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DESIGNING A WEB3 INFRASTRUCTURE FOR PEER-TO-PEER LEARNING: COMPARATIVE ANALYSIS, IMPLEMENTATION, AND EXPERIMENTAL VALIDATION

Karymsakov Amandyk Zhandosovich
242965@astanait.edu.kz
Master's student, Educational Program «Computer Science and Engineering»
Astana IT University, Astana, Republic of Kazakhstan
Scientific supervisor — Myrzakerimova Alua, PhD, Assistant Professor

Abstract **—** The integration of Web3 technologies into educational systems enables the development of decentralized, transparent, and learner-centered learning environments. However, traditional learning management systems remain limited in terms of data ownership, credential portability, and cross-institutional trust. This paper presents a layered architectural framework for Web3-based peer-to-peer (P2P) learning platforms, integrating blockchain infrastructure, smart contracts, decentralized identity (DID), and hybrid data storage. Through a systematic analysis of 29 sources published between 2018 and 2026, we identify key architectural patterns and propose a four-layer model decomposing platform concerns into Presentation, Application, Data, and Trust layers. A structured comparative analysis of eight representative platforms across six evaluation dimensions reveals critical trade-offs between experimental and production-oriented implementations. To address the lack of empirical validation identified in existing literature, the paper presents KnowledgeChain — a hybrid Web3 platform implementing three novel protocols: Proof-of-Knowledge (PoK) peer review, zkSkill zero-knowledge skill verification, and a Knowledge Bonding Curve for autonomous pricing. Agent-based simulations with 1,000 agents demonstrate strong fairness (Gini coefficient = 0.24), negligible collusion probability (P(K = 2) = 0.03%), and robust manipulation resistance under simulated conditions. The framework provides actionable design guidance for gradual institutional adoption of Web3-enabled P2P learning systems.

Keywords **—** *Web3 education, peer-to-peer learning, blockchain, decentralized identity, smart contracts, zero-knowledge proofs, soulbound tokens.*

I. INTRODUCTION

The ongoing transformation of higher education toward Education 4.0 emphasizes learner autonomy, lifelong learning, cross-institutional mobility, and sustainable digital infrastructures [1]. However, traditional centralized learning management systems (LMS) remain limited in terms of data ownership, credential portability, and trust across institutional boundaries, particularly in peer-to-peer (P2P) learning environments [2]. Recent studies highlight the growing role of Web3 technologies — including blockchain, smart contracts, decentralized storage, and decentralized identity (DID) — in addressing these limitations by enabling transparent, learner-centered, and interoperable educational ecosystems [3].

Existing research explores decentralized educational systems from multiple perspectives, including blockchain-based credential verification [4], incentive mechanisms [5], and governance models [6]. While these approaches demonstrate the potential of decentralization, they are often developed in isolation and lack a unified architectural perspective suitable for institutional adoption. In particular, challenges related to scalability, pedagogical integration, regulatory compliance, and interoperability remain insufficiently addressed across current implementations.

Moreover, the distinction between experimental prototypes and production-oriented systems is seldom made explicit. Many proposed platforms demonstrate technical feasibility in controlled environments but provide limited guidance on deployment constraints. Key gaps include transaction throughput, GDPR compliance, integration with existing student information systems, and long-term governance sustainability.

This paper addresses these gaps by proposing a structured, layered architecture for Web3-based P2P learning platforms and validating it through the implementation and experimental evaluation of KnowledgeChain — a full-stack hybrid Web3 platform. The main contributions are: (1) a synthesized four-layer architectural model aligning technical design with pedagogical requirements of P2P learning; (2) a comparative analysis of eight representative platforms across six evaluation dimensions; (3) an analytical cost and performance comparison across three blockchain deployment configurations; (4) the KnowledgeChain implementation with three novel protocols — PoK peer review, zkSkill verification, and Knowledge Bonding Curve — validated on a testnet environment; and (5) experimental evaluation through agent-based simulations demonstrating quantitative improvements over existing approaches.

II. RELATED WORK

A. Web3 Technologies in Education

Web3 technologies have increasingly been explored as an alternative to centralized educational infrastructures, aiming to enhance transparency, learner sovereignty, and cross-institutional trust. Prior studies examine decentralized academic platforms that leverage blockchain for educational data management, governance, and certification processes [7], [8], [9]. These works highlight the potential of decentralization to reduce institutional silos and enable global learning ecosystems. However, many proposed platforms remain conceptual or prototype-based, offering limited guidance on scalable architecture and long-term institutional deployment.

B. Credential Systems and Decentralized Identity

A significant body of research focuses on blockchain-based credential systems, decentralized identifiers (DIDs), and verifiable credentials (VCs) as mechanisms for secure and portable academic records. Surveys and implementation studies demonstrate how self-sovereign identity (SSI) models can improve credential verification and learner control over personal data [10], [11], [12]. Advanced approaches incorporate privacy-preserving techniques such as zero-knowledge proofs (ZKPs) to address regulatory constraints and selective disclosure requirements [13], [14], [15]. Despite these advances, existing solutions often prioritize credential verification over broader pedagogical and system-level integration.

C. Peer-to-Peer Learning and Incentive Mechanisms

P2P learning models emphasize horizontal knowledge exchange, collaborative problem-solving, and distributed expertise. Blockchain-based implementations support these paradigms through transparent peer assessment, reputation systems, and automated incentive distribution [16], [17], [18]. Several studies investigate token-based reward mechanisms to enhance learner motivation [19], [20]. While incentive systems can increase engagement, concerns remain regarding their long-term sustainability and alignment with intrinsic learning motivation [21].

D. Production-Oriented Systems and Architectural Gaps

Beyond experimental platforms, several studies report production-oriented blockchain-based educational systems prioritizing reliability, regulatory compliance, and integration with existing institutional infrastructure [22], [23]. These approaches demonstrate the feasibility of hybrid architectures combining on-chain verification with off-chain educational data storage. Nevertheless, challenges related to scalability, governance, and gradual decentralization persist, indicating the need for structured architectural frameworks that bridge the gap between research prototypes and institutional deployment.

III. RESEARCH METHODOLOGY

A. Research Approach

This study adopts a design-oriented and analytical research methodology aimed at synthesizing existing knowledge into a coherent architectural framework. Rather than evaluating a single implementation, the research focuses on identifying architectural patterns, design principles, and system-level trade-offs observed across existing Web3-based educational platforms.

B. Source Selection and Scope

The literature search followed a structured selection process. Four databases — IEEE Xplore, ACM Digital Library, Scopus, and Google Scholar — were queried using keyword combinations including “Web3 education,” “blockchain learning management,” “decentralized identity education,” and “peer-to-peer learning blockchain.” The search was limited to publications from 2018 to 2026 to capture the most relevant work following the emergence of practical smart contract platforms.

An initial pool of 87 candidate sources was identified. These were screened in two stages. In the first stage, titles and abstracts were reviewed for topical relevance, excluding purely theoretical blockchain studies without educational application. In the second stage, full texts were assessed against three inclusion criteria: (a) direct relevance to decentralized educational platforms or P2P learning; (b) description of a technical architecture or implementation; and (c) peer-reviewed publication or documented deployment. This process yielded 29 primary sources that form the basis of the comparative analysis.

C. Layered Architectural Abstraction

The proposed methodology decomposes Web3-based P2P learning platforms into interoperable functional layers. Based on synthesis of prior studies, the architecture is structured into four layers: (1) Presentation Layer, providing user-facing interfaces for learners, educators, and administrators through decentralized applications with wallet integration; (2) Application Layer, including smart contracts, incentive mechanisms, credential issuance modules, and governance components; (3) Data Layer, supporting hybrid on-chain and off-chain storage with IPFS or similar decentralized file systems; and (4) Trust Layer, responsible for on-chain consensus, transaction execution, credential anchoring, and trust-critical protocol enforcement.

This decomposition differs from generic n-tier web architectures in several respects. The Data Layer explicitly separates on-chain anchoring (hashes, credential proofs) from off-chain bulk storage (learning content, interaction logs), reflecting cost and throughput constraints unique to blockchain systems. The Application Layer incorporates governance modules (e.g., DAO voting) and incentive engines (e.g., token distribution) that have no direct analogue in traditional LMS architectures. The Trust Layer abstracts consensus mechanism selection, enabling the framework to accommodate both permissioned and public deployments.

D. Evaluation Criteria

The selected platforms were evaluated using six dimensions: (1) Scalability — transaction throughput, consensus mechanism, and Layer-2 solutions; (2) Interoperability — integration with existing LMS, cross-chain compatibility; (3) Credential Portability — DID/VC support, W3C standards compliance; (4) Governance Maturity — DAO structures, role-based access; (5) Privacy Preservation — ZKP support, GDPR compliance; and (6) Pedagogical Alignment — support for peer interaction, adaptive learning, learner autonomy.

IV. COMPARATIVE ANALYSIS RESULTS

A. Comparative Platform Analysis

The primary result of this study is a structured comparative analysis of existing Web3-based educational platforms. Eight representative platforms were selected to cover the spectrum from early-stage prototypes to deployed systems. Experimental platforms such as EtherLearn [7], Meta-learning [29], and ZKP-based credential systems [13] emphasize advanced features but typically operate on public testnets with limited user bases (fewer than 100 participants). In contrast, production-oriented systems such as BlockAdemiC [9], SALF [26], and GAVIN [14] adopt hybrid architectures with energy-efficient consensus mechanisms and controlled governance models aligned with institutional policies.

B. Architectural Insights

Several architectural insights emerge from the analysis. First, hybrid on-chain/off-chain data management is a consistent design choice across both experimental and production platforms. Storing only credential hashes and verification proofs on-chain while retaining learning content off-chain reduces transaction costs by approximately two orders of magnitude. Second, DID and VC systems provide strong guarantees of authenticity and portability, yet only two of the eight analyzed platforms implemented W3C-compliant DID methods, suggesting that standards adoption remains a barrier. Third, incentive mechanisms and DAO-inspired governance models offer opportunities for increased learner engagement, but their effectiveness depends on pedagogical alignment and long-term sustainability [28].

Table 1 — Key architectural differences between experimental and production-oriented platforms

Feature	Experimental Platforms	Production Platforms	Proposed Architecture
Blockchain type	Public, multi-chain, experimental	Ethereum (L2), Hyperledger, hybrid	Ethereum / Layer-2 or permissioned hybrid
Storage model	Fully decentralized	Hybrid on-chain/off-chain	Hybrid on-chain/off-chain
Credentials	NFTs, ZKP-based VCs	NFT certificates	SBT + Verifiable Credentials
Incentives	Tokens, experimental reputation	Token rewards or limited	Reputation-weighted incentives
Governance	Advanced DAO models	Institutional or PoA-based	Hybrid DAO + institutional
Maturity level	Prototype / experimental	Production deployments	Validated on testnet environment

C. Analytical Cost and Performance Comparison

For a hypothetical university deployment serving 5,000 active learners generating approximately 500 credential-related transactions per day, the fully on-chain approach on Ethereum mainnet would incur estimated gas costs of \$2.50–\$5.00 per transaction (at 30–50 gwei), yielding daily costs of \$1,250–\$2,500. The same workload on a Layer-2 rollup reduces per-transaction costs to approximately \$0.01–\$0.10 — a reduction of approximately two orders of magnitude. A permissioned Hyperledger Fabric deployment eliminates per-transaction gas costs entirely, with expenses limited to infrastructure hosting (\$200–\$500/month), but sacrifices public verifiability.

In terms of throughput, Ethereum mainnet supports 15–30 TPS, Layer-2 solutions achieve 2,000–4,000 TPS, while Hyperledger Fabric reaches 1,000–3,000 TPS. These figures confirm that the hybrid on-chain/off-chain architecture represents the most cost-effective and scalable strategy across all evaluated configurations.

V. KNOWLEDGECHAIN: IMPLEMENTATION AND EXPERIMENTAL VALIDATION

To move beyond the analytical framework and address the gap of empirical validation identified in Section II, we present *KnowledgeChain* — a full-stack hybrid Web3 platform that instantiates the proposed four-layer architecture with three novel protocol contributions.

A. Platform Architecture

KnowledgeChain adopts the hybrid Web2/Web3 principle of on-chain minimalism: only trust-critical operations (reputation updates, credential issuance, peer review commitments, zero-knowledge proof verification) are executed on the blockchain, while high-frequency operations (lesson delivery, progress tracking, quiz scoring) are handled by a conventional web backend. This selective approach is motivated by the cost and performance analysis presented in Section IV.C, which demonstrates that hybrid architectures reduce operational costs by approximately two orders of magnitude compared to fully on-chain deployments.

Figure 1 illustrates the four-layer architecture of KnowledgeChain, mapping directly to the framework proposed in Section III.C. The Presentation Layer provides wallet-based authentication and blockchain interaction capabilities alongside traditional UI components. The Application Layer handles business logic, session management, and orchestration of on-chain calls. The Data Layer combines relational storage for educational content with content-addressed decentralized storage for immutable artefacts. The Trust Layer comprises five smart contracts deployed on the Polygon Amoy testnet, each responsible for a specific trust-critical function: reputation management, committee-based peer review, non-transferable credential issuance, zero-knowledge proof verification, and autonomous content pricing.

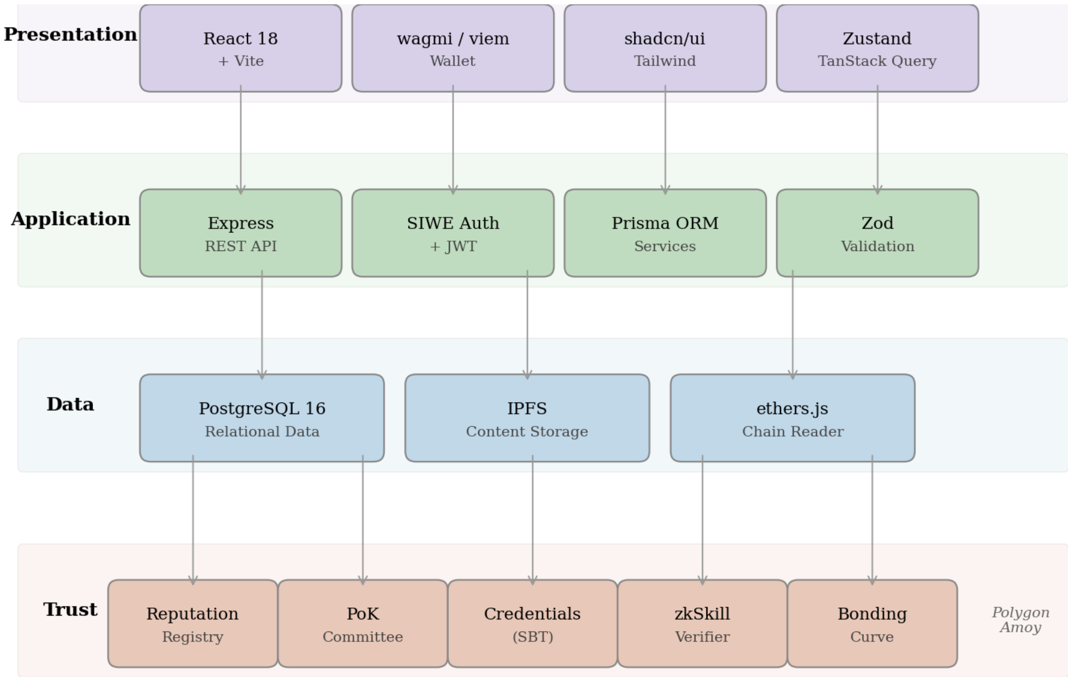

Figure 1. KnowledgeChain four-layer hybrid architecture

B. Proof-of-Knowledge (PoK) Protocol

The PoK protocol implements decentralized peer review with formal fairness guarantees. Let $A = \{a_1, a_2, \ldots, a_N\}$ denote the set of registered agents, each possessing a knowledge score $s_i(t) \in [0, S_{max}]$ for topic t. The eligible reviewer pool for a submission on topic t excludes the submission author and the course creator, retaining only agents whose topic score meets a minimum threshold s_{min} (empirically set to 100 based on score distribution analysis). Reviewers are selected via weighted random sampling without replacement, where the selection probability for agent a_i is:

$$P(a_i \in C) = \frac{s_i^{(t)}}{\sum_{k \in E(t)} s_k^{(t)}} \quad (1)$$

Each reviewer submits a score $r_i \in [0, 100]$. The aggregated review score is computed as a reputation-weighted mean:

$$\bar{r} = \frac{\sum_{i \in C} r_i \cdot s_i^{(t)}}{\sum_{i \in C} s_i^{(t)}} \quad (2)$$

A reviewer a_i is flagged as an outlier if $|r_i - \bar{r}| > \theta \cdot \bar{r}$, where the consensus threshold θ is set to 0.20 (chosen empirically to balance sensitivity to strategic scoring against tolerance for legitimate disagreement). Outlier reviewers receive a reputation penalty of −30 points, calibrated to discourage adversarial behaviour while allowing recovery over subsequent honest reviews. If $\bar{r} \geq 60$ (the passing threshold, consistent with standard academic grading scales), the submission is approved and a non-transferable Soulbound Token (SBT) credential is minted. Fairness of committee selection is quantified using two complementary metrics — the Gini coefficient (Eq. 3) measuring inequality in selection frequency, and Shannon entropy (Eq. 4) measuring diversity of committee composition:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n \sum_{i=1}^{n} x_i} \quad (3)$$

$$H = -\sum_i p_i \, log_2(p_i) \quad (4)$$

C. zkSkill: Zero-Knowledge Skill Verification

The zkSkill protocol enables privacy-preserving skill assessment using Groth16 zk-SNARKs with Poseidon hashing. The protocol addresses the following verification problem: given a coding challenge with *m* predefined test cases, a user must prove that their solution produces the correct output for each test case *without revealing the solution itself*. Formally, a challenge creator publishes Poseidon hashes of expected outputs h_i = Poseidon(o_i*) as public parameters. A user claiming to have solved the challenge possesses solution outputs {o_1, …, o_m} and must prove that Poseidon(o_i) = h_i for all *i*, without disclosing {o_i}. The resulting proof consists of two G1 points and one G2 point on the BN254 elliptic curve, totalling 192 bytes regardless of circuit complexity. On-chain verification requires approximately 300,000 gas, with replay protection enforced per (challenge, user) pair.

D. Knowledge Bonding Curve

Content pricing is governed by a logarithmic bonding curve:

$$\text{price}(n) = p_0\big(1 + \alpha \, ln(1 + n)\big) \quad (5)$$

where p_0 is the creator-defined base price, α ∈ (0, 1] is a scaling parameter controlling the rate of price increase, and *n* denotes the cumulative number of previous buyers (total supply). The logarithmic form was selected for two desirable properties: (a) monotonic increase (price′(*n*) = $p_0\alpha/(1 + n) > 0$), ensuring that early adopters always pay less than later adopters; and (b) bounded growth rate ($\lim_{n\to\infty}$ price′(*n*) = 0), maintaining long-term accessibility by dampening price acceleration at high supply levels.

VI. EXPERIMENTAL RESULTS

A. PoK Fairness Simulation

An agent-based simulation models *N* = 1,000 agents with knowledge scores drawn from a Beta(2, 5) distribution scaled to [0, 100] across 5 topics, producing a right-skewed profile representative of typical expertise distributions. Of the 1,000 agents, 641 (64.1%) meet the eligibility threshold. Committees of *K* = 5 reviewers are selected over 2,000 review rounds using the weighted random sampling mechanism defined in Eq. (1).

Table 2 — PoK fairness metrics (N = 1,000, 2,000 rounds, K = 5)

Metric	Value	Interpretation
Gini coefficient (G)	0.2397	Strong fairness (below 0.30 target)
Max/Mean selection ratio	3.08×	Moderate concentration
Entropy ratio (H / H_max)	98.57%	Near-maximum diversity
Collusion probability P(K = 2)	0.0300%	Below 0.1% design target
Collusion probability P(K ≥ 3)	0.0000%	Effectively zero

The Gini coefficient of 0.24 indicates strong fairness in reviewer selection — substantially below the 0.30 design target. The entropy ratio of 98.57% confirms near-maximal diversity in committee composition: reviewers are drawn from a broad pool rather than concentrated among a narrow elite. The probability of two colluding agents appearing on the same committee is 0.03% (approximately 3 in 10,000 reviews), and for three or more colluders it is effectively zero across 2,000 simulated rounds.

B. Bonding Curve Simulation

The bonding curve simulation models 1,000 agents distributed across three behavioural strategies: early adopters (15%), followers (60%), and speculators (25%). These proportions were chosen to reflect commonly observed adoption patterns in platform economics. Four curve types are evaluated under identical parameters (base price = 0.01 ETH, α = 0.5, max supply = 500, creator royalty = 10%).

Table 3 — Bonding curve comparison: revenue, supply adoption, and manipulation resistance

Curve	Final Supply	Total Rev. (ETH)	Mean Price (ETH)	Whale Impact	Nash Eq.
Linear	149/500	56.62	0.380	22.50×	Early
Logarithmic	500/500	18.06	0.036	3.55×	Early
Sigmoid	500/500	17.48	0.035	3.89×	Early
Polynomial	500/500	25.77	0.052	4.05×	Early

The logarithmic curve achieves the most favourable trade-off: 100% supply adoption (compared to 29.8% for the linear variant), an incentive-compatible Nash equilibrium at the early-adopter strategy, and a whale price impact ratio of 3.55× (compared to 22.5× for the linear curve), indicating substantially greater resistance to large-scale market manipulation.

C. zkSkill Protocol Benchmarks

Table 4 — zkSkill protocol performance benchmarks (Groth16, BN254)

Metric	Value
Proof size (constant)	192 bytes
On-chain verification gas cost	250,000–350,000 gas
Client-side proving time	1–3 seconds (consumer hardware)
Estimated verification cost (30 gwei, Polygon)	$0.0045

VII. DISCUSSION

The four-layer model differs from generic multi-tier architectures in its explicit treatment of blockchain-specific concerns: consensus mechanism selection, on-chain/off-chain data partitioning, and decentralized governance. Unlike prior proposals that treat blockchain as a monolithic back-end [5], [7], the layered decomposition isolates these concerns, enabling independent evolution of each layer. Compared to the EtherLearn architecture [7], which couples smart contract logic with a single public blockchain, the proposed framework abstracts the Trust Layer to support both permissioned and public deployments without modifying the Application Layer.

The experimental results from KnowledgeChain provide empirical support for the framework’s core design thesis: *selective blockchain usage can achieve near-optimal trust guarantees without significantly degrading usability or throughput.* The PoK protocol demonstrates that weighted random selection can simultaneously prioritise reviewer quality (through score-proportional selection) and prevent monopolisation (Gini = 0.24). The zkSkill benchmarks indicate that Groth16-based zero-knowledge proofs are practically deployable for educational skill assessment — a capability absent from all eight platforms examined in the comparative study. The bonding curve simulation contributes the first formal game-theoretic analysis of autonomous pricing applied specifically to educational content.

Several challenges remain open. Cross-chain credential interoperability requires standardized DID methods and resolver infrastructure that does not yet exist at scale. DAO governance in educational contexts raises unresolved questions about decision-making authority: should curriculum changes require majority vote among students, or should institutional oversight prevail? Token incentive sustainability depends on economic models that have not been empirically validated in educational settings over multi-year horizons.

VIII. LIMITATIONS

This study has several limitations that constrain the generalisability of the results. The comparative analysis is based on literature synthesis and may not capture all relevant implementations, particularly proprietary platforms or non-English publications. The evaluation scoring relies on qualitative assessment rather than quantitative benchmarks, introducing potential subjectivity. Gas prices in simulations are modelled at a constant 30 gwei; actual Polygon gas prices fluctuate with network congestion and could increase 2–5× during peak periods. Agent behaviours in the bonding curve simulation are stylised (early adopters, followers, speculators) rather than empirically calibrated from real user data. The platform is deployed on Polygon Amoy testnet; production deployment on mainnet would require formal security auditing but no architectural changes. The zkSkill circuit supports a fixed number of five test cases per challenge; variable-length inputs would require circuit redesign. The system has not been evaluated with real users — usability testing, adoption metrics, and pedagogical effectiveness are deferred to future work.

IX. CONCLUSION

This paper presented a structured analysis of Web3-based peer-to-peer learning platforms and proposed a layered architectural framework supporting decentralized, interoperable, and production-oriented educational systems. By synthesizing 29 sources and analyzing eight representative platforms across six evaluation dimensions, the study identified key trade-offs between experimental and production-oriented implementations.

Beyond analytical comparison, the paper presented KnowledgeChain — a full-stack hybrid Web3 platform implementing three novel protocols with quantitative experimental validation. The Proof-of-Knowledge protocol achieves a Gini coefficient of 0.24 and collusion probability of 0.03%, satisfying the design targets for fair and collusion-resistant peer review. The zkSkill protocol demonstrates the practical applicability of zero-knowledge proofs to educational skill verification, with constant-size 192-byte proofs verifiable on-chain for approximately $0.0045. The logarithmic Knowledge Bonding Curve achieves 100% supply adoption with whale price impact limited to 3.55×, outperforming alternative curve types across all evaluated metrics.

Future work will focus on commit-reveal review schemes to further strengthen collusion resistance, variable-length zkSkill circuits using recursive proof composition, W3C Verifiable Credentials integration for cross-platform interoperability, DAO governance transition, and a controlled user study with university students to provide empirical evidence of pedagogical effectiveness.

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