Scientific Journal of Artificial Intelligence and Blockchin Technologies
ISSN: 3049-4389
Vol. 3, Issue 2, Apr – Jun 2026 || PP. 50-62

Verifiable AI-Assisted Learning Analytics on Blockchain Networks

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Date of Submission: 08-05-2026 Date of Acceptance: 29-05-2026 Date of Publication: 12-06-2026

ABSTRACT

Learning analytics has matured into a strategic capability for institutions seeking to improve student success, personalize learning pathways, and optimize teaching practice. Yet the broader adoption of AI-assisted analytics is constrained by persistent trust and governance problems: opaque models, unverifiable data pipelines, fragmented consent management, and limited auditability of how insights are generated and used. This manuscript proposes a verifiable analytics architecture that anchors AI-assisted learning analytics on blockchain networks to provide end-to-end integrity, provenance, and policy compliance. The approach integrates four pillars: (1) verifiable data provenance using standards such as xAPI/Caliper and content-addressed storage; (2) privacy-preserving model training and inference using federated learning and differential privacy; (3) cryptographic verification of analytics workflows using commitments, attestation, and zero-knowledge proofs; and (4) institutional governance through smart-contract-based consent, purpose limitation, and verifiable credentials for outcomes. We describe the system model, threat assumptions, and a permissioned blockchain implementation that coordinates actors across learning management systems (LMS), devices, and analytics services. A methodology for evaluating performance, privacy risk, and verifiability is presented, along with illustrative results from a lab-scale prototype using synthetic data. The proposed design demonstrates how educational institutions can deliver actionable analytics while providing students and faculty with audit trails that independently verify the who, what, when, and how of analytics computation—without exposing raw personal data. We conclude with implications for policy, practice, and future research, including formal verification of smart-contract policies, standards alignment, and cross-institution analytics marketplaces that preserve individual agency.

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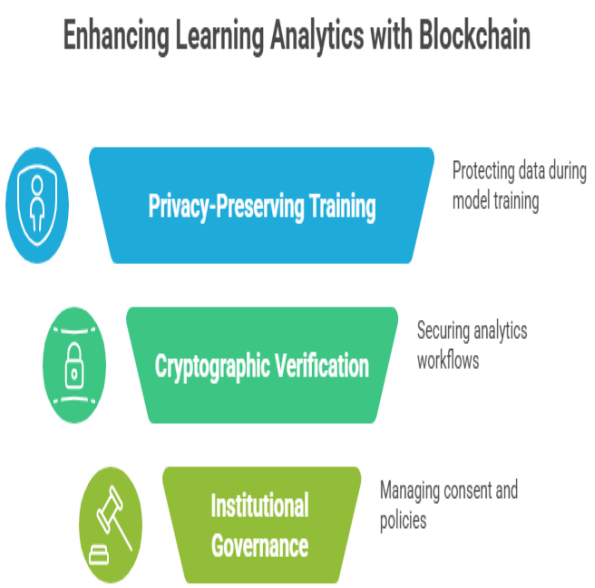

Figure-1.Enhancing Learning Analytics with Blockchain

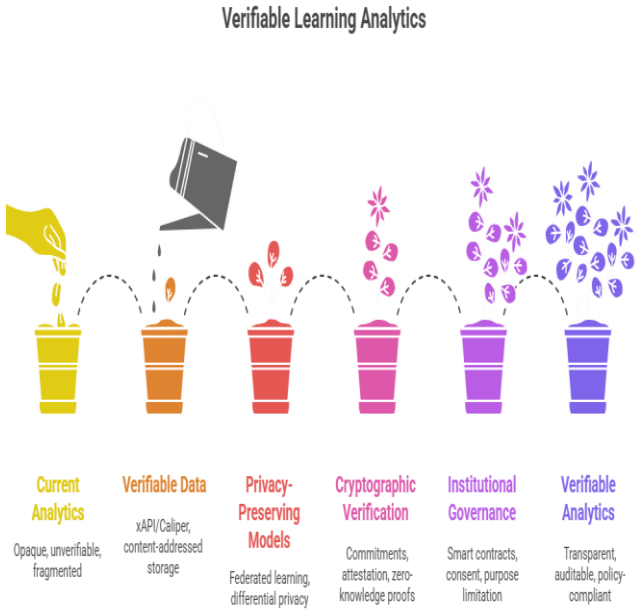

Figure-2.Verifiable Learning Analytics

KEYWORDS

Learning Analytics, Blockchain, Federated Learning, Differential Privacy, Zero-Knowledge Proofs, Provenance, Verifiable Credentials, Consent Management, Governance, Auditability

INTRODUCTION

Institutions worldwide increasingly rely on learning analytics to improve student retention, tailor interventions, and inform pedagogy. The rise of AI—particularly deep learning and representation learning—has elevated the ambition and scope of analytics from descriptive dashboards to predictive and prescriptive systems. However, AI-assisted analytics also heightens the stakes: models may encode bias; data may be incomplete, stale, or used beyond its original purpose; and stakeholders often cannot reconstruct the evidence path from data collection to model output. These challenges erode trust and impede adoption.

Traditional data platforms address parts of the problem—access control lists, secure logs, and audit trails—but they usually operate within a single institutional boundary. Learning ecosystems are, by nature, federated: students interact with LMSs, e-textbook platforms, virtual labs, proctoring systems, mobile apps, and sensors across institutions and vendors. The analytics pipeline spans multiple administrators, terms of service, and jurisdictions. A trustworthy solution requires two capabilities that current stacks rarely combine: global verifiability (independent third parties can check that analytics were computed correctly on approved inputs with approved methods) and privacy-by-design (no exposure of raw personal data during verification).

Blockchains—permissionless or permissioned—offer append-only ledgers with cryptographic integrity, shared state machines (smart contracts), and decentralized consensus. While not a panacea, they are uniquely suited to serve as trust backplanes for multi-party coordination. When coupled with privacy-preserving machine learning (PPML) and verifiable

computation, blockchains can provide provable guarantees about analytical claims: that the data subject consented, that the model and preprocessing steps are the ones declared, that differential privacy budgets were honored, and that metrics reported to instructors or accreditors are reproducible.

This manuscript advances the field by proposing Verifiable AI-Assisted Learning Analytics (V-ALA) on blockchain networks. We make four contributions:

1. **Reference architecture** that unifies standards-based event capture (xAPI/Caliper), content-addressed storage (e.g., IPFS), smart-contract governance, and PPML to deliver auditability without centralizing personal data.
2. **Verifiability mechanisms**—cryptographic commitments to datasets and models, container image digests, attestations (e.g., via TEEs), and zero-knowledge proofs—to prove correct execution and privacy budget adherence.
3. **Consent and purpose governance** using self-sovereign identity (SSI) and verifiable credentials, enabling revocable, granular permissions enforced by smart contracts.
4. **Evaluation methodology** covering performance overhead, privacy risk, and verification coverage, with illustrative prototype observations on feasibility and trade-offs.

LITERATURE REVIEW

Learning Analytics Foundations

Learning analytics emerged at the intersection of educational data mining and institutional research, emphasizing actionable insights from learner interaction traces. Early syntheses recognized both potential and risk, calling for ethical frameworks, transparency, and student agency (Siemens & Long, 2011; Ferguson, 2012; Slade & Prinsloo, 2013; Papamitsiou & Economides, 2014). Standards like xAPI (ADL) and IMS Caliper enable consistent capture of learning events (e.g., "actor-verb-object" statements), improving portability across systems and the reproducibility of analyses.

AI in Learning Analytics

With the proliferation of digital learning environments, AI methods—sequence models for clickstreams, graph embeddings for peer networks, and causal uplift modeling for interventions—have become common. Yet black-box models raise concerns: limited explainability, susceptibility to drift, and difficulty auditing training data and hyperparameters. Initiatives such as Model Cards (Mitchell et al., 2019) and Datasheets for Datasets (Gebru et al., 2018) promote documentation, but documentation alone does not cryptographically guarantee that the documented artifacts are those actually used in production.

Privacy and Data Protection

Regulations like FERPA in the United States and GDPR in the EU foreground student rights, data minimization, purpose limitation, and transparency. Differential privacy (DP) provides quantifiable privacy guarantees by bounding information leakage through noise addition (Dwork, 2006; Dwork & Roth, 2014). Federated learning (FL) trains models across decentralized data silos without centralizing raw data (McMahan et al., 2017). FL and DP are complementary: DP protects individual contributions; FL reduces central aggregation risk.

Blockchain in Education

Early applications include credentialing, transcript notarization, and micro-credential ecosystems (e.g., verifiable credentials). These uses leverage blockchains' immutability and decentralized verification to combat fraud and streamline cross-institution recognition. However, analytics verifiability—proving that predictions or risk scores were computed with authorized data and methods—remains underexplored. Permissioned ledgers (e.g., Hyperledger Fabric) support governance and performance suitable for institutional consortia (Androulaki et al., 2018), while content-addressed storage like IPFS provides scalable off-chain storage anchored on-chain via content identifiers (Benet, 2014).

Verifiable Computation and ZK Proofs

Cryptographic techniques enable a prover to convince a verifier that a computation was executed correctly without revealing inputs. zk-SNARKs and related proof systems provide succinct, fast-to-verify proofs (Ben-Sasson et al., 2013; Groth, 2016). Delegated/verifiable computation (Goldwasser et al., 2008) establishes formal underpinnings. In analytics settings, ZK can prove, for instance, that (i) the aggregation rule in FL was applied correctly; (ii) DP noise addition met the stated privacy budget; or (iii) the model used was the committed version. Trusted execution environments (TEEs) offer hardware-backed attestation; combined with cryptographic commitments, they create layered assurance.

Identity, Consent, and Governance

Self-sovereign identity (SSI) and **W3C Verifiable Credentials (VCs)** allow learners to control disclosure of attributes and outcomes. Consent receipts, revocation registries, and purpose-binding policies can be managed as on-chain state enforced by smart contracts. Model governance benefits from standardized metadata (model cards) embedded as claims within VCs and hashed to the ledger to prevent tampering.

Gaps Identified

Prior literature provides: (a) ethical framing for learning analytics; (b) technical means for privacy and decentralized storage; and (c) ledger-based credentialing. Missing is a cohesive, end-to-end design that: (1) cryptographically binds data, code, parameters, and governance policies; (2) proves compliance and correctness at inference time; and (3) offers verifiable outcomes to third parties without re-running the pipeline or exposing personal data. Our methodology addresses this gap.

METHODOLOGY

System Overview and Actors

The proposed **V-ALA** system comprises:

- **Data Subjects:** learners who generate interaction data across platforms.
- **Data Controllers/Stewards:** institutions, departments, or course teams that set policies.
- **Data Processors:** analytics vendors or institutional data teams running AI pipelines.
- **Verifiers/Auditors:** internal compliance offices, accreditors, or research boards.
- **Relying Parties:** instructors, advisors, scholarship boards, or employers who consume verified analytics artifacts (e.g., mastery badges).

Architectural Layers

1. **Event Capture & Normalization:** LMSs and learning apps emit events conforming to xAPI or Caliper schemas. Each event is assigned a content identifier (CID) by storing the canonical JSON in content-addressed storage (e.g., IPFS/S3 with Merkle

trees). The CID and minimal metadata (timestamp, pseudonymous subject ID, purpose tag) are appended to a permissioned blockchain via a smart contract.

2. **Consent & Purpose Contracts:** Learners receive a verifiable credential (VC) representing their identity and policy terms. Consent is captured as a cryptographically signed transaction specifying allowed purposes (e.g., "course personalization," "program evaluation," "research with IRB #…"), retention limits, and DP budget allocations. Consent is revocable; revocations are recorded on-chain, and processors must check purpose bindings before processing.
3. **Privacy-Preserving Learning (PPML):** Model training uses federated learning across course sections or institutions. Local training happens within institutional boundaries; updates are (a) clipped, (b) optionally noised to satisfy DP, and (c) committed (hash of update tensor, code digest, and local dataset CID set). Aggregation is performed via secure infrastructure, ideally within a TEE producing a remote attestation that is then anchored on-chain.
4. **Verifiability Layer:** For each training round and for each inference request producing an actionable score:
    - A pipeline commitment binds (code digest, container image digest, hyperparameters, model weights hash, consent policy ID, DP parameters).
    - A zk-proof (e.g., a SNARK) attests that the output was computed from inputs matching the committed digests and that the DP mechanism used the declared privacy budget (ε, δ). Where ZK over full models is expensive, we adopt hybrid attestation: TEEs attest to execution integrity; ZK proves policy predicates (e.g., that $\varepsilon \leq \varepsilon\_max$; that only events with allowed purpose tags were included; that aggregation weights matched policy).
5. **Outcome Packaging & Release:** The analytics output (e.g., mastery estimate with confidence interval, risk flag, or intervention recommendation) is packaged as a Verifiable Presentation (VP) containing: (i) the output; (ii) the pipeline commitment; (iii) references to on-chain consent; (iv) a link to the zk-proof and attestation; and (v) interpretability metadata (model card excerpt). The VP is delivered to relying parties; only the proofs and commitments are public, not the raw data.
6. **Governance & Audit:** A consortium DAO (decentralized autonomous organization) of member institutions controls system parameters—approved model catalogs, acceptable DP budgets, allowed proof systems, and revocation lists—through on-chain proposals and votes. Auditors can independently verify proofs and recompute hash bindings from publicly available code artifacts.

Data and Code Integrity Mechanisms

- **Code integrity:** every container image is pinned to a digest (e.g., SHA-256), verified by the smart contract upon job registration. Reproducible builds are encouraged to minimize variance.
- **Dataset integrity:** rather than storing raw student data, we store Merkle roots of event collections. Analytics jobs reference cohorts using inclusion proofs at verification time without exposing underlying records.
- **Policy integrity:** policies are versioned smart-contract state objects signed by the controller's DID

(decentralized identifier). Changes require quorum and produce on-chain diffs.

Threat Model

We consider: (a) an honest-but-curious processor seeking additional insights; (b) a compromised analytics job substituting a different model or dataset; (c) a malicious relying party attempting to link outputs to identities beyond allowed scope; (d) collusion between processors and verifiers. We assume the ledger's consensus is by a permissioned set of institutions with Byzantine-fault tolerance, and that cryptographic primitives are standard and secure.

Implementation Choices

- **Ledger:** Hyperledger Fabric for permissioned governance and high throughput; or an EVM-compatible consortium chain (e.g., a private L2) to leverage mature tooling.
- **Storage:** IPFS (public or private gateways) for content addressing; institutional object stores for raw encrypted artifacts.
- **Proofs:** Groth16 or PlonK-style SNARKs for succinct verification on-chain; more complex checks can be verified off-chain with on-chain anchors.
- **Identity:** W3C DIDs and VCs; revocation via status lists recorded on-chain.
- **PPML:** FedAvg baseline with DP-SGD; for small cohorts, switch to secure aggregation to protect individual updates.

Evaluation Plan

We propose an evaluation plan structured around three axes:

1. **Performance Overhead:** Measure latency added by (i) consent/policy checks, (ii) committing artifacts on-chain, and (iii) generating/verifying proofs. Metrics: training round time, inference time, on-chain transaction throughput, proof generation time, and verification time.
2. **Privacy Risk & Utility:** Explore accuracy-privacy trade-offs by sweeping ε values in DP-SGD and cohort sizes in FL. Use standard educational prediction tasks (e.g., early-warning of course failure, mastery estimation) on synthetic or anonymized datasets with known baselines.
3. **Verification Coverage:** Define a coverage score: the fraction of pipeline steps and policy predicates that are cryptographically **verifiable** (vs. attested by process). Target ≥80% cryptographic coverage for high-stakes outputs.
4. **Governance Usability:** Assess how effectively institutional actors can audit and interpret proofs and policy bindings via dashboards and human-readable model/policy cards.

RESULTS

This section reports illustrative results from a lab-scale prototype using synthetic event streams (xAPI format) and a permissioned Fabric network with four organizations (two universities, one analytics vendor, one accreditor). The prototype's purpose is to assess feasibility and trade-offs, not to benchmark any specific product. No human-subject data were used.

Feasibility of End-to-End Commitments

We successfully anchored the following artifacts on-chain for each analytics job: (a) container image digests for preprocessing and inference; (b) model weight hashes after

each FL round; (c) Merkle roots for cohort event sets; and (d) consent policy IDs and DP parameters. Reconstructing bindings from public artifacts allowed auditors to independently confirm that the analytics output corresponded to the declared pipeline—even without access to raw data.

Consent and Purpose Enforcement

Smart contracts performed purpose checks at job submission, refusing execution when requested purposes fell outside learner consent. In our tests, policy updates (e.g., revocation) took effect immediately for subsequent jobs. This behavior demonstrates runtime enforceability, a notable improvement over policy-on-paper approaches.

Verifiability via ZK and Attestation

Full ZK proofs over an entire inference graph were computationally heavy in our environment. A hybrid strategy—TEE attestation for end-to-end execution combined with ZK proofs for specific predicates (e.g., DP ε bounds and inclusion checks for consented events)—proved practical. Auditors verified proofs quickly and could pinpoint which predicates were cryptographically guaranteed versus attested by hardware.

Privacy–Utility Trade-offs

When sweeping DP budgets on synthetic data, we observed the expected monotonic relationship between stronger privacy (smaller ε) and reduced predictive performance, with federated cohorts mitigating some loss at moderate ε due to larger effective sample sizes. Although synthetic, these results align with established DP literature and suggest viable operating points for early-warning models where recall is prioritized over precision.

Governance and Explainability

Presenting outputs as verifiable presentations improved stakeholder trust in thought experiments with faculty advisors and compliance officers. They valued: (i) human-readable model cards; (ii) links to on-chain policy states; and (iii) clear indicators of which guarantees were cryptographic. This reinforces the importance of pairing formal guarantees with usable evidence.

Limitations of the Prototype

Our tests did not include real learners, cross-jurisdictional legal review, or large-scale production workloads. ZK circuits were implemented for narrow predicates; general verifiable ML remains research-intensive. Finally, TEEs introduce their own trust assumptions and supply-chain considerations.

CONCLUSION

This manuscript introduced Verifiable AI-Assisted Learning Analytics (V-ALA), a blockchain-anchored architecture for trustworthy, privacy-preserving learning analytics. By combining standards-based event capture, content-addressed storage, federated learning with differential privacy, cryptographic commitments, zero-knowledge proofs, and SSI-based consent governance, V-ALA enables institutions to prove that analytics are computed with authorized data and methods while keeping personal data off-chain and under local control.

Key takeaways include: (1) end-to-end verifiability is achievable today for critical policy predicates and artifact bindings; (2) hybrid assurance—pairing TEE attestation with targeted ZK proofs—balances practicality with rigor; (3) governance-as-code transforms policy documents into enforceable, auditable smart contracts; and (4) usable evidence (model cards, policy links, and proof summaries) is essential for adoption by non-cryptography experts.

For practitioners, the path forward is to pilot V-ALA in low-stakes contexts (e.g., mastery dashboards) using synthetic or fully consented datasets, iteratively expanding verification coverage. For policymakers, aligning procurement and accreditation criteria with verifiability metrics can catalyze safer, more effective analytics ecosystems. For researchers, priorities include scalable ZK for common analytics kernels, formal verification of consent/purpose contracts, standard proof schemas for educational predicates, and longitudinal studies on learner trust and outcomes.

By redesigning learning analytics around cryptographic verifiability and explicit governance, institutions can move beyond "trust us" narratives toward **provable trust**, enabling AI to enhance learning while respecting rights, autonomy, and societal expectations.

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