 1–14. https://jurnal.umus.ac.id/index.php/jacfin/article/view/1253?utm_source=chatgpt.com

Kobrata, D. (2025, January 10). Regulatory Update: OJK Regulation 27/2024 Redefines Crypto From Commodity to Financial Asset. *advocates.com*. https://www.kk-advocates.com/news/read/regulatory-update-ojk-regulation-272024-redefines-crypto-from-commodity-to-financial-asset

Kreppmeier, J., Laschinger, R., Steininger, B. I., & Dorfleitner, G. (2023). Real estate security token offerings and the secondary market: Driven by crypto hype or fundamentals? *Journal of Banking & Finance, 154*(September), 106940. https://doi.org/10.1016/j.jbankfin.2023.106940

Kristanto, K., Nurjamil, Jaya, I. K. N. A., & Jalianery, J. (2014). Transformasi Hukum dalam Era Revolusi Teknologi Blockhain. *In Penambahan Natrium Benzoat Dan Kalium Sorbat (Antiinversi) Dan Kecepatan Pengadukan Sebagai Upaya Penghambatan Reaksi Inversi Pada Nira Tebu*.

Kumar, D., Phani, B. V., Chilamkurti, N., Saurabh, S., & Ratten, V. (2023). Filling the SME credit gap: a systematic review of blockchain-based SME finance literature. *Journal of Trade Science, 11*(2/3), 45–72. https://doi.org/10.1108/JTS-06-2023-0003

Kusnadi, E. H., Nasir, R. R., & Hulwanullah, H. (2023). Legal Aspects of Crypto Assets on Indonesian Digital Investment Development. *Supremasi Hukum: Jurnal Kajian Ilmu Hukum, 12*(2), 145–162. https://doi.org/10.14421/sh.v12i2.3168

Lavayssière, X. (2025). Legal Structures of Tokenised Assets. *European Journal of Risk Regulation*, 1–13. https://doi.org/10.1017/err.2024.88

Lewandowska, A., Berniak-Woźny, J., & Ahmad, N. (2023). Competitiveness and innovation of small and medium enter-prises under Industry 4.0 and 5.0 challenges: A comprehensive bibliometric analysis. Equilibrium. *Quarterly Journal of Economics and Economic Policy, 18*(4), 1045–1074. https://doi.org/10.24136/eq.2023.033

Liu, A., & Chen, C. (2025). From real estate financialization to decentralization: A comparative review of REITs and blockchain-based tokenization. *Geoforum, 159*(February), 104193. https://doi.org/10.1016/j.geoforum.2024.104193

Lubis, M. A., Anshori, M. A. I. Al, Khairunnisa, K., Ardiansyah, M., Schouten, F. S., Huda, M. M., Suardi, C., Arnomo, S. A., Nopriandi, H., & Imandeka, E. (2025). Database Blockchain: Penyimpanan Data Terdesentralisasi untuk Aplikasi Modern. *CV. Gita Lentera*. https://books.google.co.id/books?hl=en&lr=&id=Xh9gEQAAQBAJ&oi=fnd&pg=PA72&dq=Eksploitasi+ini+dapat+mencakup+serangan+reentrancy,+manipulasi+oracle,+atau+flash+loan+exploits&ots=rAXwuexLPs&sig=8G14oWx9LCFCEivTHoDhCsAAoQY&redir_esc=y#v=onepage&q&f=false

Lukas, A. J. F. (2020). Blockchain Tokens From the Perspective of German Civil Law: An Updated View. *SSRN Electronic Journal*, January 28. https://doi.org/10.2139/ssrn.3526887

Moreaux, A. C., & Mitrea, M. P. (2023). Royalty-Friendly Digital Asset Exchanges on Blockchains. *IEEE Access*, 11, 56235–56247. https://doi.org/10.1109/ACCESS.2023.3283153

Moreno, S. M. B. M., Seigneur, J.-M., & Gotzev, G. (2020). A Survey of KYC/AML for Cryptocurrencies Transactions. *In Handbook of research on cyber crime and information privacy* (pp. 21–42). https://doi.org/10.4018/978-1-7998-5728-0.ch002

Nadya, N. (2022). Prospek dan tantangan dalam investasi NFT sebagai salah satu produk aset kripto [*Universitas Islam Negeri Maulana Malik Ibrahim*]. http://etheses.uin-malang.ac.id/44197/

OECD. (2020). The Tokenisation of Assets and Potential Implications for Financial Markets. https://doi.org/10.1787/83493d34-en

Osho, G. O., Bihani, D., Daraojimba, A. I., Omisola, J. O., Ubamadu, B. C., & Etukudoh, E. A. (2024). Building Scalable Blockchain Applications: A Framework for Leveraging Solidity and AWS Lambda in Real-World Asset Tokenization. *International Journal of Advanced Multidisciplinary Research and Studies, 4*(6), 1842–1862. https://doi.org/10.62225/2583049X.2024.4.6.4157

Otoritas Jasa Keuangan (OJK). (2023). Penyelenggaraan Perdagangan Aset Keuangan Digital Termasuk Aset Kripto (pp. 1–128). https://ojk.go.id/id/regulasi/otoritas-jasa-keuangan/rancangan-regulasi/Documents/RPOJK

Patil, R., Swarnkar, S. K., Bhadane, D. Y., Poddar, G. M., Patil, M. P., & Sonawane, R. C. (2025). Exploring governance frameworks and decision processes in blockchain-based decentralized autonomous organizations. *International Journal of Basic and Applied Sciences, 14*(1), 166–180. https://doi.org/10.14419/h0y6dw98

Permana, Y. S., Hadiana, A. I., & Putra, E. K. (2019). Pemanfaatan Blockchain pada Pembangunan Sistem Informasi Pembiayaan Usaha Mikro Kecil Menengah. *Seminar Nasional Sistem Informasi Dan Teknologi, 3*(1), 12–17.

Polikarpova, M. (2018). Settlement risk in cross-border transactions: traditional and new approaches [*Norwegian School of Economics*]. http://hdl.handle.net/11250/2585438

Ponniah, V. M. (2014). A study of relationship between receivables management variables of micro small and medium enterprises (MSMEs) in Tamilnadu and their problems. *International Journal of Physical and Social Sciences, 4*(1), 5–14.

Pramudya, H., Alamsyah, A., & Tricahyono, D. (2024). Blockchain-Based Tokenization for Green Bonds: A Model for Transparency and Compliance in Sustainable Finance. *2024 IEEE Asia-Pacific Conference on Geoscience, Electronics and Remote Sensing Technology (AGERS)*, 64–

69. https://doi.org/10.1109/AGERS65212.2024.10932908

Riabokin, M., Kotukh, Y., Nikolaievskyi, D., & Yefimenko, Y. (2025). Legal regulation of real asset tokenization: prospects for the development of Ukrainian legislation on virtual assets. Economics. *Finances. Law, 3*/2024, 84–92. https://doi.org/10.37634/efp.2025.3.15

Robertson, D. (2016). Introduction to Operational Risk. *In Managing Operational Risk* (pp. 1–17). Palgrave Macmillan US. https://doi.org/10.1007/978-1-137-44217-8_1

Rozario, A. M., & Thomas, C. (2019). Reengineering the Audit with Blockchain and Smart Contracts. *Journal of Emerging Technologies in Accounting, 16*(1), 21–35. https://doi.org/10.2308/jeta-52432

Rudzeyt, O., Nedyak, A., & Zainetdinov, A. (2020). Tokenization of assets and products. *Russian Journal of Resources, Conservation and Recycling, 7*(2). https://doi.org/10.15862/10INOR220

Saqib, N. A., & AL-Talla, S. T. (2023). Scaling Up Security and Efficiency in Financial Transactions and Blockchain Systems. *Journal of Sensor and Actuator Networks, 12*(2), 31. https://doi.org/10.3390/jsan12020031

Soni, U., Fines, O., & Sun, J. (2025). An Investment Perspective on Tokenization Part I: A Primer on the Use of Distributed Ledger Technology (DLT) to Tokenize Real-World and Financial Assets. *www.cfainstitute.org*.

Tan, H., Yan, S., Zou, X., Xie, G., Zhang, H., & Li, Z. (2023). FCToken: A Flexible Framework for Blockchain-Based Compliance Tokenization. *2023 IEEE International Conference on Data Mining Workshops (ICDMW)*, 671–681. https://doi.org/10.1109/ICDMW60847.2023.00093

Tarhini, M. (2021). Application of asset tokenization, smart contracts and decentralized finance in agriculture. *Journal of Financial Studies, 6*(10), 152–163. https://doi.org/10.55654/JFS.2021.6.10.11

Teis, S., & Clarke, M. (2024). A token-based operating model unifying traditional and token-based operations for security services. *Journal of Securities Operations & Custody, 16*(3), 247. https://doi.org/10.69554/LHWE1167

Treleaven, P., Greenwood, A., Pithadia, H., & Xu, J. (2022). Web 3.0 Tokenization and Decentralized Finance (DeFi). *SSRN Electronic Journal*, 1–19. https://doi.org/10.2139/ssrn.4037471

Waher, P. (2019). Neuro-LedgerTM Executive Summary (pp. 1–9).

Waher, P. (2021). Neuro-Ledger ® and Sustainability. 1–3.

Waher, P., Araoz, K., Pablo Pulgar, R., & Mostrom, D. (2022). Tokenization of sustainable real estate in Smart Cities : Monetization as basis for construction, authorization and carbon neutralization in CPS. *IECON Proceedings (Industrial Electronics Conference), 2022*-October. https://doi.org/10.1109/IECON49645.2022.9968404

Wahida, N. (2025, May 22). Tantangan dan Solusi Implementasi Transformasi Digital bagi UMKM. *UKM Indonesia.id*. https://ukmindonesia.id/baca-deskripsi-posts/5-tantangan-dan-solusi-implementasi-transformasi-digital-bagi-umkm

Wibowo, A. (2023). Teori Ekonomi Berbasis Big Data (J. T. Santoso (ed.)). Yayasan Prima Agus Teknik bekerja sama dengan Universitas Saints dan Teknologi Komputer. https://digilib.stiestekom.ac.id/assets/dokumen/ebook/feb_AMiGPd_pUA0kmI-eyELO-KqX7dg-crBWgDCk8TyJkA7UpdkG9XLcQQ_1704770517.pdf

Wicaksono, E. S. (2023). Kejatuhan FTX Dan Pelajaran Penting Bagi Solusi Crypto Custody: Analisis Risiko Sistemik Dan Perlindungan Aset. *Bridging Journal of Islamic Digital Economics and Management, 1*(1), 238–249. https://journal.alshobar.or.id/index.php/bridging/article/view/144

World Economic Forum. (2025). Asset Tokenization in Financial Markets : The Next Generation of

Value Exchange. https://www.weforum.org/publications/asset-tokenization-in-financial-markets-the-next-generation-of-value-exchange/

Yaramolu, L. S. K. G. (2025). Smart contracts in Fintech: Revolutionizing financial transactions. *World Journal of Advanced Research and Reviews, 26*(1), 4149–4159. https://doi.org/10.30574/wjarr.2025.26.1.1514

Zhitomirskiy, E., Schmid, S., & Walther, M. (2023). Tokenizing assets with dividend payouts–a legally compliant and flexible design. *Digital Finance, 5*(3–4), 563–580. https://doi.org/10.1007/s42521-023-00094-w