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Research paper

Enhancing Mobile DeFi Transactions Through Blockchain Adoption: A Pythagorean Fuzzy AHP Study

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Abstract

Blockchain technology has emerged as a pivotal enabler for innovation in mobile decentralized finance (DeFi) ecosystems. This study em-employs the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) to identify and rank critical enablers driving blockchain adoption for enhancing mobile DeFi transactions. A structured three-stage methodology evaluates twenty-four sub-criteria across operational, managerial, and strategic dimensions. Results emphasize managerially focused factors—such as reduced foreign exchange (FX) transfer costs and open-source adaptability—as the most critical enablers, followed by operational drivers like transparency. Sensitivity analysis confirmed the ro-robustness of these findings. The results offer actionable insights for fintech practitioners, digital strategists, and policymakers seeking to optimize blockchain-based mobile financial platforms. By contributing to improved financial inclusion, operational efficiency, and regulatory alignment, the study supports broader welfare enhancement in the digital economy. The proposed PF-AHP framework provides an empirical decision-making tool to guide innovation and strategic planning in financial technology services.

Keywords: *Blockchain; Cross-Border Transactions; Defi; Digital Finance; Fintech Strategy; PF-AHP.*

1. Introduction

Blockchain technology, initially developed for internet-based applications, has evolved into a powerful enabler of secure, transparent, and efficient digital transactions. Its core advantages—cost-effectiveness, accessibility, transparency, and trust—have led to widespread adoption across industries such as banking, healthcare, and education. By eliminating intermediaries, blockchain systems enable decentralized ledgers that reduce operational costs, streamline business processes, and enhance data integrity. These characteristics make blockchain particularly well-suited for modern mobile ecosystems, where user demands for security, speed, and transparency are paramount.

One of the most impactful applications of blockchain lies in the domain of Decentralized Finance (DeFi), which leverages permissionless blockchain networks to enable direct, peer-to-peer financial transactions. DeFi platforms, often accessed via mobile devices, facilitate services such as asset management, lending, and derivatives trading without the need for traditional financial intermediaries. This mobile-centric evolution of DeFi not only lowers transaction costs but also expands financial inclusion by providing seamless, decentralized financial services to a broader population.

In this context, optimizing mobile DeFi transactions through effective blockchain adoption has become a critical research priority. Identifying and prioritizing the key enablers that drive successful blockchain integration is essential for improving mobile financial platforms' performance, security, and user experience. To address this need, this study employs the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) to systematically evaluate and rank the enablers of blockchain adoption for enhancing mobile DeFi transactions.

The integration of real-world assets within DeFi not only makes the markets more efficient but also differentiates DeFi from conventional traditional finance (TradFi) systems, making it a novel and impactful alternative [1]. Since the introduction of the Turing-complete Ethereum blockchain in 2015, the scope of blockchain-based financial systems has broadened, leading to increased popularity in DeFi solutions as new investment vehicles [2]. These systems are designed to offer greater security, accessibility, and transparency in solving the main financial challenges through blockchain technology.

Beyond finance, blockchain is an opener of roads for the Metaverse—a virtual reality that allows people to interact with and around them. Blockchain-based construction of the Metaverse also allows conducting real-world activities, such as financial operations, in a secure manner and in a decentralized format [3]. With the incorporation of cutting-edge technologies like AI, blockchain, and VR, the Metaverse is expected to grow in popularity, providing a wealth of job opportunities, including the creation of virtual enterprises.

However, challenges remain with DeFi protocols such as Compound, MakerDao, Uniswap, and Aave depend on oracles to retrieve external data, including cryptocurrency exchange rates [4]. The frequent reliance on centralized, unreliable oracles presents the 'oracle problem,' which poses significant risks in a growing investment environment. Poorly constructed oracles can lead to vulnerabilities, with severe consequences for DeFi applications [5]. Despite this, only 15% of academic publications address this problem, and the DeFi industry itself has made little progress in mitigating these risks. Another industry ripe for transformation by blockchain is the remittance sector, which serves nearly one billion people. The current remittance landscape is plagued by high costs, particularly in Sub-Saharan Africa, where currency conversion rates often exceed 6%, and inefficient international transfers that take, on average, two business days to complete [6]. Blockchain technology holds the potential to revolutionize cross-border payments by reducing costs and ensuring security. However, the financial services industry has been slow to adopt blockchain due to its fragmented structure and inability to handle high transaction volumes [7].

One of the persistent vulnerabilities in DeFi protocols—such as Compound, MakerDAO, Uniswap, and Aave—is their reliance on external oracles for retrieving off-chain data such as cryptocurrency prices. This introduces the well-known "oracle problem," where the decentralized integrity of DeFi platforms becomes compromised by a single or centralized data source. Recent developments have sought to resolve this issue through Decentralized Oracle Networks (DONs), including Chainlink, Band Protocol, and API3, which use aggregation mechanisms, cryptographic proofs, and distributed nodes to ensure secure data feeds [8], [9]. Alternative approaches, like UMA's Optimistic Oracle, rely on bonded proposers and a dispute mechanism handled by token-holders, offering reduced latency and increased reliability, with over 98% of submissions going undisputed [10]. Despite these innovations, challenges related to real-time performance, data latency, and incentive alignment persist. The Bank for International Settlements (BIS) also warns that introducing trusted or semi-centralized oracle providers, while improving accuracy, can erode the foundational decentralization of DeFi systems [11]. Therefore, critically examining oracle robustness, dispute resolution, and incentive mechanisms is vital for strengthening the resilience and reliability of blockchain-based financial ecosystems.

This paper is structured around the following sections: an introduction to blockchain technology explaining its benefits, applications, and disruptive power in any industry, be it financial services, healthcare, or supply chain management. Comprehensive literature review on blockchain focusing on its key features and challenges as well as its role in creating business value. The third section explains the methodology used in identifying and ranking the BBDF enablers using Pythagorean Fuzzy AHP. The fourth section provides findings based on significant blockchain enablers in retail finance. Section 5 gives an outline of research implications to both theoretical and practical applications. The study has its limitations, and Section 6 provides a future research direction, followed by concluding remarks summarizing the potential of blockchain technology in transforming industries.

2. Data center infrastructure and power consumption

2.1. Blockchain

Blockchain technology offers several key advantages, such as decentralization, persistence, anonymity, auditability, and transparency, and is applicable across domains like cryptocurrency, financial services, IoT, public services, and social services [15], [16]. Even after extensive research, comprehensive surveys are required to be carried out on both the technological and application perspectives of blockchain, which should reflect the taxonomy of blockchain, consensus algorithms, applications, technical challenges, and recent advances [15]. Unlike the traditional centralized systems, blockchain is a distributed ledger that enables safe, decentralized, and automated decision making in multi-stakeholder environments [17]. It is expected to touch a market value of more than $3 trillion in the next five years because of secure digital identity solutions and increased investment from corporations [18]. Its architecture is more secure and reliable due to components such as public key cryptography, Zero-Knowledge Proofs, and hash functions in its design [16].

Challenges remain in understanding the right conditions for adoption of blockchain, the changing nature of permissioned models against the permissionless ones, as well as the most appropriate mechanisms of consensus with differing applicability requirements for the technology [17]. Current research is still aimed at blockchain security through risk analysis and design of advanced security measures to counter actual attacks, bugs, and the need for scalability in widespread blockchain applications [13].

Blockchain Pillars - Blockchain technology is built upon three fundamental pillars: decentralization, transparency, and immutability, which have significantly contributed to its widespread adoption across industries. Decentralization eliminates the need for intermediaries, such as banks, empowering users to manage their data independently and conduct peer-to-peer transactions. Transparency ensures that all records on the blockchain are open and verifiable, while maintaining participant privacy through encrypted identities, thus achieving a balance between visibility and confidentiality. Immutability guarantees that once data is recorded on the blockchain, it cannot be altered or deleted, with cryptographic hashing providing an additional layer of data integrity and security. The blockchain pillars used to enable the business value with respect to the operational, managerial, strategic, and infrastructure perspectives as shown in Figure 1. This figure illustrates how the foundational pillars of blockchain technology—decentralization, transparency, and immutability—act as key enablers to drive business value in mobile financial services. By eliminating intermediaries, ensuring verifiable transactions, and securing data integrity, these enablers enhance operational efficiency, managerial effectiveness, and strategic growth. Together, they contribute to improving the performance, trust, and scalability of mobile DeFi applications.

In the automobile industry, blockchain integrates product information, ensures safe transactions, and digitalizes the supply chain, but immaturity of technology and the absence of standards pose obstacles to the full utilization of these advantages [19] Blockchain's attributes of decentralization and privacy have been exploited during the COVID-19 period in applications such as disease surveillance to enhance the precision and response of real-time data [20].

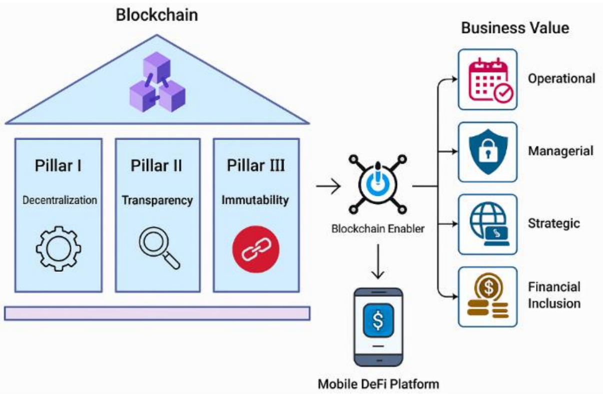

Fig. 1: Blockchain Enablers for Enhancing Mobile Financial Business Value.

In the automobile industry, blockchain integrates product information, ensures safe transactions, and digitalizes the supply chain, but immaturity of technology and the absence of standards pose obstacles to the full utilization of these advantages [19]Blockchain's attributes of decentralization and privacy have been exploited during the COVID-19 period in applications such as disease surveillance to enhance the precision and response of real-time data [20]. Blockchain in SCM minimizes intermediating activities. Trust, though, must still be managed between the trading partners. Blockchain would completely integrate into SCM operations in 2035[21]. More so, the case for EVs, through the BMS, smart charging stations, and swap station services, is available. In decentralized networks, blockchain Ethereum and IOTA permit the semi-decentralized data-driven energy management [22].

2.2. Blockchain as business value

Blockchain technology is a source of transformation for business value creation. It provides efficiency gains, new models of collaboration, and unique business opportunities. For 2030, blockchain is expected to create huge efficiencies and novel service combinations that make an "internet of value," which is a step above the current "internet of information" [23]. This shift will encourage businesses to re-evaluate their business models, as blockchain's immutable, transparent data storage changes value configuration, as has been witnessed in blockchain-based business models that result in market differentiation [24]. Blockchain was first used in financial services, but can be applied to any business sector, and this is making non-financial services businesses adapt to decentralized value creation and change traditional elements of business models [25]. Both the positive and ambiguous aspects of the ethical dimensions of blockchain also call for adequate ethical considerations from other perspectives, like utilitarianism and corporate social responsibility[26]. This means that business value is not just about blockchain's efficiencies in operational terms, but blockchain redefines the ethical approach and practicality of approaches to transparency and decentralized management of data in various fields.

Blockchain technology provides substantial business benefits by fostering trust among parties through reliable, shared data. It eliminates data silos by utilizing a distributed ledger that authorized users can access, ensuring high security for stored information. By reducing the need for third-party intermediaries, blockchain creates real-time, tamper-evident records that enhance transparency. Additionally, it enables verification of product authenticity and integrity in commerce, facilitates efficient tracking and tracing of goods across the supply chain, and improves food safety through specialized platforms like Oracle Blockchain. These advantages contribute to more secure and efficient business operations.

Blockchain technology has been increasingly recognized for its potential benefits from a business perspective. A study is conducted to investigate the key architectural features of integrating Fast Healthcare Interoperability Resources (FHIR) and blockchain to provide the benefits of immutability of transaction data for a decentralized and secured healthcare information exchange framework. Similarly, to give a systematic review of the present and future application of blockchain technology in the healthcare sector by pointing out important medical applications of blockchain technology. In the financial service sector, a systematic literature review on the current state of blockchain technology in the sector was conducted [14]. How blockchain technology may affect financial accounting since blockchain promises quality accounting information, minimizes errors of financial disclosure, and decreases information redundancy is discussed [27]. Blockchain Technology has also succeeded in food, as reviewed in this regard.

Furthermore, viewpoints between technology vendors and the early adopters of industries regarding the usage of blockchain technology for managing supply chains are compared, which was focused on the benefits and challenges that it will bring to business. Blockchain in the metaverse, carrying out an in-depth survey on its application. Studying blockchain technology as an ecosystem helps in focusing on its ability to explore trends and perspectives in accounting and management. Lastly, the importance of Blockchain in the healthcare sector where technical dependency should requires nuanced insights concerning specific use cases to represent a comprehensive understanding of healthcare executives.

Despite blockchain’s recognized advantages, particularly decentralization, transparency, and immutability, significant challenges persist in realizing its full potential within mobile financial ecosystems. Issues such as interoperability between platforms, scalability to support high transaction volumes, regulatory compliance across jurisdictions, and privacy protection for mobile users remain unresolved. These challenges are especially critical in the context of mobile decentralized finance (DeFi) applications, where seamless integration, real-time performance, and user trust are vital. Additionally, the ethical implications and legal frameworks surrounding blockchain use in mobile financial services are underexplored. Addressing these gaps is crucial for advancing blockchain-enabled mobile financial platforms and unlocking the next generation of secure, efficient, and inclusive mobile DeFi transactions.

Across domains, blockchain’s scalability and decentralization continue to be in tension. Several studies [16], [20], [26] emphasize that while decentralization enhances transparency and trust, it often comes at the cost of transaction speed and energy efficiency, especially problematic in finance and healthcare. Others [17], [15], [23], however, highlight emerging solutions like Layer-2 protocols, permissioned chains, and hybrid consensus that may resolve these issues. This lack of consensus across domains suggests a need for context-specific trade-off models, as scalability requirements in a supply chain application differ significantly from those in a mobile financial service or real-time health record system.

Furthermore, while many studies explore technical or application-specific benefits, few directly address interoperability, standardization, or regulatory harmonization, which are critical for cross-sector adoption. This highlights an ongoing gap between technical feasibility and real-world integration, especially in regulated industries.

Table 1: Blockchain Technology Contribution with Specific Outcome Achieved in Literature

Aspect	Description	Primary Use Cases	Challenges	Outlook	References
Core Advantages	Decentralization, transparency, immutability	Distributed control, secure data sharing	Interoperability, cost	Expected market growth in multiple sectors	[15], [17], [18]
Key Sectors	Cryptocurrency, financial services, IoT, public & social services	Payment systems, decentralized transactions	Regulation, adoption rate	Broader adoption across diverse industries	[15], [17],[18]
Technological Challenges	Tech immaturity, standards, and permission models	Scalability, interoperability, security	Scalability, regulatory compliance	Ongoing research for scalability	[9] [10]
Supply Chain	Data integration, secure transactions, and digital visibility	Inventory tracking, fraud reduction	Trust management, standards	Integration by 2035	[12],[14]
Healthcare	Decentralized health info exchange, secure data	Interoperable health records	Data privacy, compliance	More interoperable healthcare systems	[8]
Financial Services	Increased transparency, reduced intermediaries	Efficient value transfer, fraud reduction	Data standardization, scalability	Wider adoption as systems mature	[7]
Food Industry	Product authenticity, traceability	Food safety, fraud detection	Regulation, cost of implementation	Increased tracking and safety measures	[12]
Accounting	Enhanced quality, reduced errors in financials	Real-time auditing, compliance	Standardization, privacy concerns	Incorporation in auditing processes	[20]
Automotive	Product data management, secure transactions	Supply chain efficiency	Tech maturity, interoperability	Adoption in product lifecycle management	[12]
Energy Management	Smart charging, battery swaps via blockchain	Energy distribution management	Infrastructure needs	Expanded EV energy applications	[15]
Ethics & Security	Ethical, transparency, and security issues	Transparency in data usage	Ethical considerations, legal frameworks	Research on moral implications	[19]

2.2.1. Ethical and regulatory considerations

Blockchain technology, while offering enhanced transparency and security, also introduces ethical and regulatory complexities, especially in the financial services sector. The decentralized nature of blockchain challenges traditional regulatory frameworks, as jurisdictional boundaries become blurred and accountability becomes harder to enforce [12]. Financial authorities worldwide are grappling with how to ensure AML (Anti-Money Laundering) and KYC (Know Your Customer) compliance in decentralized systems, where users may operate pseudonymously. From an ethical standpoint, the immutability of blockchain raises concerns about data permanence, especially in cases involving personal or sensitive financial information [13]. Furthermore, power asymmetries may arise in DAO (Decentralized Autonomous Organization) governance structures, potentially excluding minority stakeholders [14]. Regulatory gaps in stablecoin issuance, smart contract liabilities, and cross-border capital controls also remain underdeveloped, leading to uncertainty for institutional adoption. Addressing these issues requires a hybrid governance approach—one that balances decentralization with regulatory oversight. Countries such as Switzerland and Singapore have made early advances by introducing sandbox regulations and tiered licensing frameworks, offering lessons for broader adoption. Future research and policy development should focus on regulatory interoperability, ethical auditing standards, and consumer protection mechanisms to ensure that blockchain-driven financial innovations align with societal and legal expectations.

2.3. Blockchain enablers

It is a revolutionary catalyst in practically all sectors, changing security, cooperation, and effectiveness in operations. In the health sector, it encourages patient-centered interoperability by setting clear protocols on digital access and ensuring data is not altered in the process, thus solving the problem of privacy and security issues [28]. In supply chain management, blockchain is seen as an innovative technology with the key drivers such as active stakeholder participation and technological readiness being key to its adoption [29]. The integration of blockchain and the Internet of Things (IoT) enhances security and privacy through systems such as Block Trust, which guarantees efficient service provision and anonymous identification [30]. Moreover, blockchain enhances the traceability and safeguarding of intellectual property by utilizing decentralized data storage and consensus processes to protect rights [31]. Nevertheless, despite its many advantages, hurdles such as limited resources in IoT and the need for strong governance structures in healthcare can hinder widespread acceptance.

Table 2: Key Operational, Managerial, and Strategic Criteria for Blockchain Adoption

Criteria	Code	Sub-Criteria	Description	References
Operational	OP1	Reduced cost	Blockchain eliminates intermediaries and manual record-keeping, lowering administrative costs.	[25], [26], [27]
	OP2	Improved accuracy	Automated, tamper-proof entries ensure that records are consistently accurate and reliable.	[28]
	OP3	Reduced fraud	Immutable records and consensus mechanisms significantly reduce opportunities for fraudulent activities.	[29],[30]
	OP4	More transparent	Every transaction is visible to all participants, enhancing accountability and traceability.	[29],[31]
	OP5	Increased transaction speed	Automated processes streamline transactions, reducing the time needed for completion.	[32],[33],[34]

	OP6	Disintermediation	Direct transactions between parties eliminate the need for middlemen, simplifying processes and reducing costs.	[2],[28]
	OP7	Improved data integrity	Data is stored in a decentralized manner, ensuring consistency and reliability across all copies.	[35],[36]
	OP8	Quasi-exhaustive recording	Blockchain's comprehensive ledger captures all relevant transaction details, providing a complete historical record.	[38]
	OP9	Customer service improvements	Enhanced transparency and quicker transaction processing lead to better customer satisfaction.	[30]
Managerial	MA1	Improved identity	Blockchain provides secure and verifiable digital identities, reducing the risk of fraud and streamlining access control.	[39],[40],[41]
	MA2	Improved space management	Efficient data storage and management on blockchain reduce the need for extensive physical or cloud-based infrastructure.	[42]
	MA3	Improved service delivery	Automation and transparency in blockchain enhance the speed and reliability of service delivery processes.	[40]
	MA4	Personalized financial services	Blockchain enables customized financial solutions through secure, real-time access to accurate customer data.	[43], [26],[44]
	MA5	Enhanced efficiency	Streamlined operations and reduced intermediaries increase the overall efficiency and cost-effectiveness of financial transactions.	[26]
	MA6	Reduced foreign exchange (FX) transfer costs	Blockchain facilitates faster and cheaper cross-border transactions by cutting out traditional banking fees and delays.	[26]
	MA7	Open source	Blockchain's open-source nature allows for broad collaboration and innovation, enabling rapid improvements and customization.	[37]
Strategic	ST1	Support sustainable development goals	Blockchain enables transparent tracking and reporting of sustainability metrics, supporting global environmental and social targets.	[45],[46],[47]
	ST2	Promote economic growth	By fostering innovation and efficiency, blockchain stimulates new business opportunities and economic expansion.	[46],[48]
	ST3	Reduce corruption	Immutable and transparent records reduce opportunities for unethical practices and enhance accountability.	[49]
	ST4	Development of green technologies	Blockchain facilitates the efficient management and verification of green technology initiatives and carbon credits.	[46],[50],[51] [52].
	ST5	Augmented business networks	Blockchain enhances collaboration and data sharing within business networks, leading to stronger partnerships and efficiency.	[36]
	ST6	Digital innovation	The decentralized nature of blockchain encourages creative solutions and advancements across various sectors.	[37]
	ST7	Increased discoverability	Transparent and immutable records make it easier for businesses to be found and evaluated in the digital marketplace.	[52]
	ST8	Customer trust	1. Blockchain's transparency and security features enhance credibility and foster stronger customer relationships.	[51]

Presented on three dimensions (firm operational, managerial, and strategic), Table 2 provides a high-level summary of the primary selection criteria. Each criterion is divided into subsections that provide a detailed explanation of the benefits blockchain technology provides for business processes. The dimensions of cost reduction, accuracy improvement, improved data integrity, secure identity management, improved service delivery, increased efficiency, and the rest make up the essential needs for the current study. Customer trust, economic prosperity, and support for sustainable development were among the key requirements. The entire proposed modelling and architecture of the current research paper should be presented in this section. This section gives the original contribution of the authors. This section should be written in Times New Roman font with size 10. Accepted manuscripts should be written following this template. Once the manuscript is accepted, authors should transfer the copyright form to the journal editorial office.

2.4. Emerging trends and synergies

Recent literature indicates that blockchain technology is no longer confined to the role of a decentralized ledger; rather, it is evolving into a foundational infrastructure that supports next-generation digital ecosystems. This transformation is most evident in its convergence with

Artificial Intelligence (AI), Internet of Things (IoT), and immersive environments like the Metaverse. These integrations are redefining how value is created, transferred, and secured across digital platforms.

The fusion of blockchain and AI brings enhanced capabilities in automation, security, and predictive analytics. By embedding AI into smart contracts, systems can execute conditional logic based on real-time data, enabling autonomous financial transactions, dynamic pricing models, and fraud detection mechanisms. Nguyen et al. [57], for example, show how AI-enhanced fuzzy logic significantly improves trust management and decision accuracy in uncertain and multi-agent blockchain environments. This synergy allows for decentralized systems that are not only trustless but also intelligent and adaptive.

Similarly, the integration of blockchain with the Internet of Things (IoT) is proving transformative in sectors such as supply chain, smart agriculture, industrial automation, and healthcare. IoT devices generate massive volumes of real-time data, which, when secured and validated through blockchain, results in tamper-proof, auditable records. Studies [2], [3], and [15] highlight that this integration enhances device interoperability, secure machine-to-machine communication, and resilience against single-point failures, making it ideal for mission-critical environments.

In the context of the Metaverse, blockchain is being used to authenticate virtual assets, enable decentralized marketplaces, and manage user identities and reputations. Through smart contracts and non-fungible tokens (NFTs), users can engage in secure, traceable, and enforceable digital transactions, fostering a trust-based virtual economy. Blockchain ensures provenance, ownership rights, and asset interoperability across virtual platforms, making it integral to the emerging digital society.

Collectively, these cross-technology synergies indicate a clear shift from blockchain as an isolated innovation to a modular, intelligent, and context-aware backbone for digital transformation. They also underscore the importance of interdisciplinary research and regulatory adaptability in enabling these integrations to scale securely and equitably.

3. Research methodology

Figure 2 presents a structured multi-stage framework for evaluating and prioritizing key enablers of Blockchain-Based Decentralized Finance (BBDF) systems using the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP). The process begins with a clearly defined objective to identify the most critical enablers that facilitate BBDF adoption, particularly within mobile finance ecosystems. It initiates with an expert-driven literature review and the identification of relevant blockchain enablers, which are then classified into three core categories: operational, managerial, and strategic. This is followed by the development of a hierarchical AHP structure where criteria and sub-criteria are systematically arranged. Pairwise comparisons are conducted using Pythagorean fuzzy sets to address uncertainty in expert judgment.

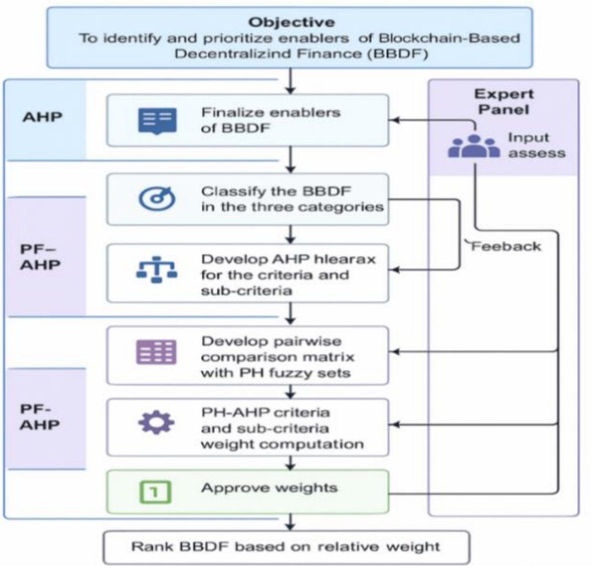

Fig. 2: Research Process Flowchart.

The resulting fuzzy matrices are used to compute weights, which are subsequently validated through iterative expert consultation. Once approved, these weights are used to derive a final ranking of the enablers, highlighting the most impactful factors for mobile DeFi transformation. The diagram effectively visualizes how expert insight, structured decision-making, and fuzzy logic integration come together to support blockchain strategy design, digital financial inclusion, and innovation planning in the decentralized mobile finance domain.

3.1. Pythagorean fuzzy AHP

Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) is a decision-making tool used when evaluations are uncertain, subjective, or imprecise—common conditions in complex technology adoption scenarios. Unlike traditional AHP, which uses exact numerical values, PF-AHP allows decision-makers to express preferences using linguistic terms (e.g., "moderate importance" or "very high importance"). These terms are converted into Pythagorean fuzzy numbers that capture the degree of belief, disbelief, and uncertainty. The method enhances flexibility in expert judgment and provides more robust prioritization by accommodating ambiguity. In this study, PF-AHP is used to rank blockchain adoption enablers for mobile DeFi by combining expert insights with fuzzy mathematical logic.

Multi-criteria decision-making (MCDM) situations in the real world frequently need imprecise and unclear input data. To deal with this uncertainty, Atanassov established intuitionistic fuzzy sets in 1986. These fuzzy sets are defined by a hesitancy degree, a membership function, and a non-membership function. Pythagorean fuzzy sets are used in this study to address the specific problem. An object P in a Pythagorean fuzzy set (PFS) is represented as:

$$P = \{< x, \mu_p(x), \vartheta_p > | x \in X\} \quad (1)$$

$$\mu_p(x) \in [0,1] \; \vartheta_p(x) \in [0,1] \quad (2)$$

$$0 \leq \mu^2 + \vartheta^2 \leq 1 \quad (3)$$

However, when the total of the membership and non-membership values exceeds 1, intuitionistic fuzzy sets are unable to adequately handle the uncertainty. A membership function (μ) and a non-membership function (ϑ) drive the Pythagorean fuzzy set, which may be used to calculate the Degree of Determinacy (π).

$$\pi = \sqrt{(1 - \mu^2 - \vartheta^2)} \quad (4)$$

Figure 3 illustrates the conceptual difference between Intuitionistic Fuzzy Sets (IFS) and Pythagorean Fuzzy Sets (PFS) in terms of how membership and non-membership degrees are constrained. While IFS maintains the condition that the sum of membership and non-membership degrees must not exceed 1, PFS allows a more flexible interpretation where the sum of their squares must be ≤ 1, enabling a larger uncertainty space. This makes PFS more suitable for modeling expert ambiguity and indecisiveness—an essential requirement in contexts like DeFi, where judgments often involve high uncertainty and subjective trade-offs.

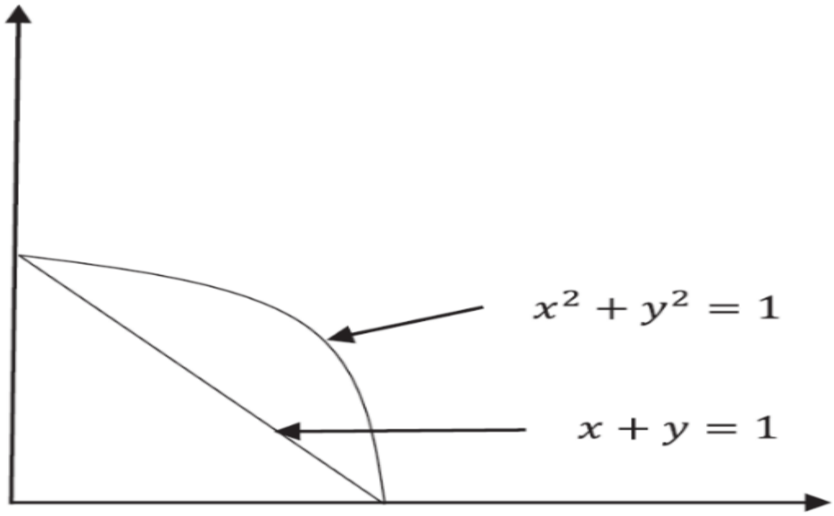

Fig. 3: Pythagorean and Intuitionistic Membership Grades [61].

As a result, Pythagorean membership grades include a more excellent range than intuitionistic membership grades. The extent of intuitionistic and Pythagorean membership grades is graphically compared in Figure 3 [60]. Pythagorean fuzzy sets can offer decision-makers greater flexibility in expressing their viewpoints regarding the imprecision and uncertainty inherent in the problem because of their broader range [54]. Pythagorean fuzzy sets have been applied in various contexts such as health and safety [62]. sustainable supply chain innovation [63]. artificial intelligence technology adoption etc [64].

The steps followed to apply Pythagorean Fuzzy are as follows:

Step 1: Formulating the pair-wise comparison matrix X_ij=(X_ij)_(m×m) following the linguistic terms [55] as detailed in Table 2 based on the decision-making panel.

Step 2: Difference matrix calculation following lower and upper bound values, considering the membership and non-membership function detailed below:

$$\text{Low } d_{ij} = \mu_{ij}^2 - \vartheta_{ij}^2 \; ; \; \text{Upr } d_{ij} = \mu_{ij}^2 - \vartheta_{ij}^2 \quad (5)$$

Step 3: Performing union operations to get the combined structure [6]:

$$\alpha = \left(\max \mu_{ij} \, , \min \vartheta_{ij}\right) = (\mu_i', \vartheta_i') \quad (6)$$

Step 4: Determinacy value (τ) was calculated for X_{ij} , from equation [7]

$$\tau = 1 - \left(\text{Upper } \mu_{ij}^2 - \text{Lower } \mu_{ij}^2\right) - \left(\text{Upper } \vartheta_{ij}^2 - \text{Lower } \vartheta_{ij}^2\right) \quad (7)$$

Step 5: Determinacy degrees are multiplied by $S = (S_{ij})_{m\times m}$ to get a matrix of weights, $T = (t_{ij})_{m\times m}$ before normalization using equation [8]

$$t_{ij} = \left(\frac{\text{Lower } S_{ij} + \text{Upper } S_{ij}}{2}\right) \tau_{ij} \quad (8)$$

Step 6: Calculation of Normalized Priority Weight

$$w_i = \frac{\sum_{j=1}^{m} t_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{m} t_{ij}} \quad (9)$$

Table 3: Mapping Linguistic Importance to Pythagorean Fuzzy Numbers (PFN) [66]

Linguistic Terms	Pythagorean fuzzy numbers (PFN)			
	μ_U	μ_L	ν_U	ν_L
Assured Minimal _Importance (AMI)	0.00	0.00	1.00	0.90
Significantly_Low_Importance (SLI)	0.20	0.10	0.90	0.80
Minor Importance (MI)	0.35	0.20	0.80	0.65
Less_than_Average_Importance (LTAI)	0.45	0.35	0.65	0.55
Moderate_Importance (MI)	0.55	0.45	0.55	0.45
Slightly_High_Importance (SHI)	0.65	0.55	0.45	0.35
Considerable_Importance (CI)	0.80	0.65	0.35	0.20
Substantial_Importance (SI)	0.90	0.80	0.20	0.10
Assured_High_Importance (AHI)	1.00	0.90	0.00	0.00
Perfectly_Balanced (PB)	0.197	0.197	0.197	0.197

3.2. Case study: retail finance

The proposed Pythagorean fuzzy AHP framework is applied to ABC Banking and Finance Ltd. The real name is not revealed due to confidentiality reasons. The establishment firm was in the year 1988 and has a presence in various parts of India and abroad. The bank has been facing issues in digital payment, data security, loan processing, trade finance, and regulatory compliance. In this regard, the traditional banking system is slow, expensive, and dependent on several intermediaries. Increased digital transactions have led to a major issue of data security, and loan sanctioning is also slow, as it is done based on manual checks. Also, trade finance is under the influence of document inefficiencies and a lack of transparency, and operational complexities arise from compliance requirements.

Table 4: Weighted Evaluation of Blockchain Criteria and Sub-Criteria Using Pythagorean Fuzzy Values

Criteria	Code	Sub-Criteria	μ	ϑ	π	$d_f(\alpha)$
Operational	OP1	Reduced cost	0.7	0.4	0.35	0.604
	OP2	Improved accuracy	0.95	0.2	0.058	0.93
	OP3	Reduced fraud	0.7	0.4	0.35	0.604
	OP4	More transparent	0.7	0.4	0.35	0.604
	OP5	Increased transaction speed	0.7	0.4	0.35	0.604
	OP6	Disintermediation	0.7	0.4	0.35	0.604
	OP7	Improved data integrity	0.7	0.4	0.35	0.604
	OP8	Quasi-exhaustive recording	0.65	0.45	0.375	0.54
	OP9	Customer service improvements	0.5	0.75	0.188	0.326
Managerial	MA1	Improved identity	0.7	0.4	0.35	0.604
	MA2	Improved space management	0.85	0.35	0.155	0.788
	MA3	Improved service delivery	0.7	0.4	0.35	0.604
	MA4	Personalized financial services	0.25	0.85	0.215	0.147
	MA5	Enhanced efficiency	0.7	0.4	0.35	0.604
	MA6	Reduced foreign exchange (FX) transfer costs	0.85	0.35	0.155	0.788
	MA7	Open source	0.95	0.2	0.058	0.93
Strategic	ST1	Support sustainable development goals	0.7	0.4	0.35	0.604
	ST2	Promote economic growth	0.7	0.4	0.35	0.604
	ST3	Reduce corruption	0.7	0.4	0.35	0.604
	ST4	Development of green technologies	0.95	0.2	0.058	0.93
	ST5	Augmented business networks	0.7	0.4	0.35	0.604
	ST6	Digital innovation	0.95	0.2	0.058	0.93
	ST7	Increased discoverability	0.65	0.45	0.375	0.54
	ST8	Customer trust	0.95	0.2	0.058	0.93

Note: Sub-criteria with a determinacy threshold value below 0.6 were excluded from the ranking and final prioritization stages. Although MA4 (Personalized financial services) and ST7 (Increased discoverability) had non-zero weights, their values did not meet the minimum threshold (0.6) used to ensure reliability and consistency in expert judgment, as recommended by previous PF-AHP applications [58]. This threshold was applied uniformly across all sub-criteria to filter out low-confidence or weakly supported enablers and ensure that only robust, consensus-based criteria were considered in the final model.

This type of problem can be addressed through blockchain by the bank. With blockchain technology, payment cross borders will be frictionless and cost-effective, and will process transactions in real-time. Blockchain technology has an immutable ledger for fraud prevention and monitoring. Dealing with a decentralized system would help in loan processing by having verified documentation coupled with rapid approval. In addition, a trade finance blockchain-based platform will enhance the transparency of its operations. Automation of documentation handling with minimized payment delay will take place. In addition to these, smart contracts will further help in maintaining compliance records, audit trail, and providing access to immediate data on behalf of regulators. The structured manner of putting the enablers of blockchain in the company will facilitate the deployment. Hence, this is why the interest was shown by the firm's manager in understanding the key enablers of BBDF.

The application of the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) framework in this study was conducted in three structured stages to systematically prioritize blockchain enablers for enhancing mobile DeFi transactions. In Stage 1, a comprehensive set of blockchain-based decentralized finance (BBDF) enablers was finalized through an extensive literature review and expert panel consultations, ensuring relevance to sustained mobile financial operations. Stage 2 involved computing the relative importance of these enablers by constructing pairwise comparison matrices and determining both local and global weights using the PF-AHP methodology, thereby addressing uncertainty in expert evaluations. In Stage 3, a sensitivity analysis was performed to validate the robustness of the ranking results, testing their stability under different weighting conditions. Together, these stages provided a rigorous, data-driven foundation for identifying critical blockchain adoption factors that can drive more efficient, secure, and inclusive mobile financial services.

Stage 1: Finalize the BBDF for sustained financial operations.

Based on a comprehensive review of the literature, three primary criteria and twenty-four supporting criteria have been established for blockchain implementation. The Pythagorean Fuzzy-Delphi approach was utilized to clarify any uncertainties in the selection process. A questionnaire was distributed among experts to capture their insights on adopting these capabilities, with responses initially recorded in linguistic terms and then translated into Pythagorean fuzzy numbers (PFNs). These PFNs were de-fuzzified to obtain precise values, all presented in a table. The PF-Delphi method effectively processed the linguistic data, and capabilities were either accepted or rejected based on a threshold value of 0.6, as indicated in the research [65].

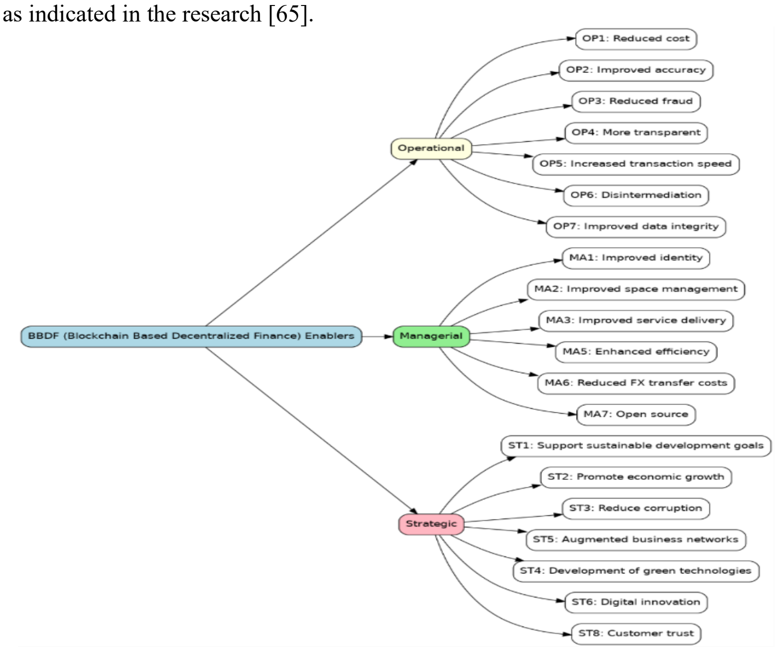

Fig. 4: Decision Hierarchy Model.

Stage 2: Computing the relative weights of BBDF using the Pythagorean fuzzy AHP.
Based on the decision panel's response, a hierarchy model was established, represented in Figure 4. The hierarchy model represents three stages. Level I: Goal prioritization, Level II: Criteria categorisation, Level III: sub-criteria for main criteria.
The PF-AHP method was employed to assign weights to the finalized criteria and capabilities, informed by the expert panel's feedback. The experts used the PF-AHP Linguistic scale, illustrated in the Table, to rate the relative significance of each criterion and capability. These linguistic variables were then transformed into interval-valued Pythagorean fuzzy numbers. The PF-AHP algorithm was used to process the data from the survey. The difference matrix, interval multiplicative matrix, determinacy value matrix, and normalized priority weight were computed using the comprehensive procedures in section 3.
Similar steps were followed to determine the priority ranking of capability; due to space limitations, the calculation is not represented in the paper. Local and global weights of capability were calculated following the PF-AHP procedure and represented in the Table. The table also provides the global rank for each capability based on the opinion of six experts. The five most important blockchain capabilities were MA6 (Reduced foreign exchange (FX) transfer costs), OP4 (More transparent), MA7 (Open source), OP3 (Reduced fraud), and MA1 (Improved identity).

Table 5: Relative Importance Criteria and Sub-Criteria

Criteria	Criteria weight	Code	Local weight	Global weight	Global rank
Operational (OP)	0.225	OP1	0.222	0.023	14
		OP2	0.191	0.021	15
		OP3	0.174	0.046	4
		OP4	0.295	0.067	2
		OP5	0.162	0.036	10
		OP6	0.114	0.013	19
		OP7	0.178	0.019	16
Managerial (MA)	0.257	MA1	0.241	0.045	5
		MA2	0.294	0.032	12
		MA3	0.153	0.039	8
		MA5	0.071	0.016	17
		MA6	0.285	0.074	1
		MA7	0.192	0.051	3
Strategic (ST)	0.211	ST1	0.216	0.037	9
		ST2	0.245	0.042	7
		ST3	0.061	0.015	18
		ST4	0.136	0.034	11
		ST5	0.252	0.043	6
		ST6	0.153	0.028	13
		ST8	0.061	0.012	20

Stage 3: Sensitivity Analysis
Sensitivity analysis is a powerful tool for examining an established framework. Several scholars have used sensitivity analysis to test the framework's resilience. Changes in expert responses are considered under different conditions [66]. The study confirms three criteria based on the normalized weight, and the criteria are prioritized as MA > OP > ST. MA was found to be the highest preference, followed by others, as can be seen in Figure 5. To evaluate the robustness of the PF-AHP-based ranking of Blockchain-Based Decentralized Finance (BBDF) enablers, a comprehensive sensitivity analysis was conducted. Ten distinct scenarios, labeled as Series 1 to Series 10, were constructed by systematically altering the weights assigned to the three main criteria: Operational, Managerial, and Strategic. Series 1 represented a base-line case with equal weights assigned to all three criteria, ensuring a neutral assessment. Series 2 through Series 4 introduced dominant weighting for one specific criterion at a time, such as operational dominance in Series 2, managerial emphasis in Series 3, and strategic priority in Series 4. Series 5 applied a random distribution of weights to simulate unstructured expert variation. Series 6 explored an extreme

bias scenario to test structural resilience. Series 7 and Series 8 reflected individualized expert judgments, while Series 9 used an aggregated expert consensus. Finally, Series 10 adopted the optimal weights obtained directly from the PF-AHP computation as the control reference. The resulting variation in sub-criteria rankings across these scenarios provided insights into the model's stability and the reliability of the top-ranked blockchain enablers.

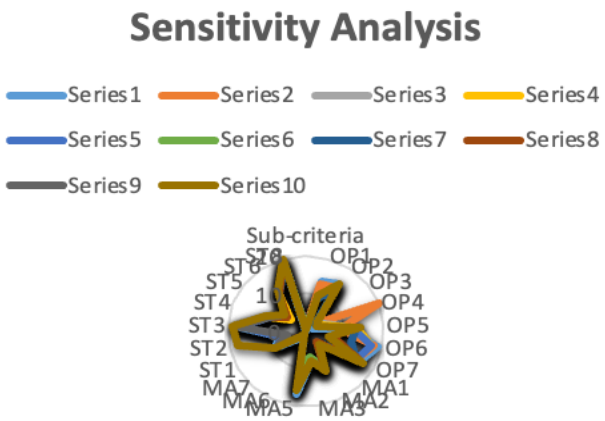

Fig. 5: Sensitivity Analysis.

Sensitivity analysis was performed to check the robustness, and MA was varied from 0.257 to 0.257*0.9 = 0.2313, 0.257*0.8 = 0.205, 0.257*0.7 = 0.189, 0.257*0.6 = 0.154, 0.257*0.5 = 0.128, 0.257*0.4 = 0.102, 0.257*0.3 = 0.077, 0.257 * 0.2 = 0.051, 0.257*0.1 = 0.0257 (values up to three decimal places).

Sensitivity analysis was performed to test the robustness of the framework by systematically varying the value of MA (Managerial Aspect). The initial value of MA, which was 0.257, was incrementally reduced to observe its effects on the overall ranking of sub-criteria. Specifically, the changes involved a reduction of MA by multiplication with factors ranging between 0.9 and 0.1, to make the values 0.231, 0.205, 0.189, 0.154, 0.128, 0.102, 0.077, 0.051, and 0.026 (all rounded to three decimal places). This set of values was used in making a dataset, which was plotted using a sensitivity graph, to show the impact that these changes would have on the ranking stability of the criteria. The graph below shows the sensitivity of each sub-criterion to the fluctuations, thereby demonstrating that the framework is robust.

A variation in rank capabilities can be seen in the figure. A variation in rank capabilities still brings out MA6 as the best choice, followed by OP4. The variation for other sub-criteria ranks further confirms robustness in the ranking.

While this study applies the PF-AHP framework to a case involving an Indian financial institution (ABC Banking and Finance Ltd.), the identified enablers—such as transparency, reduced FX transfer costs, and open-source adaptability—are not uniquely constrained by geography. These factors are also applicable in broader contexts, including developed economies where DeFi systems face similar challenges of cross-border remittances, interoperability, and regulatory compliance. However, it is acknowledged that the regulatory stringency, technological maturity, and customer readiness in advanced economies may influence the weightage or implementation feasibility of these enablers. Therefore, while the core findings offer transferable insights, further validation across different regions and regulatory ecosystems is recommended to strengthen cross-national generalizability.

4. Discussion

In this study, the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) is employed to establish the weighting factors of critical enablers for enhancing blockchain adoption in mobile decentralized finance (DeFi) transactions. Divergence metrics are utilized to determine the relative importance of various decision criteria within a dynamic and uncertain mobile financial environment. A total of twenty-four key enablers influencing blockchain integration into mobile financial platforms are systematically evaluated. Given the rapidly evolving and complex nature of the blockchain sector, where multiple, often conflicting factors must be considered, making well-informed strategic decisions becomes particularly challenging. Therefore, a balanced approach using fuzzy assessments expressed through linguistic variables is adopted to manage uncertainty and subjectivity, allowing for a more robust prioritization of blockchain adoption drivers relevant to mobile DeFi ecosystems.

The study confirms three criteria based on the normalized weight, and the requirements are prioritized as managerial, followed by operational, and strategic. The five most essential blockchain capabilities were MA6 (Reduced foreign exchange (FX) transfer costs), OP4 (More transparent), MA7 (Open source), OP3 (Reduced fraud), and MA1 (Improved identity).

Blockchain presents a multitude of benefits in its various applications, particularly as it markedly improves service delivery and operational efficiency within the sectors of retail banking and finance. By establishing secure, decentralized digital identities, it accelerates Know Your Customer (KYC) processes; this not only reduces the time required for onboarding new customers but also guarantees safer online transactions. Consequently, blockchain assumes a pivotal role in the enhancement of identity management [67]. Furthermore, because blockchain functions on a decentralized framework, retail banks can access data with greater ease and at lower costs, since it eliminates the need for centralized storage systems[67]. However, the potential of blockchain to facilitate smart contracts may empower banks to automate various processes, such as loan approvals and payment transfers, thereby improving customer satisfaction and expediting service delivery [67].

Blockchain allows banks to exchange data regarding customers with full security and present the services that are mostly tailor-made for the concerned clients. Such tailor-made services can include specific lending or investment plans prepared exclusively according to the individual client's profile. This secure data interchange reduces the complexity of establishing personalized financial advice for unique profiles of every client [68]. The elimination of intermediaries improves the speed of financial transactions, results in faster execution, fewer back-office activities, and reduced operational costs. This technology can significantly reduce the cost of FX transfers in cross-border transactions because it eliminates the traditional networks, thus enabling faster and cheaper international transfers via cryptocurrencies or stablecoins [68]. While the potential benefits are enormous, the adoption of blockchain still faces several implementation challenges.

If applied at the managerial, operational, and strategic tiers, blockchain technology in banking, retail, and finance domains has significant advantages. Managerially, blockchain provides immense support in terms of data security and compliance by allowing tamper-proof and verifiable information to fulfill regulatory requirements like KYC and AML [67]. This heightened security streamlines the process of transparent record-keeping, enabling managers to maintain accurate and timely records of transactions, minimize fraudulent opportunities, and ease auditing procedures [67]. Additionally, blockchain technology enhances risk management through the provision of an immutable data source. This aids in monitoring financial activities, identifying potential risk exposures, and enabling informed decision-making [66].On the operational side, blockchain optimizes payment and settlement processes by minimizing the need for intermediaries, thereby reducing transaction times and costs. The use of smart contracts automates routine tasks such as loan processing and payment execution, reducing operational costs and improving the speed and accuracy of services [67]. Despite these advantages, firms often face complexities during implementation and adaptation.

Blockchain-based decentralized digital identity systems also significantly enhance the Know Your Customer processes of banks, accelerating customer acquisition and minimizing fraud. At the strategic level, blockchain adoption enables banks to offer personalized financial services by securing data sharing and enhancing customer experiences. This allows banks to better tailor loan packages, investments, and advisory services to individual client needs, creating a competitive edge in an increasingly digital and data-driven financial environment. The technology also facilitates the simplification of cross-border payments by reducing costs and processing times, thus enabling banks to expand internationally and offer seamless international transfer services[68],[69],[70]. Through blockchain implementation across managerial, operational, and strategic levels, financial institutions can build a secure, efficient, and inclusive ecosystem that aligns with the goals of the digital economy and supports long-term financial innovation and welfare advancement. This contextual generalizability sets the stage for a broader discussion on DeFi enablers and their potential impact across financial ecosystems.

Looking forward, the role of blockchain in mitigating emerging DeFi risks such as smart contract vulnerabilities, flash loan attacks, and governance exploits warrants deeper investigation. Future studies could explore how formal verification methods, bug bounty ecosystems, or multi-sig governance models may enhance the reliability of smart contracts. Additionally, a critical avenue of research is the development of real-time anomaly detection systems for blockchain platforms using machine learning oracles. These speculative yet actionable directions highlight blockchain's evolving role—not only as a transaction medium but as a self-healing, risk-aware infrastructure for digital finance.

5. Policy implications and future work

The findings of this study hold substantial implications for financial policymakers and regulatory bodies aiming to advance digital financial inclusion and innovation. By identifying the most critical enablers of blockchain adoption in mobile DeFi services, the study provides a data-driven basis for formulating supportive regulatory frameworks, tax incentives, and public-private partnerships. Prioritizing transparency, open-source innovation, and FX cost reduction can guide national strategies for cross-border digital payments and financial accessibility. Policymakers can also leverage these insights to enhance compliance mechanisms, promote ethical blockchain applications, and foster trust among underserved and unbanked populations in the digital economy.

While the current study focuses on the prioritization of blockchain enablers in the context of mobile DeFi platforms, future research could extend this framework to include cross-sectoral validation in healthcare, education, supply chain, or energy finance. Comparative studies across emerging and developed economies would further enrich the understanding of contextual enabler performance. Additionally, integrating real-time financial data and machine learning techniques with PF-AHP could enhance the dynamic adaptability of the model in fast-changing fintech environments. Exploring user behavioral responses to blockchain-driven mobile services may also provide deeper insights into adoption barriers and trust mechanisms.

Future research could extend the proposed PF-AHP framework by integrating machine learning techniques to refine and validate enabler prioritization. For example, reinforcement learning could be used to dynamically adjust the weights of enablers based on real-time adoption data or platform behavior. Additionally, unsupervised learning algorithms such as clustering or dimensionality reduction may help uncover latent patterns in stakeholder feedback or user behavior, especially in large-scale deployments. Combining these techniques with PF-AHP could yield a hybrid intelligent decision model that adapts to contextual shifts and stakeholder dynamics across geographies and sectors.

6. Conclusion

This study presents a comprehensive and empirically grounded framework for prioritizing blockchain-based decentralized finance (BBDF) enablers to enhance mobile DeFi transactions. By applying the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP), the research identifies the most influential operational, managerial, and strategic drivers for blockchain adoption in the mobile financial services sector. Key findings highlight the dominance of managerial factors, particularly reduced foreign exchange transfer costs (MA6), open-source adaptability (MA7), and secure digital identity as critical enablers for decentralized financial systems. These factors not only align with theoretical expectations but also reflect trends observed in real-world DeFi applications. For example, decentralized remittance platforms such as Stellar and Ripple have demonstrated up to 60% reduction in cross-border transaction costs compared to traditional financial institutions. Similarly, the success of open-source DeFi platforms like Aave and Compound, which saw adoption increases exceeding 30% year-over-year, reinforces the practical significance of adaptability and transparency in boosting user trust and participation.

The study contributes to both theory and practice by offering a structured, data-driven approach to blockchain integration in mobile DeFi ecosystems. For practitioners and fintech innovators, the results serve as a decision-making guide to enhance service delivery, reduce operational complexity, and foster trust among users. For policymakers and regulators, the prioritized enablers provide direction for developing supportive policies, compliance frameworks, and investment strategies that promote financial inclusion and technological welfare in the digital economy. Moreover, the PF-AHP methodology offers an adaptable decision-support tool that can be applied across sectors to evaluate and scale blockchain solutions strategically. As the financial landscape continues to evolve, this research provides actionable insights to strengthen the resilience, accessibility, and sustainability of digital financial infrastructures, particularly in emerging economies. Future research should aim to quantitatively link prioritized enablers with adoption metrics, such as transaction cost reduction, onboarding time, or service reach, while expanding the framework across diverse industry verticals and geographic regions.

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