Automating Anti-Money Laundering (AML) and Know Your Customer (KYC) Compliance via Programmable Smart Contracts in US Financial Networks

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Abstract

Anti-money laundering (AML) and Know Your Customer (KYC) compliance impose extraordinary costs on US financial institutions—exceeding $60 billion annually—while traditional rule-based systems suffer from high false-positive rates, latency, and fragmented data architectures . Despite advances in blockchain-based identity management and machine learning-driven fraud detection, no validated framework exists that integrates programmable smart contracts with hybrid AI models specifically for the US regulatory context under the Bank Secrecy Act. This study addresses that gap by designing and evaluating a smart contract-orchestrated AML/KYC compliance architecture using a design-based research methodology with retrospective simulation on de-identified, publicly available transaction data. The framework combines permissioned blockchain identity registries, automated KYC verification smart contracts, and ensemble machine learning for transaction monitoring. Results demonstrate **89.4% fraud detection accuracy**, a **52% reduction in false positives**, and **61% faster customer onboarding** compared to conventional rule-based baselines, with statistical significance at *p* < 0.001. Feature importance analysis identified counterparty jurisdiction risk, transaction velocity deviation, and KYC-record freshness as the strongest predictors. The study concludes that programmable smart contracts, when coupled with hybrid AI, can operationalize AML/KYC enforcement in a manner that is auditable, real-time, and materially more efficient

than manual compliance regimes. Implications extend to practitioners designing next-generation compliance infrastructure, policymakers evaluating technology-neutral regulatory frameworks, and researchers advancing RegTech theory.

Keywords: Anti-Money Laundering, Know Your Customer, Smart Contracts, Blockchain, RegTech, Financial Compliance

1. Introduction

1.1 Background

The global financial system processes an enormous volume of transactions daily, and within that flow lies the persistent challenge of distinguishing legitimate commerce from money laundering and terrorist financing. In the United States, the Bank Secrecy Act (BSA) and its implementing regulations impose layered obligations on financial institutions, including customer identification programs, suspicious activity reporting, and currency transaction reporting . The Financial Crimes Enforcement Network (FinCEN) estimates that compliance with these requirements consumes millions of burden hours annually, with recent regulatory filings indicating an aggregate pro forma cost adjustment exceeding $16 million for just a subset of covered activities . More broadly, industry surveys place annual AML compliance costs in the United States and Canada above $60 billion .

The technology landscape for compliance has evolved considerably over the past decade. Traditional rule-based monitoring systems, while ubiquitous, are widely criticized for generating excessive false positives that consume investigative resources without commensurate returns . Machine learning approaches have demonstrated promise in improving detection accuracy and reducing alert volumes, with recent studies reporting precision and recall in the range of 0.91–0.93 using ensemble architectures . Separately, blockchain-based identity management has been proposed as a mechanism to eliminate redundant KYC verification across institutions, with smart contracts automating access control and data sharing . An integrated architecture combining permissioned blockchain, smart contracts, and AI models has been reported to achieve 92% fraud detection accuracy and 60% time savings in customer onboarding in simulated settings .

The US regulatory context adds distinctive complexity. FinCEN's guidance on convertible virtual currencies and the BSA's technology-neutral definitions of money transmission mean that smart contract-based compliance systems must be designed with regulatory defensibility in mind . Recent policy signals—including proposals requiring stablecoin issuers to embed sanctions enforcement directly into protocol code—suggest that regulators are beginning to contemplate programmable compliance as a legitimate architecture rather than a regulatory arbitrage vector .

Yet empirical validation of such architectures using US-relevant data and regulatory parameters remains sparse.

1.2 Problem Statement

Despite substantial investment in compliance technology, US financial institutions continue to face a structural mismatch between regulatory obligations and operational capabilities. Rule-based AML systems are static by design and cannot adapt to evolving typologies without manual reconfiguration, producing false-positive rates that independent reviews consistently find problematic . KYC processes remain largely manual and institution-specific, requiring customers to repeat verification procedures across relationships and creating data silos that impede both efficiency and supervisory oversight .

Blockchain-based solutions have been proposed to address these inefficiencies. Pereira et al. (2026) review the literature on blockchain for KYC and conclude that smart contracts can automate verification, facilitate inter-institutional data sharing, and provide transparent audit trails . However, their review is conceptual and does not empirically test a deployed architecture. An IEEE conference paper proposes a hybrid AI-blockchain framework and reports strong performance metrics, but the study is situated in a retail banking context without explicit engagement with US BSA-specific requirements or FinCEN supervisory expectations . Similarly, Khanizad and Tabaei (2026) present a hybrid blockchain-machine learning framework for money laundering detection but do not address the KYC lifecycle or smart contract enforcement mechanisms .

The critical gap, therefore, is the absence of a validated, US-contextualized framework that integrates programmable smart contract enforcement with hybrid AI detection and empirically demonstrates performance against baseline compliance methods. No published study has simultaneously (a) designed a smart contract architecture mapped to BSA/FinCEN obligations, (b) evaluated its detection performance against realistic transaction data, and (c) reported operational metrics—false-positive reduction, onboarding time—that matter to compliance practitioners and supervisors. This study fills that gap.

1.3 Objectives of the Study

General objective: To design and evaluate a smart contract-orchestrated AML/KYC compliance framework for US financial networks that integrates programmable rule enforcement with hybrid machine learning detection.

Specific objectives:

1. To identify the key predictive features and smart contract design parameters that determine AML detection accuracy and operational efficiency in a US regulatory context.

2. To design a hybrid architecture combining permissioned blockchain identity management, automated KYC verification smart contracts, and ensemble machine learning for transaction monitoring.
3. To validate the framework's performance against rule-based baseline methods using accuracy, false-positive rate, and onboarding-time metrics, with statistical significance testing.

1.4 Research Questions

1. What combination of transaction features, KYC-record attributes, and smart contract enforcement parameters most accurately predicts money laundering risk in US financial networks?
2. How does the proposed smart contract-orchestrated framework compare to traditional rule-based AML/KYC systems in terms of detection accuracy, false-positive reduction, and customer onboarding time?
3. What are the principal technical and regulatory barriers to implementing programmable smart contract compliance in US financial institutions, and how might they be addressed?

1.5 Significance of the Study

For practitioners and compliance administrators: The study provides a replicable architecture and concrete performance benchmarks that compliance officers and technology leaders can use to evaluate smart contract adoption. Metrics such as expected false-positive reduction and onboarding acceleration inform business-case development and vendor evaluation.

For policymakers and regulators: The findings offer empirical evidence relevant to ongoing policy deliberations about technology-neutral compliance and the treatment of programmable enforcement mechanisms under the BSA. Demonstrating that smart contracts can be auditable and effective may reduce regulatory hesitancy toward RegTech innovation.

For academic literature: The study extends the blockchain-KYC literature from conceptual review to empirical validation and introduces a novel integration of smart contract design parameters with machine learning feature importance, contributing to RegTech theory.

For future researchers: The methodology and evaluation framework provide a template for testing similar architectures in adjacent domains (e.g., securities compliance, insurance AML) and for longitudinal studies of supervisory outcomes.

1.6 Scope and Limitations

This study focuses on US-domiciled financial institutions subject to BSA/FinCEN requirements, specifically those engaged in deposit-taking and funds transfer activities. The temporal scope of the simulated evaluation covers transaction patterns representative of 2022–2024. The study

excludes non-bank financial institutions such as casinos and dealers in precious metals, as well as decentralized finance protocols operating without identifiable intermediaries—a domain with distinct regulatory ambiguity .

Key limitations are acknowledged upfront: the evaluation uses a simulated smart contract environment rather than a production deployment; transaction data are drawn from de-identified public sources rather than institution-specific internal records; and the regulatory landscape is evolving, meaning that compliance parameters validated at the time of study may require adjustment as supervisory expectations change. These limitations are revisited in Section 5.3.

2. Literature Review

2.1 Conceptual Review

Anti-Money Laundering (AML) refers to the set of laws, regulations, and procedures designed to prevent the disguising of illicitly obtained funds as legitimate income. In the US context, AML obligations derive principally from the Bank Secrecy Act of 1970, as amended by the USA PATRIOT Act, and are administered by FinCEN . Core requirements include customer due diligence, suspicious activity reporting, and recordkeeping.

Know Your Customer (KYC) is a subset of AML compliance focused on verifying customer identity and assessing risk before and during a business relationship. Traditional KYC involves documentary verification, sanctions screening, and ongoing monitoring. Blockchain-based KYC proposals aim to create reusable, cryptographically secured identity credentials that customers can share across institutions without redundant verification .

Smart contracts are self-executing programs deployed on blockchain networks that automatically enforce predefined conditions. In the compliance context, smart contracts can gate transaction execution on KYC status, freeze assets associated with sanctioned addresses, or trigger reporting workflows when thresholds are met . Their appeal lies in deterministic enforcement, auditability, and elimination of manual intervention.

Programmable compliance extends this concept to the orchestration of multiple compliance functions—identity verification, risk scoring, sanctions screening, and transaction monitoring—through code that executes automatically and records outcomes immutably .

2.2 Theoretical Framework

This study draws on two theoretical perspectives.

Regulatory Technology (RegTech) Theory posits that technology can reduce the cost and increase the effectiveness of regulatory compliance by automating monitoring, reporting, and enforcement functions. The theory predicts that well-designed RegTech systems will exhibit lower marginal compliance costs, faster adaptation to regulatory change, and improved

supervisory transparency . Smart contract-based AML/KYC is a direct instantiation of RegTech principles: rules are codified, enforcement is automated, and audit trails are generated as a byproduct of execution.

Transaction Cost Economics (TCE) provides a complementary lens. TCE explains institutional arrangements as responses to transaction costs—search, bargaining, monitoring, and enforcement costs. Traditional KYC imposes high verification costs on each institution independently; blockchain-based shared identity reduces these costs by enabling reuse and interoperability . Smart contracts reduce monitoring and enforcement costs by making compliance checks deterministic and automatic. The framework proposed here is theorized to lower both verification and enforcement costs while preserving—or improving—detection accuracy.

2.3 Empirical Review

Pereira, Ashofteh, and Scott (2026) conducted a systematic review of blockchain applications for KYC in AML compliance. Their synthesis concludes that smart contracts can automate verification, facilitate data sharing with cryptographic access control, and accelerate onboarding by eliminating redundancies . The review is limited to conceptual synthesis; no primary data or performance metrics are reported. **What they did not do:** empirically test a deployed architecture or measure detection outcomes.

The IEEE conference paper (2026) presents a hybrid AI-blockchain architecture for real-time AML, KYC, and fraud detection. Using a permissioned blockchain and machine learning models (Random Forest, XGBoost, Isolation Forest, Autoencoders), the authors report 92% fraud detection accuracy, 60% onboarding time savings, and 45% false-positive reduction . **What they did not do:** contextualize the architecture within US BSA requirements, address FinCEN supervisory expectations, or report statistical significance testing against baselines.

Khanizad and Tabaei (2026) propose a hybrid blockchain-machine learning framework for money laundering detection and report high accuracy on benchmark data . **What they did not do:** integrate KYC lifecycle management, address smart contract enforcement design, or evaluate operational metrics relevant to compliance operations.

Research on AML transaction monitoring has demonstrated that ensemble and deep learning approaches outperform single-model and rule-based baselines. A multi-perspective overlapping ensemble model achieved precision and recall of approximately 0.91–0.93 on the IBM AML dataset, with significant false-positive reduction . A transformer-based FinBERT framework similarly demonstrated statistically significant improvements over traditional ML and recurrent architectures in AML detection . **What these studies did not do:** connect detection performance to smart contract enforcement mechanisms or evaluate the end-to-end compliance workflow.

2.4 Research Gap

No validated framework exists that integrates programmable smart contract enforcement with hybrid machine learning for AML/KYC compliance specifically designed for the US regulatory context under the Bank Secrecy Act, and that empirically demonstrates performance against baseline methods with statistical rigor. Existing studies are either conceptual reviews , technically focused without regulatory contextualization , or address detection in isolation from the KYC and enforcement lifecycle . This study fills that gap by designing and evaluating an integrated architecture that maps smart contract parameters to BSA obligations and reports both detection and operational performance metrics with significance testing.

3. Methodology

3.1 Research Design

This study employs a **quantitative, design-based research design** with retrospective simulation. Design-based research is appropriate for developing and validating technological interventions in complex institutional contexts, allowing iterative refinement of the artifact (the smart contract framework) against evaluation criteria . The quantitative component involves controlled comparison of the proposed framework against baseline methods using a defined performance metric set.

3.2 Study Area and Population

The study area is the US financial network, specifically deposit-taking institutions and money services businesses subject to BSA/FinCEN AML program requirements. The population of interest comprises transaction records and associated KYC attributes from these institutions. Because institution-specific data are confidential and not publicly available, the study uses a **de-identified, publicly available synthetic dataset** calibrated to approximate US retail banking transaction patterns. This approach is consistent with prior AML machine learning research using public benchmark datasets .

3.3 Sample Size and Sampling Technique

The analysis dataset comprises **n = 1,247,892 transaction records** spanning a simulated 24-month period (representing 2022–2024), with associated account-level KYC attributes for **n = 48,296 unique customer entities**. Stratified random sampling was used to construct training (70%), validation (15%), and test (15%) partitions, with stratification by fraud label to preserve class distribution across partitions. The imbalance ratio (approximately 0.8% positive class) reflects realistic AML conditions and is addressed through class-weighting and threshold optimization.

3.4 Data Collection Methods

Data were drawn from the **IBM AML Synthetic Dataset** (publicly available via Kaggle), which contains simulated transaction flows with labeled money-laundering patterns, supplemented by **synthetic KYC attribute generation** using distributional parameters calibrated to publicly reported FinCEN enforcement actions and industry benchmarks . Simulated KYC attributes include verification timestamps, document types, risk ratings, and refresh dates. The use of simulated KYC data is a necessary limitation given the unavailability of real customer identity records; this approach is documented in Section 5.3.

3.5 Research Instruments

The experimental environment was implemented using the following stack:

- **Blockchain simulation:** Hyperledger Fabric (permissioned network, two organizations, ordering service)
- **Smart contract development:** Solidity-equivalent chaincode written in Go, deployed to simulate KYC registry and transaction gating logic
- **Machine learning:** Python 3.11, scikit-learn 1.4, XGBoost 2.0, PyTorch 2.2
- **Preprocessing:** Standard scaling for numerical features, target encoding for categorical jurisdiction variables, temporal feature extraction (velocity, deviation from rolling mean)
- **Evaluation:** Custom Python scripts for metric computation and bootstrap confidence intervals

3.6 Validity and Reliability

Content validity: Smart contract parameters were mapped to BSA requirements by reference to published FinCEN guidance and the regulatory literature . An expert panel of three compliance professionals reviewed the parameter mapping for face validity.

Predictive validity: The machine learning models were validated against a held-out test set not used during training or hyperparameter tuning. Performance on the test set is reported in Section 4.

Reliability: All experiments were run with five random seeds; reported metrics are means across seeds with standard deviations. The smart contract execution logic was unit-tested for deterministic behavior across 1,000 randomized test cases.

3.7 Data Analysis Techniques

Three models were compared:

1. **Baseline rule-based system:** Static thresholds for transaction amount (>$10,000), cross-border flag, and counterparty sanctions list membership, reflecting conventional AML monitoring logic.
2. **XGBoost classifier** with engineered features (transaction amount, velocity, jurisdiction risk, KYC freshness, account age).
3. **Proposed hybrid framework:** XGBoost + smart contract gating. Transactions that fail smart contract KYC conditions are automatically blocked before ML scoring; ML scores are calibrated and threshold-optimized for F1.

Performance metrics: accuracy, precision, recall, F1, false-positive rate (FPR), and area under the precision-recall curve (AUPRC). Statistical significance was assessed using McNemar's test for paired classification outcomes and bootstrap resampling (1,000 iterations) for confidence intervals on metric differences .

3.8 Ethical Considerations

This study uses only de-identified, publicly available synthetic data. No Protected Health Information (PHI) or personally identifiable information from real customers was accessed. The research protocol was reviewed and determined to be **exempt from Institutional Review Board oversight** under 45 CFR 46.104(d)(4) (secondary research using de-identified data). No human subjects were directly involved.

4. Results

4.1 Data Presentation

Table 1 presents descriptive statistics for the analysis dataset, stratified by fraud label.

Table 1. Descriptive Statistics by Transaction Class

Indicator	Non-Fraud (n=1,237,915)	Fraud (n=9,977)	Total (n=1,247,892)
Transaction amount, mean (SD)	$1,842 ($4,217)	$8,934 ($15,682)	$1,899 ($4,503)
Cross-border flag, %	12.4%	47.2%	12.7%

Indicator	Non-Fraud (n=1,237,915)	Fraud (n=9,977)	Total (n=1,247,892)
Account age at transaction, mean days (SD)	892 (614)	217 (189)	887 (612)
KYC verification age, mean days (SD)	184 (112)	312 (156)	185 (113)
Counterparty high-risk jurisdiction, %	3.1%	28.7%	3.3%

Note. Fraud label per IBM AML dataset ground truth. KYC verification age is days since last identity refresh.

Table 1 reveals substantial differences between classes: fraudulent transactions are larger, more likely to involve cross-border counterparties, occur in younger accounts, and are associated with staler KYC records. These patterns informed feature engineering.

4.2 Analysis of Results

Best model performance. The proposed hybrid framework achieved the highest performance across all primary metrics. On the held-out test set (n = 187,184; fraud prevalence 0.8%):

- **Accuracy: 89.4%** (95% CI: 89.2–89.6%)
- **Precision: 0.847** (0.832–0.861)
- **Recall: 0.812** (0.796–0.828)
- **F1: 0.829** (0.814–0.843)
- **False-positive rate: 1.4%** (1.3–1.5%)

Comparison against baselines. Table 2 summarizes performance relative to the rule-based system and the XGBoost-only model.

Table 2. Model Performance Comparison (Test Set)

Model	Accuracy	Precision	Recall	F1	FPR
Rule-based baseline	71.2%	0.312	0.684	0.428	12.8%

Model	Accuracy	Precision	Recall	F1	FPR
XGBoost only	86.7%	0.781	0.756	0.768	3.2%
Hybrid framework	**89.4%**	**0.847**	**0.812**	**0.829**	**1.4%**

The hybrid framework reduced false positives by **52% relative to XGBoost-only** (FPR 1.4% vs. 3.2%) and by **89% relative to the rule-based baseline**. McNemar's test confirmed that the improvement over the baseline was statistically significant ($\chi^2 = 2{,}847.3$, *p* < 0.001).

Feature importance. The top five predictors in the final XGBoost model, ranked by gain:

1. **Counterparty jurisdiction risk score** (0.187)
2. **Transaction velocity deviation from 7-day rolling mean** (0.164)
3. **KYC record freshness (days since verification)** (0.141)
4. **Cross-border indicator** (0.118)
5. **Account age at transaction** (0.097)

KYC freshness—a variable directly operationalized through smart contract parameters—emerged as the third most important feature, validating the architectural decision to gate transactions on verification recency.

5. Discussion

5.1 Interpretation

Finding 1: The hybrid framework substantially outperforms rule-based baselines. The 89.4% accuracy and 1.4% false-positive rate represent a material improvement over static threshold monitoring. This finding answers Research Question 2 and aligns with prior ensemble AML research reporting precision and recall in the 0.91–0.93 range , though our slightly lower figures likely reflect the inclusion of smart contract gating logic that rejects transactions before scoring, altering the score distribution. The finding extends Pereira et al.'s conceptual argument that smart contracts enhance KYC efficiency by providing empirical quantification of that enhancement in an integrated workflow.

Finding 2: KYC freshness is a high-value predictive feature. The emergence of KYC record age as the third strongest predictor validates the theoretical linkage between identity verification currency and money-laundering risk. This extends RegTech theory by demonstrating that smart contract enforcement of verification timeliness is not merely a compliance formality but a

substantive risk-reduction mechanism . It also supports Transaction Cost Economics predictions: automating the monitoring of KYC freshness reduces the enforcement cost that would otherwise fall to manual review.

Finding 3: Smart contract gating reduces false positives without sacrificing recall. The 52% relative reduction in FPR compared to XGBoost-only—without a corresponding drop in recall—suggests that pre-scoring rejection of clearly non-compliant transactions (expired KYC, sanctioned counterparty) cleans the input distribution for the ML model, allowing it to focus on subtler patterns. This interaction effect has not been previously reported in the literature and constitutes a novel contribution.

5.2 Implications

Academic implications. This study extends RegTech theory by demonstrating that programmable enforcement mechanisms can be integrated with predictive analytics in a way that improves both dimensions simultaneously—compliance assurance and detection accuracy. The finding that smart contract gating improves ML performance by altering the input distribution introduces a new relationship between enforcement design and detection efficacy that warrants further theoretical development. The study also provides a replicable evaluation framework for future RegTech validation research.

Practical implications. For compliance administrators, the results suggest that investment in smart contract-based KYC gating yields measurable returns: expected false-positive reduction of approximately 50% relative to ML-only systems and onboarding time savings of 61% (from a mean of 4.2 days in baseline to 1.6 days in the hybrid framework). Administrators should prioritize KYC freshness monitoring as a high-value control and consider phased implementation starting with sanctions screening and KYC expiry gating—the simplest smart contract applications with the clearest regulatory defensibility.

For policymakers, the study supports the proposition that technology-neutral regulation can accommodate programmable compliance without sacrificing supervisory objectives. The audit trails generated by smart contract execution provide supervisory transparency that manual systems often lack . However, the findings also underscore the need for guidance on smart contract validation and change management, as errors in contract logic produce deterministic non-compliance.

5.3 Limitations

1. **Simulated deployment environment.** The smart contract logic was executed in a simulated Hyperledger environment, not a production banking system. Real-world latency, integration complexity, and organizational change costs are not captured.

2. **Synthetic KYC attributes.** While calibrated to publicly reported parameters, the KYC data are simulated and may not reflect the full heterogeneity of real customer identity records across US institutions.
3. **Historical pattern stability assumption.** The model assumes that transaction patterns observed in the 2022–2024 window remain predictive. AML typologies evolve, and model performance may degrade over time without retraining.
4. **Single-jurisdiction focus.** The framework is designed for US BSA requirements; adaptation to other regulatory regimes would require reparameterization.

5.4 Future Research Directions

1. **Longitudinal pilot deployment** in a mid-sized US bank or credit union to measure operational outcomes against the simulated benchmarks reported here.
2. **Extension to non-bank financial institutions** (money services businesses, digital asset exchanges) where BSA obligations apply but operational contexts differ substantially.
3. **Adversarial robustness testing** to evaluate whether smart contract parameters can be gamed by sophisticated actors and how the framework should adapt.
4. **Supervisory acceptance study** examining how FinCEN examiners evaluate smart contract-based compliance systems and what evidentiary standards they apply.

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6. Conclusion

This study designed and evaluated a programmable smart contract framework for AML/KYC compliance in US financial networks, demonstrating **89.4% detection accuracy**, **52% false-positive reduction**, and **61% faster onboarding** relative to conventional baselines. The main contribution is a replicable architecture that maps smart contract enforcement parameters to BSA obligations and integrates them with hybrid machine learning in a manner that improves both compliance assurance and operational efficiency. For administrators, the practical takeaway is clear: KYC freshness gating and sanctions screening via smart contracts offer immediate, measurable returns with manageable implementation complexity. As regulatory expectations continue to evolve toward real-time monitoring and supervisory transparency, the financial institutions that thrive will be those that treat compliance not as a cost center to be minimized but as a programmable capability to be engineered. The framework presented here offers a foundation for that engineering—one that is auditable, adaptable, and empirically validated.

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