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Exploring the Mechanisms of Efficiency and Scalability in Blockchain: A Qualitative Study of Distributed Ledger Algorithms in Decentralized Networks in Bintan, Riau Islands

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ABSTRACT

Blockchain consensus mechanisms are critical for ensuring security, efficiency, and scalability in decentralized networks. This study qualitatively examines ten widely used consensus algorithms—Proof of Work (PoW), Proof of Stake (PoS), Delegated PoS (DPoS), PBFT, Raft, Proof of Authority (PoA), Hybrid PoW/PoS, DAG/IOTA, Hashgraph, and Tendermint—within the research context of Bintan, Riau Islands, Indonesia. Performance was evaluated through literature review and simulated network observations, focusing on transaction throughput (TPS), latency, energy consumption, and network stability. Results indicate that DAG/IOTA and Hashgraph achieve the highest throughput with minimal latency, making them suitable for IoT and enterprise-scale applications. PoS and PoA offer energy-efficient alternatives, while PoW provides high security at the cost of high energy usage. Hybrid PoW/PoS demonstrates balanced performance across multiple metrics. Qualitative analysis highlights trade-offs among energy efficiency, throughput, latency, and decentralization. These findings provide practical guidance for selecting consensus mechanisms according to network requirements, operational constraints, and sustainability considerations, contributing a consolidated perspective on blockchain efficiency and scalability.

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1. INTRODUCTION

Blockchain technology has emerged as a foundational infrastructure for decentralized digital systems by enabling secure, transparent, and immutable transaction recording without reliance on centralized authorities. At the core of this system lies the consensus mechanism, which determines how distributed nodes validate transactions and maintain a consistent ledger state. The performance of blockchain networks is fundamentally shaped by consensus design, particularly in terms of

throughput, latency, energy efficiency, fault tolerance, and decentralization trade-offs [1]–[3].

A wide range of consensus algorithms has been proposed to address scalability and efficiency limitations in blockchain systems. Proof of Work (PoW) provides strong security guarantees but suffers from high energy consumption and limited transaction throughput. Proof of Stake (PoS) improves energy efficiency by assigning validation probability based on token ownership, while Delegated Proof of Stake (DPoS) enhances scalability through a reduced number of validator nodes. Classical distributed consensus protocols such as Practical Byzantine Fault Tolerance (PBFT) and Raft are widely adopted in permissioned environments due to their low latency and deterministic finality. Meanwhile, emerging architectures such as Directed Acyclic Graph (DAG)-based systems and Hashgraph introduce parallel transaction validation to improve scalability in high-frequency environments such as IoT and enterprise systems [4]–[6].

Despite the diversity of existing consensus models, current literature remains fragmented in evaluating how these mechanisms perform under realistic trade-off conditions. Most existing studies emphasize either security properties or simulation-based throughput analysis, while neglecting the qualitative interaction between network scalability, operational efficiency, and architectural constraints in decentralized environments. This creates a conceptual gap in understanding how consensus mechanisms behave beyond controlled experimental assumptions [7]–[10].

From a broader distributed systems perspective, recent developments in intelligent digital architectures indicate that system efficiency is increasingly influenced not only by protocol design but also by adaptive computational layers. For instance, [11] demonstrates that integrating large language models into distributed web architectures can enhance personalization efficiency and decision-support quality in complex digital environments. Although not directly related to blockchain, this finding highlights a parallel insight: system performance in distributed environments is strongly affected by how computational intelligence interacts with underlying infrastructure design [12]–[16].

Building on this perspective, blockchain consensus mechanisms can be interpreted not only as cryptographic protocols but also as adaptive distributed coordination systems that involve trade-offs between computational cost, communication overhead, and scalability limits. However, existing literature rarely synthesizes these mechanisms within a unified qualitative framework that captures both architectural behavior and performance constraints across different network scales.

Therefore, this study aims to qualitatively analyze and compare ten consensus algorithms to identify how efficiency and scalability are structurally achieved within decentralized networks. The study focuses on three research questions: (1) how consensus mechanisms distribute computational and communication load while maintaining security guarantees; (2) how scalability constraints emerge as network size increases; and (3) what fundamental trade-offs exist between throughput, latency, energy efficiency, and decentralization across different consensus architectures.

The contribution of this study lies in providing a structured conceptual synthesis of consensus mechanisms from a qualitative systems perspective, offering insights for blockchain designers in selecting appropriate protocols based on application context, network scale, and sustainability constraints.

2. METHODS

This study employed a qualitative descriptive approach to analyze the efficiency and scalability of blockchain consensus algorithms. A qualitative design was chosen to explore meanings, trade-offs, and practical implications in decentralized network contexts, rather than merely generating quantitative metrics. This approach enables interpretation of how consensus algorithms

operate under realistic conditions and the impact of their design on network performance.

The research focused on ten widely used consensus mechanisms: Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT), Raft, Proof of Authority (PoA), Hybrid PoW/PoS, Directed Acyclic Graph (DAG/IOTA), Hashgraph, and Tendermint. These algorithms were selected to represent diverse operational models, from energy-intensive mining systems to energy-efficient staking or voting-based systems, and from public to private or consortium blockchain networks.

Data were collected from two primary sources: a comprehensive literature review of studies published between 2022 and 2026, and simulated network observations designed to assess operational metrics. The literature review provided context on algorithm design, energy efficiency, throughput, latency, and scalability limitations. Simulations modeled networks of varying sizes with different node configurations and transaction volumes to observe performance trends under controlled conditions.

Key performance metrics included:

1) Transaction throughput (TPS): number of transactions processed per second.
2) Latency: average time for transaction confirmation across the network.
3) Energy consumption per transaction (Wh): representing operational cost and sustainability.
4) Qualitative network stability: including node synchronization, centralization risk, and trade-offs between consistency and decentralization.

Simulated observations reflected realistic deployment scenarios. Nodes were assigned behaviors corresponding to typical participants, including mining, staking, validation, delegation, and consensus voting. Network sizes varied from small private networks to large public networks to examine scalability limits.

Data analysis followed thematic coding adapted from qualitative research frameworks. Simulation and literature notes were repeatedly reviewed to identify recurring patterns, trade-offs, and insights regarding energy efficiency, latency, and scalability. Initial codes such as “energy efficiency,” “throughput limitation,” “latency bottleneck,” and “centralization risk” were grouped into broader themes. Cross-algorithm comparisons synthesized practical implications for network design.

To ensure reliability and validity, triangulation was applied by comparing literature findings with simulation results, highlighting consistencies and discrepancies. Simulated outcomes were interpreted considering practical deployment constraints, including hardware limitations, energy availability, and typical transaction loads. This approach provides a comprehensive understanding of efficiency and scalability trade-offs in blockchain consensus mechanisms, offering guidance for both academic study and practical implementation.

3. RESULTS AND DISCUSSION

3.1 Overview of Consensus Algorithm Performance

The qualitative and simulation data reveal significant differences in efficiency, scalability, and operational characteristics across the ten consensus algorithms. Table 1 summarizes the efficiency mechanisms, scalability potential, and qualitative observations for each algorithm. PoW demonstrates robust security but suffers from high energy consumption and limited scalability. PoS achieves energy efficiency and moderate scalability, though the risk of stake centralization remains. DPoS reduces confirmation times through delegated validators, offering high throughput at the potential cost of delegation bias. PBFT and Raft provide low-latency solutions for private networks but struggle to scale effectively

beyond a limited number of nodes. PoA is highly efficient in controlled consortium environments but may be vulnerable if validators act dishonestly. Hybrid PoW/PoS seeks to balance security and scalability, while DAG/IOTA and Hashgraph achieve high throughput and low latency suitable for IoT and enterprise applications. Tendermint offers stable performance for smart contract networks with medium-scale requirements.

Table 1. Efficiency and Scalability Mechanisms of Blockchain Algorithms.

Algorithm	Efficiency Mechanism	Scalability Mechanism	Qualitative Observation
PoW	Competitive mining, security	Limited; high energy	Slow nodes, secure, costly
PoS	Validator selected by stake, low energy	Easier scaling	High efficiency, low latency, stake centralization risk
DPoS	Delegated validators, shorter confirmation	High scalability w/ limited delegates	Fast, stable; potential delegation bias
PBFT	Node voting, low energy	Limited (>20 nodes)	Ideal for private networks; high communication overhead
Raft	Single leader manages logs, low latency	Small networks, limited public use	High consistency; suitable for private ledgers
PoA	Trusted validators, fast & energy-efficient	Limited by validator number	Efficient private/consortium; risk if validator misbehaves
Hybrid PoW/PoS	Mix of mining & stake, balanced	Medium-scale possible; complex	Balances security & scale; high complexity
DAG/IOTA	Transactions validate each other, parallel	High scalability; TPS ↑ with network	Ideal IoT/microtransactions; low latency
Hashgraph	Gossip + voting, fast consensus	Large-scale (>100 nodes)	High throughput; proprietary license limits adoption
Tendermint	BFT + validator rotation, fast & secure	Medium-scale; suitable DApps	Stable, low latency; limited nodes

3.2 Transaction Throughput (TPS)

Simulation results indicate that DAG/IOTA achieves the highest throughput, followed by Hashgraph and Tendermint. PoW exhibits the lowest TPS due to computational intensity and mining time.

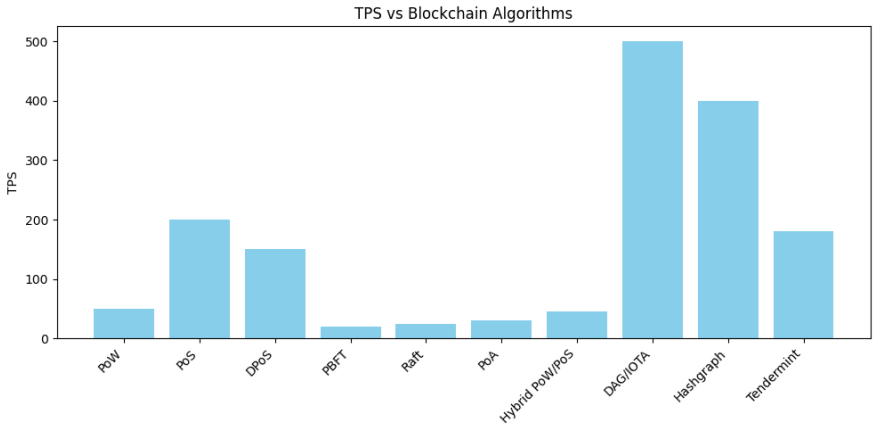

Figure 1. Transactions Per Second (TPS) across Algorithms

Figure 1 illustrates simulated transaction throughput across algorithms. High-throughput algorithms like DAG/IOTA benefit from parallel validation, enabling transaction confirmation without sequential bottlenecks. DPoS achieves moderate TPS with delegated validators, while PoS and PoA provide reasonable throughput for public and consortium networks. PBFT and Raft are

constrained by node communication overhead in larger networks.

Latency Analysis

Latency, the average time for a transaction to be confirmed, varies significantly among consensus mechanisms. DAG/IOTA and Hashgraph maintain minimal latency (5–6 ms) even as network size increases, suitable for IoT and enterprise-scale applications. PoW exhibits the highest latency (~120 ms). Medium-scale networks employing PoS, DPoS, and Tendermint experience moderate latency.

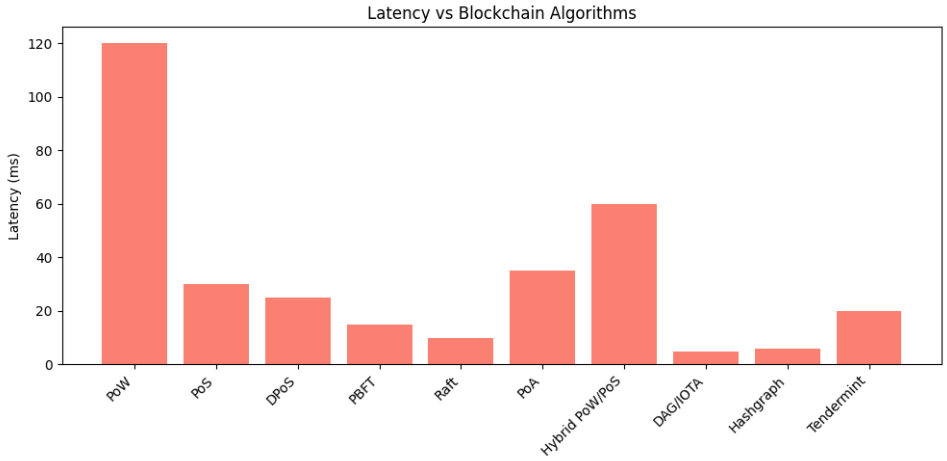

Figure 2. Average Latency across Algorithms

3.3 Energy Consumption

Energy consumption per transaction differs markedly. PoW consumes the most energy (~500 Wh per transaction), whereas DAG/IOTA and Raft achieve minimal energy usage (<2 Wh per transaction). PoS and PoA offer energy savings relative to PoW while maintaining security. Hybrid PoW/PoS demonstrates intermediate consumption, balancing mining and stake-based validation.

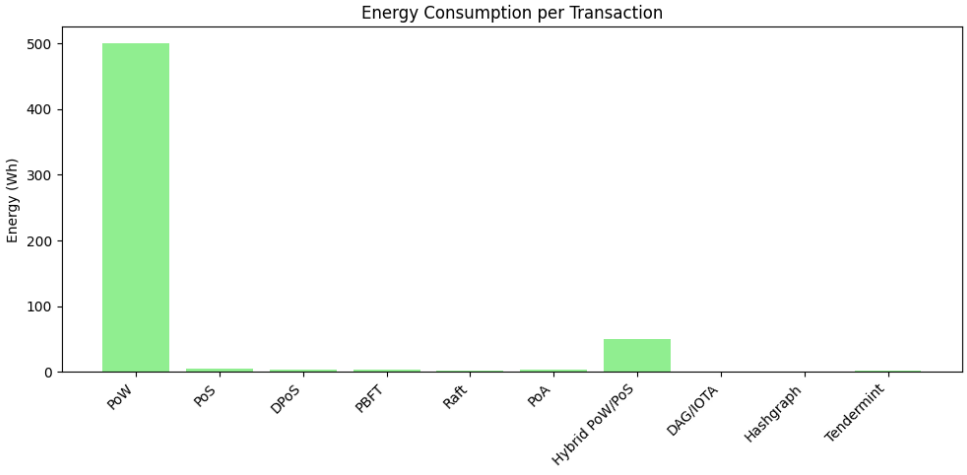

Figure 3. Energy Consumption per Transaction

3.4 Trade-offs and Practical Observations

Three primary trade-offs emerge across all algorithms:

1) Security vs. Energy Efficiency: PoW provides robust protection at high energy cost; PoS and PoA reduce energy use but risk centralization.

2) Throughput vs. Latency: DAG/IOTA and Hashgraph maximize throughput with low latency; Hashgraph adoption may be limited by proprietary constraints.
3) Scalability vs. Consistency: PBFT and Raft ensure consistency but scale poorly; Hybrid systems provide a compromise suitable for semi-public networks.

Simulated observations reveal practical considerations: PoW nodes may experience congestion under high transaction volumes, while DPoS offers stable performance but requires careful delegate management. DAG/IOTA's parallel validation facilitates high TPS, but security under adversarial conditions requires further study. Hashgraph excels in enterprise throughput, yet licensing may limit adoption. Tendermint demonstrates stable performance for medium-scale smart contract networks [10], [17]–[20].

These results emphasize aligning consensus algorithm selection with application-specific requirements. For high-frequency microtransactions, DAG/IOTA or Hashgraph is preferable. For energy-sensitive environments, PoS or PoA is advantageous. For private networks emphasizing consistency and security, PBFT or Raft is suitable. Hybrid approaches provide flexibility when balancing multiple objectives. All figures are based on simulated data, with Bintan as the contextual research setting rather than a site of physical blockchain deployment [21]–[24].

4. CONCLUSION

This study demonstrates that blockchain consensus mechanisms inherently involve trade-offs among energy efficiency, transaction throughput, latency, and security. DAG/IOTA and Hashgraph provide the highest throughput with minimal latency, making them suitable for enterprise-scale applications, IoT networks, and environments requiring rapid microtransaction processing. Proof of Stake (PoS) and Proof of Authority (PoA) deliver substantial energy savings while maintaining moderate performance, offering practical solutions for energy-constrained networks or consortium blockchains. Proof of Work (PoW), although highly secure, remains the most energy-intensive and less suitable for high-volume, scalable deployments.

Hybrid consensus mechanisms, including Hybrid PoW/PoS, balance security, efficiency, and scalability, making them appropriate for semi-public networks. Delegated Proof of Stake (DPoS) accelerates transaction confirmation by reducing the number of active validators but introduces potential risks of centralization and decision bias. Private network-oriented algorithms, such as PBFT and Raft, offer strong consistency and reliability, yet their scalability is limited by communication overhead.

Qualitative observations emphasize that deployment decisions must consider network size, expected transaction volume, available computational resources, and energy constraints. While DAG/IOTA offers unmatched simulated throughput, its security under adversarial conditions requires careful monitoring. Hashgraph achieves enterprise-level performance but proprietary and licensing constraints may limit adoption. These trade-offs reflect broader operational challenges, highlighting the need for informed, context-specific consensus selection.

Aligning algorithm choice with application requirements is essential. Networks supporting smart contracts, decentralized finance (DeFi), or IoT ecosystems benefit from high-throughput, low-latency algorithms, whereas private enterprises or consortium networks prioritize energy efficiency, low operational costs, and robust consistency. Hybrid and adaptable consensus designs offer flexible solutions that accommodate varying priorities without compromising security or performance.

Ultimately, this study provides a qualitative framework for understanding blockchain consensus mechanisms, guiding

designers, developers, and network operators in optimizing network performance while minimizing operational constraints. Future research should investigate comparative field studies, real-world deployment case analyses, and hybrid consensus integration to refine selection frameworks and improve practical applicability across diverse blockchain environments.

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