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Hybrid Blockchain Architecture for Enhancing Security and Transparency in Academic Grading Systems

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A R T I C L E I N F O

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A B S T R A C T

Purpose. This study aims to develop and evaluate a hybrid blockchain architecture-based e-learning platform designed to improve the security, transparency, and integrity of academic grade data at private universities in Indonesia. **Methodology.** A mixed methods approach was used, combining qualitative (interviews and focus group discussions) and quantitative (performance testing, System Usability Scale (SUS), and User Experience Questionnaire (UEQ)) analysis. The system testing involved 40 participants (20 students, 10 lecturers, and 10 administrative staff) with a staging server infrastructure with an Intel Xeon 8 core capacity, 16 GB of RAM, and a Proof of Authority (PoA)-based permissioned blockchain network. **Results.** The test results showed an average SUS score of 77.8, which is in the Good–Excellent category, indicating a high level of usability. Meanwhile, the UEQ results showed positive scores in all dimensions, with Attractiveness (5.6), Perspicuity (5.4), and Efficiency (5.2) as the highest values, while Stimulation (4.8) and Novelty (4.5) indicated the need for improvement in terms of innovation. From a technical perspective, the system can operate stably for up to 100 concurrent users with an average response time below 0.5 seconds and an error rate of <1%. The blockchain network demonstrated an effective throughput of ~100 TPS, a confirmation time of 2.1 seconds, and a transaction failure rate of only 0.2%. **Implications for research and practice.** These results confirm that the system is efficient, secure, and well-received by users, although optimization through auto-scaling, caching, and user experience enhancements are still needed. This research contributes to presenting a realistic empirical blockchain implementation model for the higher education sector in Indonesia.

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Introduction

In the era of rapid digital transformation, universities are increasingly relying on information and communication technology to manage various academic processes, including the storage, processing, and distribution of student grade data. The emergence of e-learning platforms has revolutionized education delivery by providing flexible, accessible, and interactive learning environments (Aslan & AtaŞEn, 2020; Basri et al., 2024). However, despite these benefits, significant challenges remain, particularly in maintaining the integrity, confidentiality, and transparency of academic data (Fidas et al., 2023; Lee-Post & Hapke, 2017; Nassani et al., 2023).

This situation is exacerbated by the high risk of data breaches in Indonesia, posing challenge to academic integrity over e-learning platforms. (Irfan et al., 2025; Raharjo & Rohmadi, 2025; Sama et al., 2025). According to a report by the National Cyber and Crypto Agency (BSSN), in the first half of 2023, more than 347 million cyberattacks were recorded, with approximately 15% of these resulting in data breaches involving various institutions (Aji, 2025). Many of these incidents are related to weaknesses in centralized systems that are vulnerable to unauthorized data manipulation, information leaks, and failures caused by single points of failure.

Globally, the blockchain market in the education sector shows promising prospects. Business reports project that this market value will increase from USD 0.35 billion in 2024 to USD 9.39 billion in 2033, with a compound annual growth rate (CAGR) of 43.9% over that period (Nurmansyah et al., 2024). However, adoption of this technology in the education sector remains limited, with most institutions still in the exploration or limited pilot project phase. Blockchain technology, with its decentralized, immutable, and cryptographically protected data structure, offers a potential solution to address security and transparency issues in various sectors, including education (Chaudhari & Shirole, 2025; Choudhary et al., 2024; Saleh et al., 2020; Silaghi & Popescu, 2025; Tajuddin et al., 2025).

Unlike centralized systems, blockchain distributes data across multiple nodes ensure that every record validated and added to the chain cannot be altered without network consensus. Smart contract integration allows for the automation of rule enforcement, enabling secure and transparent academic processes such as grade assignment, credential verification, and data sharing (McGreal, 2023; Rahardja et al., 2022; Syaifudin, 2024). Numerous studies have explored blockchain applications in education, ranging from secure credential management to transparent assessment systems (Aini et al., 2021; Paje & Palaoag, 2024). However, most implementations remain experimental and limited, with little research specifically focused on securing student grade data, particularly in private universities in developing countries.

In Indonesia, blockchain adoption for academic data management in private universities is still in its early stages. Barriers include low technological awareness among educational stakeholders, limited user-friendly interfaces for non-technical users, and concerns about integration with existing systems (Bahauddin et al., 2023; Karyani et al., 2024). Furthermore, previous research has generally focused on conceptual frameworks or limited case studies, without producing functional prototypes that address both security and usability challenges in e-learning environments (Bidry et al., 2023; Chen et al., 2022; Mawgoud et al., 2025)

Based on the reviewed literature, this study operationalizes three core analytical dimensions: (1) system usability, measured using the System Usability Scale (SUS); (2) user experience quality, evaluated through the User Experience Questionnaire (UEQ); and (3) system performance and blockchain efficiency, assessed using load testing metrics and blockchain-level indicators such as throughput, confirmation time, and transaction failure rate. While previous studies have examined these variables separately, empirical research integrating all three dimensions within a single blockchain-based academic grading system remains limited, particularly in the context of private universities in developing countries.

Empirical studies (Bahauddin et al., 2023; Irfan et al., 2025; Nassani et al., 2023; Saleh et al., 2020; Sama et al., 2025) reported improved transparency and data verification using blockchain-based educational systems; however, their evaluations primarily focused on functional feasibility rather than comprehensive usability and performance metrics. Similarly, studies (Aini et al., 2021; Basri et al., 2024; Raharjo & Rohmadi, 2025) highlighted the potential of blockchain for academic record verification, in the Indonesian context, but did not provide detailed load-testing or user experience data. This study addresses these gaps by empirically evaluating usability, performance, and blockchain efficiency simultaneously.

This research aims to develop and optimize a blockchain- integrated e-learning platform specifically designed for the secure management of student grade data at private universities. Using a mixed methods approach and a Software Development Life Cycle (SDLC) framework, this research encompasses design, development, testing, and user evaluation. Through the implementation of blockchain and smart contracts, the proposed platform is expected to reduce the risk of data manipulation and leakage, while providing transparent and verifiable access to academic data for students and institutions.

The main strength of this research lies in three distinctly novel aspects. First, it focuses on a local context, namely private universities in Indonesia, which have so far had limited adoption of blockchain technology for academic data management. Second, it produces a functional, ready-to-use prototype, rather than just a conceptual model, allowing for empirical evaluation of performance and user acceptance. Third, it adopts a comprehensive approach that considers not only data security but also system performance and user experience. The combination of these three aspects makes this research potentially bridge the gap between theory and practice in secure and transparent academic data management.

By producing solutions ready for empirical testing, this research is designed to bridge the gap between theory and practice in transparent and secure academic data management. The results are expected to not only strengthen academic trust but also serve as a reference for educational digitalization policies in Indonesia and other developing countries.

Literature Review

Blockchain in Education: Concepts, Applications, and Empirical Evidence

Blockchain is a distributed ledger technology characterized by decentralization, immutability, and cryptographic security. In the educational context, blockchain applications span various domains, such as verifiable credentials management, tracking learning histories and micro-credentials, the integrity of online assessment and examination processes, and the management of academic data such as student transcripts and grades (Aslan & AtaŞEn, 2020; McGreal, 2023). Several systematic reviews and implementation studies have shown that blockchain can improve traceability, facilitate third-party verification, and prevent manipulation of academic administration (Aini et al., 2021; Basri et al., 2024).

However, a critical review of the existing literature reveals that most research remains at the conceptual, review study, or small-scale laboratory prototype stage, with little empirical evidence at medium to large scales that includes performance metrics and user acceptance indicators. For example, Sama et al. (2025) proposed a blockchain-based e-learning framework to enhance data security, but its implementation was limited to simulations. Similarly, a longitudinal study by Fidas et al. (2023) studied online learning environments to judge the significance of AI-centered proctoring system in tertiary educational institutions, but remained a proof-of-concept. This situation highlights the need for research that links blockchain architecture choices—such as fully on-chain storage, hybrid models with off-chain storage, or layer-2 utilization —with measurable outcomes in terms of security, cost, and user experience, particularly in the context of student grade management.

Security and Privacy Challenges in Conventional E-Learning Systems

E-learning platforms have a number of recurring vulnerabilities, including internal data manipulation, information leaks due to insecure server configurations or cyberattacks, limited transparency for students to check grade changes, and the risk of a single point of failure in centralized architectures (Ali et al., 2025; Aliakbari et al., 2025). The significant increase in e-learning usage over the past few years has also resulted in a larger volume of sensitive data, such as grades, student identities, and academic history, which in turn increases security risks (Aji & Prakoso, 2026; Ali et al., 2025; Nassani et al., 2023).

Traditional mitigation measures, such as encryption, access control, and data backup, provide only partial protection and often fail to provide independently verifiable evidence of data changes. Furthermore, there is a trade-off between security and ease of use: overly complex solutions can potentially reduce adoption by non-technical faculty or administrative staff. Another challenge is the lack of studies quantitatively comparing operational costs (such as server costs and system maintenance) with the reduction of security incidents or increased stakeholder trust. This underscores the importance of developing solutions that are not only secure but also efficient and easy to use for all system users.

Smart Contracts for Value Management: Design Patterns, Technical Risks, and Practical Solutions

Smart contracts enable the automation of academic procedures, such as recording grades with timestamps, automatically validating grading scales, and providing cryptographic proof of the existence of these records for audit purposes (McGreal, 2023; Rahardja et al., 2022). Integrating smart contracts into grade management workflows is believed to reduce manual intervention, increase transparency, and strengthen data traceability.

However, the application of smart contracts in academic data management faces several technical and ethical challenges. From a privacy perspective, storing sensitive data directly on-chain can violate personal data protection regulations, so a commonly proposed solution is off-chain storage with encrypted data and only storing hash signatures on-chain. From a security perspective, smart contracts with vulnerabilities in code or unverified logic can open new avenues for attacks, so formal auditing and verification processes are essential. From a performance perspective, on-chain operations can incur transaction costs (gas fees) and latency that are unsuitable for academic processes that require real-time speed. Various studies offer solutions, such as the use of permissioned blockchains, sidechains, or layer-2 blockchains, to reduce costs and speed up processes, but these choices come at a cost to the system's level of decentralization and security.

Existing literature tends to address privacy, cost, and security solutions separately, with little research testing these design combinations in a real-world value management context. Therefore, research that comparatively examines different architectural configurations, both from a technical and user experience perspective, is urgently needed.

Barriers to Implementation, Institutional Adoption, and Research Gaps in Indonesian Private Universities

Studies on technology adoption in private universities, particularly in developing countries, show that non-technical barriers are often as influential as technical challenges. These barriers include low technological literacy among lecturers and administrators, limited budgets for IT investments, resistance to procedural changes, and demands for compliance with local regulations (Aslan & AtaŞEn, 2020; Bahauddin et al., 2023; Irfan et al., 2025). Policy analysis also emphasizes that successful adoption requires a roadmap that includes increased human resource capacity, a clear business model, and infrastructure support such as cloud computing services, backup, and service-level agreements (SLAs).

From a research perspective, several gaps remain to be filled, including the lack of empirical studies that combine technical evaluations (such as throughput , latency, and cost) with social evaluations (level of trust and ease of use), the lack of economic analyses comparing blockchain solutions with enhanced centralized systems, the absence of a clear governance model regarding the role of node managers and access rights, and limited policy studies related to the legality of storing academic data on blockchain in Indonesia. These gaps provide opportunities for research that can produce functional prototypes, be empirically tested, and be accompanied by comprehensive implementation recommendations for the context of private universities in Indonesia.

Research Methodology

Research Design

This research uses a mixed methods approach, combining qualitative and quantitative methods to obtain a comprehensive picture of user needs and measure the effectiveness of the developed system. The qualitative approach was used to explore user perceptions and experiences through in-depth interviews and focus group discussions (FGDs). Meanwhile, the quantitative approach was used to measure the system's technical performance and user satisfaction levels using a standardized survey instrument.

The system testing involved 40 participants, consisting of 20 students, 10 lecturers, and 10 administrative staff from partner universities. The trial process was carried out on a campus staging server with hardware specifications including an 8-core Intel Xeon processor, 16 GB of RAM, and NVMe SSD storage, to ensure optimal system performance. The blockchain system used is a permissioned blockchain with a Proof of Authority (PoA) consensus mechanism and runs on four virtual machine (VM)-based validator nodes.

Load testing was conducted by simulating concurrent users of 10, 50, 100, and 200 users, to measure the system's response time and throughput at various usage levels. User experience was evaluated using two instruments, namely the System Usability Scale (SUS) with 10 items on a Likert scale of 1–5 and the User Experience Questionnaire (UEQ) consisting of 20 items on a bipolar scale of 1–7, covering six dimensions: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty.

type of research falls under the research and development (R&D) framework, which adheres to the Software Development Life Cycle (SDLC) framework. The SDLC approach was chosen because it provides systematic stages, from planning and requirements analysis, design, development, testing, implementation, and system maintenance. The SDLC approach allows for an iterative and measurable development process, allowing each stage to be evaluated and adjusted based on user feedback and test results.

Research Procedures

The research stages follow the SDLC model as follows:

1. Planning: Establishing research objectives and analyzing the initial feasibility of developing a blockchain-based e-learning platform. This activity includes a literature review on blockchain applications in education and identifying the security and transparency needs of academic data at private universities.
2. Needs Analysis: This was done through primary and secondary data collection. Primary data was obtained from interviews, focus group discussions (FGDs), and direct observation of the value management process, while secondary data came from academic policy documents, data security reports, and previous research. The analysis results were presented in a Software Requirement Specification (SRS), which outlines the system's features and technical specifications.
3. System Design: Designing a system architecture encompassing frontend, backend, blockchain integration, and smart contracts for value management. The chosen model is a hybrid architecture, combining off-chain storage for large data and on-chain hash recording to ensure data integrity. The user interface is designed to be user-friendly for non-technical users.
4. Development: The coding process is based on a predetermined design. The system's key features include smart contract-based value recording, data change verification, and audit trail access for authorized parties. Development is modular for easy testing and integration.

5. Testing: Includes three types of testing, namely functional testing to ensure all features run according to specifications, security testing to detect potential vulnerabilities, and usability testing using SUS and UEQ instruments.
6. Implementation: Systems that have passed the trials are implemented on a limited scale at partner universities. This phase includes user training and the development of system documentation.
7. Maintenance: After implementation, the system is monitored periodically to detect errors, make updates, and add new features based on user feedback.

Data Collection Techniques

Data collection involved 40 participants from among lecturers, administrative staff, and active students at a private university in West Java that used an e-learning system. This number was selected based on recommendations from Nielsen (2000) and Sauro and Lewis (2016), who stated that 20–40 respondents are sufficient to identify most usability issues and obtain a representative picture of system acceptance.

Various techniques were used to obtain complete data, namely:

1. In-depth interviews, to explore user perceptions and challenges in digital value management.
2. Focus group discussions (FGD), to validate interview results and determine priority system needs.
3. Direct observation, to map the input, management, and verification processes of values that are potentially error-prone.
4. Documentation, in the form of collecting academic policies and data security reports.
5. System logs, which are used to analyze technical performance and security levels during testing.
6. The questionnaire consists of: System Usability Scale (SUS) to assess the ease of use of the system, User Experience Questionnaire (UEQ) to assess user experience based on six main dimensions, and two open-ended questions to collect qualitative feedback regarding the advantages and disadvantages of the system.

This approach produces a combination of complementary quantitative and qualitative data, so that the research results can provide a comprehensive picture of the performance and acceptance of blockchain-based e-learning systems.

Data Analysis

Quantitative data were analyzed using System Usability Scale (SUS) and User Experience Questionnaire (UEQ) scores. The average score for each dimension was calculated and compared with international benchmarks to determine the level of usability and user experience. Qualitative data from open-ended questions were then analyzed using thematic analysis to identify common patterns regarding system strengths, challenges, and suggestions for improvement. The combination of these two approaches allows for a comprehensive assessment of technical performance and user satisfaction.

System Architecture

The developed system uses a hybrid blockchain architecture to balance security, cost efficiency, and performance. Primary academic data is stored in an encrypted off-chain database to maintain privacy and storage efficiency, while hashes of student grades are stored on-chain via smart contracts to ensure integrity and prevent manipulation.

The main components of the system include:

1. Presentation Layer (Frontend) – A user-friendly web interface designed for students, lecturers, and administrators.
2. Application Layer (Backend) – Manages business logic and communication between the frontend, database, and blockchain network.
3. Blockchain Layer – Manages smart contracts for hash value recording and verification processes.
4. Off-chain Storage Layer – Stores complete academic data in encrypted form.
5. API Gateway – Provides a secure communication path between internal campus systems and blockchain services.

This architecture was designed to keep on-chain transaction overhead low, thus reducing operational costs without compromising security. This approach also allows integration with the existing Academic Information System (SIAKAD), ensuring implementation does not disrupt ongoing academic processes.

Ethical Considerations

This research was conducted in accordance with ethical research principles in the field of information technology and education. All participants were provided with complete information regarding the study's objectives, procedures, and potential benefits and risks. Written consent was obtained prior to data collection.

Personal data is kept confidential through the use of anonymized codes and encrypted storage, with access restricted to the research team. The principle of privacy by design was applied in system development, ensuring that data security and protection are integral to the system architecture. This research also complies with the Indonesian Personal Data Protection Law (UU PDP). Any published results will be presented without including any information that could identify individuals or institutions, to maintain the privacy and confidentiality of participants.

Results and Discussion

Beyond conceptual discussion, this study provides practical, technical, and policy-level implications for the adoption of blockchain-based academic systems. From a practical perspective, the empirical results demonstrate that a hybrid blockchain architecture with Proof of Authority (PoA) consensus can be realistically implemented in private universities with limited infrastructure, while maintaining acceptable performance, usability, and security. From a technical standpoint, the findings show clear operational thresholds, particularly the stable performance up to 100 concurrent users—which can serve as a reference for system sizing and deployment planning. At the policy level, the results imply that blockchain adoption in Indonesian higher education does not necessarily require fully public blockchains but can instead leverage permissioned models that align better with data protection regulations, institutional governance, and cost efficiency.

Table 1 presents the results of the Brooke's System Usability Scale (SUS) test which indicate that the developed blockchain-based e-learning system has a good level of usability (Irawan et al., 2025). The test was conducted on 40 participants, consisting of students, lecturers, and administrative staff. Each respondent rated ten SUS statements using a Likert scale of 1–5, which was then converted to a 0–100 scale standard method. Based on the data processing results (Table 1), the average SUS score was 77.8, with a standard deviation (SD) of 8.4, a minimum score of 60.0, a maximum of 95.0, and a median of 78.8. This value indicates that most users rated the system as being in the "Good" to "Excellent" category, meaning the system is easy to use, the interface is quite intuitive, and does not cause excessive cognitive load for users.

Table 1

Summary statistics of SUS

Statistics	Mark
Mean SUS (0–100)	**77.8**
Elementary School	8.4
Min	60.0
Max	95.0
Median	78.8

Note: SUS results (n = 40) SUS conversion method: each item is processed standard → score 0–100.

The score distribution in Table 2 supports these results, with 22 participants (55%) rating the system as Good (70–84), and 9 participants (22.5%) rating the system as Excellent (85–100). Eight participants (20%) rated the system as OK/Marginal (50–69), and only one participant (2.5%) rated the system as Poor (<50). These results indicate that overall, the system meets good usability standards and has been positively received by users. The average SUS score of 77.8 is also above the threshold of 70, which is internationally interpreted as a level of usability acceptable for operational implementation. Therefore, the system is considered to have a user-friendly interface and easy-to-operate functions. However, there is still room for improvement in aspects of display consistency and navigation efficiency, especially for user groups with lower digital literacy levels.

Table 2

Distribution of categories (SUS)

Category	SUS Range	Number of participants
Excellent	85–100	9
Good	70–84	22
OK / Marginal	50–69	8
Poor	<50	1

As an illustration, some individual scores from the first ten respondents ranged from 65.0 to 91.3, indicating a variation in user perceptions of the system's ease of use. While some ratings were moderate, most respondents expressed high levels of satisfaction with the system's performance and ease of use, reinforcing the finding that the platform has potential for wider adoption in academic settings.

The obtained SUS score of 77.8 is not only above the commonly accepted usability threshold of 70 but also comparable to usability levels reported in mature academic systems. For instance, Sauro and Lewis (2016) indicate that systems scoring between 75–80 are typically associated with high user acceptance and lower training costs. The relatively low standard deviation (SD = 8.4) further suggests consistency in user perceptions across different stakeholder groups, indicating that the system interface is equally accessible to students, lecturers, and administrative staff.

Although most UEQ dimensions scored positively, the lower scores in Stimulation and Novelty indicate a functional rather than experiential strength. This suggests that while blockchain integration enhances trust and transparency, it does not automatically translate into perceived innovation at the interface level. This finding aligns with observations by McGreal (2023), who noted that blockchain benefits in education are often "invisible" to end-users unless explicitly visualized through interface design.

Table 3 results show that the Attractiveness dimension obtained the highest score (mean = 5.6), indicating that users found the system interface attractive, intuitive, and enjoyable to use. The Perspicuity dimension also received a high score (mean = 5.4), indicating that the system is easy to learn and does not cause confusion for new users. Efficiency and Dependability were in the range of 5.0–5.2, indicating that the system worked smoothly and reliably, although there is still room for optimization of system performance and stability.

Table 3

UEQ results (n = 40) – mean scores per dimension (scale 1–7)

Dimensions	Mean	Elementary School	Short interpretation
Attractiveness	**5.6**	0.7	Users rated the interface as attractive
Perspicuity (Clarity)	**5.4**	0.8	Easy to understand
Efficiency	**5.2**	0.9	Efficient enough for general tasks
Dependability	**5.0**	0.9	Stable but there is room for improvement
Stimulation	**4.8**	1.0	Interesting but not very motivating
Novelty	**4.5**	1.1	Moderately innovative, could be more unique

Meanwhile, the Stimulation (mean = 4.8) and Novelty (mean = 4.5) dimensions showed slightly lower scores than the other dimensions. This indicates that although the system provides a pleasant experience, users have not yet fully experienced significant novelty or innovation compared to conventional e-learning systems. The relatively moderate Novelty score also reflects that users focus more on the system's functionality and ease of use than on its appearance or unique features.

Overall, the average score above 5.0 for most dimensions confirms that the system has good user experience, in accordance with international UEQ interpretation standards. This finding reinforces the results of previous SUS tests, which showed that the developed blockchain-based e-learning system has met the usability and user convenience criteria suitable for implementation in academic environments, with potential improvements in innovation and visual appeal for subsequent versions.

System Performance Results (load test)

System performance testing was conducted to assess the blockchain-based e-learning platform's ability to handle concurrent user loads. This test simulated key usage scenarios, including login, grade data access, blockchain hash verification, and grade PDF file downloads. Key parameters observed included throughput (requests per second), average response time, 95th percentile response time (p95 response time), CPU and memory usage, and error rate (See Table 4)

Table 4

Performance summary per concurrent users scenario

Concurrent users	Throughput (req/s)	Avg response time (ms)	p95 response time (ms)	CPU avg (%)	Memory (MB)	Error rate
10	80	120 ms	220 ms	15%	300 MB	0%
50	200	240 ms	520 ms	40%	600 MB	0%
100	320	480 ms	980 ms	70%	1200 MB	0.5% (retry timeout)
200	400	920 ms	1800 ms	95%	2000 MB	2.5% (timeouts & 5xx)

Based on these results in Table 4, the system demonstrated stable performance with up to 100 concurrent active users. Under these conditions, the average response time remained below 0.5 seconds (480 ms), indicating the system's ability to respond to requests quickly and consistently. CPU utilization was at 70% with a very low error rate (0.5%), demonstrating the system's efficiency and reliability in handling moderate loads.

In scenarios with 10 to 50 users, system performance was optimal, with a very fast response time (120–240 ms) and no errors (error rate = 0%). This demonstrates that the hybrid blockchain architecture used can maintain communication efficiency between the front end, backend, and permissioned blockchain network components. However, when the number of concurrent users increased to 200, there was a significant increase in response time (920 ms) and a spike in CPU load of up to 95%, accompanied by an increase in the error rate to 2.5%. This indicated that the system was beginning to experience resource saturation, particularly on the application server side and in communication with blockchain nodes. This phenomenon is common in distributed systems that have not been optimized for large scale.

Overall, the test results indicate that the system meets the performance criteria for medium-scale institutional use, with a stable capacity of up to 100 active users. For larger production-scale deployments, scaling strategies are recommended, both vertically (additional server CPU and memory resources) and horizontally (additional application instances and blockchain nodes). Further optimizations, such as caching, load balancing, and asynchronous request handling, can also increase throughput while reducing system latency under high load conditions.

Test results on a permissioned blockchain network with a Proof of Authority (PoA) consensus mechanism provide insight into the system's performance in recording and verifying academic grade data through smart contracts. The primary objective of this testing was to ensure that blockchain integration within the e-learning system can operate with efficient processing times, high reliability, and reasonable resource consumption.

The measurement results are presented in Table 5, which displays various key blockchain performance metrics, including block formation time, number of transactions per block, effective throughput (TPS), confirmation time, verification latency, transaction failure rate, and storage space usage per node. These results show that the blockchain system used has very fast and stable transaction performance. An average block time of 2 seconds and an effective throughput of around 100 transactions per second (TPS) demonstrate that the permissioned PoA network can process medium-volume data with high efficiency. These values are considered good for academic environments, where transaction frequency is less intense than in financial systems but still requires high data security and consistency.

Table 5

Blockchain Metrics (Permissioned PoA)

Metric	Results
Block time (average)	**2.0 s**
Tx per block (avg)	200 tx
Effective TPS	**~100 polling stations**
Average confirmation time (tx included in block)	~**2.1 s**
Verification latency (end-to-end hash check on UI)	~**350–800 ms** (depending on caching & network)
Tx failure rate	0.2% (mostly due to malformed payloads / nonce mismatch)
Disk usage per node (after 10k tx)	~1.1 GB

The average transaction confirmation time of approximately 2.1 seconds indicates that every student's grade recorded on the blockchain can be verified in near real time. End-to-end latency when users verify hashes through the system interface ranges from 350 to 800 milliseconds, depending on network conditions and caching mechanisms. These results indicate that users can validate data quickly without significant delays in the user interface (UI).

The transaction failure rate (0.2%) is very low and is mostly due to malformed payloads or nonce mismatches, rather than network stability issues. The storage usage of 1.1 GB per node for 10,000 transactions demonstrates that the implemented hash storage mechanism is efficient and does not burden server storage capacity. Furthermore, the results of the audit function and student grade verification tests demonstrated good performance. The verification process for a single grade—which involves retrieving a hash from the blockchain, matching it with an off-chain database, and displaying the results in the UI—took an average of 360 milliseconds (SD ±120 ms). A mass verification process of 50 grades took approximately 14 seconds. This time is still considered reasonable for an academic system, although it could be further optimized through request batching or catching verification results.

Overall, these results demonstrate that the hybrid blockchain architecture with the PoA mechanism can deliver fast, stable, and efficient performance for the recording and verification of academic grade data. The short block and confirmation times demonstrate PoA's advantages in a permissioned network environment, where speed and reliability are top priorities. Therefore, this system is suitable for implementation as a trusted digital solution to improve the security and transparency of academic data in higher education.

The combined testing results of the System Usability Scale (SUS) and User Experience Questionnaire (UEQ) provide a comprehensive overview of the usability and user experience of the developed blockchain-based e-learning system. Summary results are presented in Table 6, which displays the mean, standard deviation (SD), and general interpretation for each indicator.

Table 6

SUS & UEQ results (summary)

Method	N	Mean	Elementary School	Notes
SUS (0–100)	40	77.8	8.4	Good—high acceptance rate
UEQ – Attractiveness (1–7)	40	5.6	0.7	User-friendly UI
UEQ – Perspicuity	40	5.4	0.8	Easy to understand
UEQ – Efficiency	40	5.2	0.9	Quite efficient
UEQ – Dependability	40	5.0	0.9	Good stability
UEQ – Stimulation	40	4.8	1.0	Moderate motivation
UEQ – Novelty	40	4.5	1.1	Need more innovation

Overall, a SUS score of 77.8 indicates that the system has a good level of usability (categorized as "Good"), with a high level of user acceptance. This score is above the internationally accepted threshold of 70 for operational implementation. This means that most users found the system easy to use, not confusing, and with an intuitive navigation structure.

In terms of user experience (UEQ), the results show that all dimensions scored above 4.0 (on a scale of 1–7), indicating a positive perception of the system. The Attractiveness dimension scored the highest (5.6 ± 0.7), indicating that users found the interface attractive and enjoyable to use. High scores were also found for Perspicuity (5.4) and Efficiency (5.2), confirming that the system is easy to learn, efficient to use, and capable of supporting academic activities without significant difficulties.

The Dependability dimension (5.0) indicates that users consider the system to be quite stable and reliable in carrying out its primary functions, particularly in the blockchain-based value recording and verification process. However, the last two dimensions, Stimulation (4.8) and Novelty (4.5), showed lower scores than the other dimensions. This indicates that although the system is considered functional and convenient to use, users have not yet fully experienced significant motivation or novelty in their interactions with the system.

The combined results of the SUS and UEQ demonstrate that the blockchain-based e-learning system meets usability and user experience standards. The system is considered easy to use, efficient, and has an attractive interface, although improvements in design and interactivity are still needed to make the user experience more dynamic and engaging. Overall, these results support the finding that the developed system is ready for implementation in an academic environment with a high level of user acceptance.

The results of the performance and load tests demonstrate the system's ability to handle varying numbers of concurrent users. The purpose of these tests is to assess the stability, response speed, and efficiency of server resource usage under increased load conditions. Summary results are presented in Table 7.

Table 7

Performance & Load Test (summary)

Scenario	Avg RT	p95 RT	Throughput	CPU	Mem	Errors
10 users	120 ms	220 ms	80 req/s	15%	300 MB	0%
50 users	240 ms	520 ms	200 req/s	40%	600 MB	0%
100 users	480 ms	980 ms	320 req/s	70%	1200 MB	0.5%
200 users	920 ms	1800 ms	400 req/s	95%	2000 MB	2.5%

These results demonstrate that the system can operate stably with up to 100 concurrent active users, with an average response time (Avg RT) below 0.5 seconds (480 ms) and a very low error rate (0.5%). This indicates that the system is quite efficient in processing user transactions and requests without experiencing significant delays.

Under light to moderate conditions (10–50 users), system performance is at optimal levels, indicated by fast response times (120–240 ms), relatively low CPU usage (15–40%), and no errors. This indicates that the system has high processing efficiency and good resource management in handling normal loads. However, when the number of concurrent users increased to 200, there was a significant increase in latency (920 ms) and CPU usage (95%), accompanied by an increase in error rates of up to 2.5% due to timeouts and server errors (5xx). This condition indicated that the system was starting to reach its optimal capacity limit (saturation).

Overall, the test results show that this blockchain-based e-learning system has high performance and stability for medium-scale institutional use, with an optimal capacity of up to approximately 100 concurrent users. For larger-scale deployments, server capacity scaling strategies are recommended, both vertically (increasing CPU and memory resources) and horizontally (adding new application nodes or servers), to ensure the system remains responsive and reliable under high load conditions.

Based on the results of the system performance testing, blockchain metrics, and usability evaluations (SUS and UEQ) discussed previously, several technical recommendations can be developed to improve the performance, scalability, and user experience of this blockchain-based e-learning system. These recommendations are formulated based on empirical findings from load testing, blockchain PoA metric results, and user assessments of functional aspects and interface experience.

First, performance test results show that the system begins to saturate with >100 concurrent users, characterized by increased latency of up to 920 ms and CPU usage reaching 95%. To address this, a scaling strategy needs to be implemented using auto-scaling on the backend, either through horizontal pod scaling (additional application instances) or load balancing. This approach allows the system to dynamically adjust resource capacity based on user load, maintaining stability in intensive usage scenarios.

Second, based on blockchain metrics, hash verification latency still ranges between 350–800 ms, primarily due to the repetitive communication process with blockchain nodes. To reduce this response time, it is recommended to implement a caching mechanism for hash verification results and batch RPC calls to process multiple transactions simultaneously. This strategy will reduce network overhead and improve communication efficiency between nodes.

Third, from a database perspective, observations indicate potential for increased audit trail data search efficiency. Therefore, database optimization is necessary by adding indexes to key columns such as student ID and timestamp, resulting in faster and more efficient query processing, especially when searching for historical grades or large volumes of audit data.

Fourth, to maintain sustainable system performance, it is recommended to implement active monitoring through Application Performance Monitoring (APM) , which includes an automatic alert system, for example, when CPU usage exceeds 80% or the error rate exceeds 1%. This monitoring is essential for early detection of disruptions, identifying bottlenecks , and real-time system repair.

Finally, based on the UEQ evaluation results, two dimensions with relatively lower scores were Novelty (4.5) and Stimulation (4.8). This indicates a need for improvements in the system's innovation and visual appeal. Interface adjustments (UX tweaks) are recommended, such as adding an onboarding guide, interactive tooltips, or visual feedback upon successful hash verification. This can improve user perception of innovation, making the system feel more modern, interactive, and enjoyable to use.

Overall, implementing these five recommendations will strengthen the system both technically (scalability, latency, reliability) and in terms of user experience (usability and interactivity). Thus, the developed blockchain-based e-learning system will not only be efficient and reliable but also provide an engaging and sustainable digital experience for all users in the academic environment.

The findings of this study are largely consistent with previous empirical research, particularly regarding the trade-off between system decentralization and performance. Like the results reported by Bayan et al. (2024), the use of a permissioned blockchain significantly reduced latency and transaction costs compared to public blockchain implementations. However, this study extends prior work by empirically demonstrating that such performance gains do not compromise user trust or perceived system reliability, as reflected in the positive SUS and UEQ scores.

Conversely, the observed scalability limitations beyond 100 concurrent users partially diverge from simulation-based studies such as Ubaka-Okoye et al. (2020), which reported higher theoretical throughput. This discrepancy highlights the importance of real-world empirical testing, as simulation environments often underestimate network overhead, resource contention, and user interaction complexity.

Conclusion

This research successfully developed a prototype e-learning system based on hybrid blockchain architecture that is able to guarantee the security and transparency of academic grade data efficiently. Based on the test results, the system demonstrated a good level of usability (SUS = 77.8) and a positive user experience (UEQ > 5 in most dimensions), indicating that the interface is easy to use and preferred by users. In terms of technical performance, the system was able to maintain stability for up to 100 active users with a response time below 0.5 seconds and minimal error rates, while the PoA blockchain network produced an effective throughput of around 100 TPS with an average transaction confirmation time of 2 seconds.

Although performance and user acceptance were relatively high, the results of the study indicate the need for improvements in the aspects of interface innovation and system scalability, especially when the user load exceeds 100 concurrent users. Therefore, it is recommended to implement auto-scaling, caching, database indexing, and active monitoring to improve efficiency, as well as enrichment of UX features such as interactive tooltips and visual feedback to enhance the Novelty and Stimulation dimensions. Overall, this research proves that blockchain integration in e-learning systems can be implemented realistically and effectively in higher education environments, while also being the first step towards secure, transparent, and verified academic digitalization in Indonesia.

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