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BLOCKARC: A BLOCKCHAIN BASED SMART CONTRACT FOR REWARD SYSTEM IN E-COMMERCE

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ABSTRACT

The increasing reliance on e-commerce platforms has amplified challenges related to transparency, trust, fraud, and inefficiencies in reward distribution systems. Existing centralized architectures fail to address these issues effectively. This paper proposes BlockArc, a blockchain-based smart contract framework designed to revolutionize reward systems in e-commerce. The system leverages a permissioned blockchain and smart contracts to automate reward distribution, enhance security, and ensure transaction transparency. The framework consists of four layers: Blockchain Layer, Smart Contract Layer, Application Layer, and User Roles, each addressing key challenges such as reward fragmentation, fraudulent transactions, and inefficient refund processes. Smart contracts autonomously handle reward issuance, redemption, and expiration while integrating oracles for real-world data validation. Security is reinforced using cryptographic hashing, Zero-Knowledge Proofs (ZKPs), and Role-Based Access Control (RBAC) to prevent fraudulent activities. A performance evaluation demonstrated 112 transactions per second (TPS) under moderate load, fraud detection accuracy of 100%, and a 37% reduction in operational costs by eliminating intermediaries. User satisfaction surveys indicated high levels of trust and transparency. The study concludes that BlockArc enhances e-commerce reward systems by improving efficiency, security, and decentralization, paving the way for scalable and interoperable blockchain applications in digital commerce.

I. INTRODUCTION

E-commerce platforms have transformed the way trade and commerce are conducted, offering a seamless interface for transactions between buyers and sellers. However, as these platforms expand, they face critical challenges such as lack of transparency, trust issues, fraud, and inefficiencies in reward systems and product return mechanisms. Centralized architectures, which dominate the e-commerce landscape, are often unable to address these challenges effectively. The need for a decentralized, transparent, and automated solution has led to the exploration of blockchain technology and smart contracts as transformative tools for the e-commerce sector.

Centralized e-commerce platforms act as intermediaries, controlling various aspects such as payments, reward distributions, and dispute resolution. This centralization often results in opaque processes, high operational costs, and vulnerabilities to fraud. Reward systems, a critical feature of e-commerce, are plagued by fragmentation and inefficiencies. They often lack interoperability, limiting customers to specific platforms and reducing the overall value of loyalty programs. Similarly, the product return and refund process is fraught with delays and disputes, leaving both customers and merchants dissatisfied. These inefficiencies highlight the urgent need for a paradigm shift toward a decentralized and transparent approach.

Blockchain technology, with its decentralized and immutable architecture, offers a compelling solution to these challenges. By recording transactions on a distributed ledger, blockchain eliminates the need for intermediaries, ensuring transparency and security.

Smart contracts, a key feature of blockchain, enable self-executing agreements that automate processes such as payments, reward distributions, and return management. These contracts operate on pre-defined conditions, reducing manual intervention and enhancing efficiency.

A blockchain-based smart contract to store the data of payments for e-commerce platform can revolutionize the industry by addressing trust and transparency issues. Blockchain ensures that every transaction is permanently recorded and verifiable, fostering accountability among stakeholders. It also introduces tokenized reward systems where customers can earn cryptocurrency or non-fungible tokens (NFTs) for their purchases. These rewards can be securely stored, transferred, or redeemed across multiple platforms, creating a seamless and interoperable ecosystem. Furthermore, smart contracts can automate the refund process, releasing funds only when pre-defined conditions, such as product verification, are met. This reduces disputes and builds trust among users.

Fraud prevention is another critical area where blockchain excels. By providing verifiable and immutable records, blockchain reduces the risk of counterfeit products, fake reviews, and unauthorized transactions. Reputation systems built on blockchain allow users to rate merchants and products transparently, promoting accountability and trust. Additionally, NFTs can be used to tokenize products, offering proof of authenticity and ownership, which further enhances customer confidence.

This research aims to design a blockchain-based smart contract system that integrates seamlessly into e-commerce platforms to enhance reward mechanisms, streamline returns, and improve trust. The proposed system issues cryptocurrency or NFT rewards for completed transactions, automates the refund process using smart contracts, and ensures transparency through immutable records. By eliminating intermediaries, the system reduces operational costs and enhances efficiency. A security framework will also be implemented to mitigate potential vulnerabilities, ensuring the robustness of the solution.

The study contributes to the field by proposing a decentralized framework for e-commerce that addresses existing challenges in trust, transparency, and efficiency. The framework includes a tokenized reward system, a fraud prevention mechanism. It also evaluates the cost-efficiency and scalability of the proposed solution through performance analysis. The insights gained from this research will pave the way for the adoption of blockchain technology in e-commerce, fostering a more equitable and user-centric ecosystem.

II. RELATED REVIEWS

The rapid growth of e-commerce platforms has led to significant advancements in trade and commerce, but these platforms continue to face challenges such as fraud, lack of transparency, inefficiencies in reward systems, and dispute resolution issues. Centralized e-commerce models, which dominate the industry, struggle to address these concerns effectively due to their reliance on intermediaries, opaque processes, and high operational costs. In response, blockchain technology and smart contracts have emerged as transformative solutions to enhance decentralization, trust, and automation in e-commerce.

Recent research has explored the application of blockchain across various domains, demonstrating its potential to improve security, transparency, and efficiency. In the context of mobile crowdsensing (MCS) systems, blockchain has been proposed as a means to decentralize reward allocation, ensuring fair compensation for participants while addressing privacy concerns. A three-stage Stackelberg game model has been utilized to optimize utility and engagement, though challenges such as operational costs and energy efficiency remain significant hurdles [1]. Similarly, blockchain's potential in e-commerce has been demonstrated through the development of a product grading system (PGS), which standardizes product quality assessments to reduce disputes and enhance consumer trust. However, issues related to scalability, interoperability, and computational costs persist, indicating the need for further research [2].

The use of blockchain for incentivizing decentralized data sharing has also been explored, with studies leveraging evolutionary game theory to create adaptive incentive mechanisms that minimize data silos and enhance participation. While these models highlight the theoretical benefits of blockchain, real-world validation remains a challenge, and concerns such as incentive saturation and virtual currency inflation need further investigation [3]. Another significant study has introduced a blockchain-based delay-tolerant payment system for rural areas, utilizing private Ethereum blockchains to facilitate transactions in regions with intermittent connectivity. While the prototype demonstrates feasibility, concerns about infrastructure costs and scalability remain [4].

Blockchain’s role in social media platforms has been examined through an empirical study of Steemit, an incentivized blockchain-based social media network. The study reveals that while blockchain enhances content monetization, decentralization remains a challenge due to the concentration of power among large stakeholders under the Delegated Proof-of-Stake (DPoS) protocol [5]. Additionally, blockchain has been proposed as a solution for data traceability in industries such as energy, where its immutable ledger and consensus mechanisms improve accountability and security. However, real-time data processing and scalability remain major concerns [6]. In the domain of military communications, the TDL-Chain system leverages blockchain and smart contracts to enhance data transmission security and consistency, demonstrating its effectiveness but also highlighting challenges such as high communication costs and blockchain scalability in defense applications [7].

Blockchain’s applicability to software licensing has been explored through the integration of Non-Fungible Tokens (NFTs), where smart contracts enable decentralized software ownership and royalty distribution. Despite offering a more transparent licensing framework, concerns over transaction costs, security vulnerabilities, and Ethereum network dependencies persist [8]. More broadly, the increasing adoption of blockchain-based smart contracts across various industries has been documented through qualitative research involving industry leaders. Key benefits include decentralization, efficiency, transparency, and security; however, challenges such as regulatory uncertainty, scalability limitations, and integration with legacy systems remain barriers to widespread adoption [9].

In e-commerce, blockchain has been proposed as a foundation for decentralized loyalty programs, allowing multiple brands to collaborate on a unified reward system that enhances customer engagement and reduces operational costs. Unlike traditional loyalty programs, blockchain-based solutions offer interoperability, enabling customers to redeem rewards across different platforms [10]. Furthermore, blockchain oracles have been identified as a crucial technology for enabling interoperability between private blockchain networks, particularly in business-to-business (B2B) applications. Oracles facilitate secure cross-network transactions, improving efficiency and trust in enterprise blockchain implementations [11].

The existing body of research underscores the transformative potential of blockchain and smart contracts in addressing the limitations of centralized e-commerce platforms. By leveraging decentralized transaction recording, tokenized reward systems, and automated refund mechanisms, blockchain can enhance trust, transparency, and efficiency. However, challenges such as scalability, regulatory compliance, and security vulnerabilities must be addressed for broader adoption in e-commerce. This research aims to build on these findings by designing a blockchain-based smart contract system that integrates seamlessly into e-commerce platforms, focusing on reward mechanisms, dispute resolution, and fraud prevention, ultimately fostering a more transparent and user-centric marketplace.

III. METHODOLOGY

III.1 SYSTEM DESIGN

The system design phase began with defining the architecture, components, and interactions of the proposed framework using a modular approach to ensure scalability and flexibility. This phase was critical to align the system's objectives with stakeholder requirements and to establish a blueprint for implementation.

III.1.1 Requirement Analysis:

The design process started with an in-depth requirement analysis. Surveys and interviews were conducted with e-commerce stakeholders, including customers, merchants, and platform administrators, to identify the key pain points of existing reward systems. Transparency, security, automation, and interoperability were identified as critical features. Stakeholders also expressed a need for reduced operational costs and better integration with modern payment systems. Additional in-depth interviews were conducted with financial institutions to assess compliance requirements and fraud prevention challenges, ensuring regulatory adherence.

III.1.2 Architecture Design:

A four-layered architecture was devised to structure the system:

1. Blockchain Layer: Responsible for managing transactions, maintaining the ledger, and executing smart contracts.
2. Smart Contract Layer: Implements the core business logic for reward distribution, redemption, and expiration.
3. Application Layer: Acts as the interface between users and the blockchain system, ensuring seamless interactions.
4. User Roles Layer: Defines interactions for customers, merchants, and administrators.

The design incorporated a microservices-based architecture in the application layer to ensure better scalability, fault tolerance, and modular expansion. Each service (e.g., transaction processing, reward issuance, user authentication) operates independently, improving system resilience.

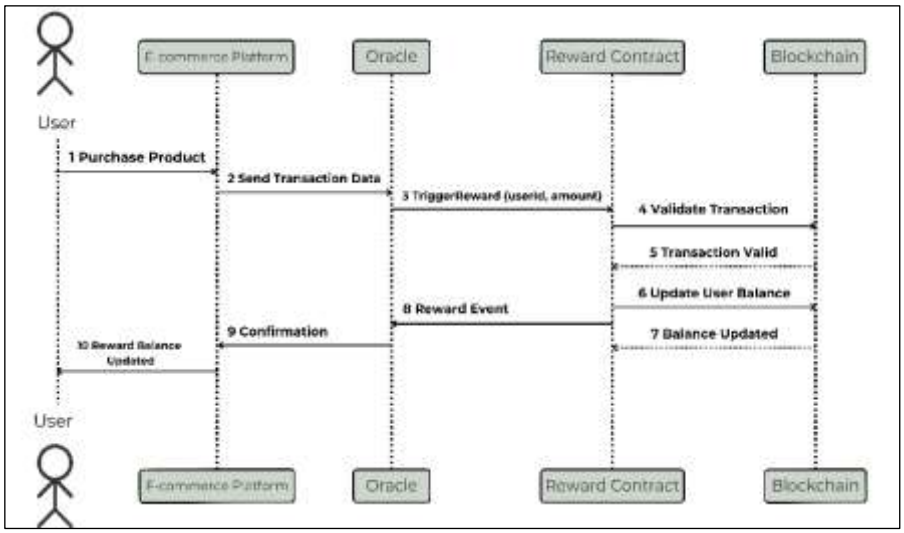

Figure 1: Sequence Diagram.
Source: Authors, (2025).

III.1.3 Consensus Mechanism Selection:

After evaluating several consensus mechanisms, Proof of Authority (PoA) was chosen for its low energy consumption, high transaction throughput, and suitability for permissioned networks. Unlike Proof of Work (PoW), PoA ensures scalability and affordability, making it ideal for e-commerce environments. This choice minimized gas fees and reduced latency in transaction processing.

Additional tests were conducted on Delegated Proof of Stake (DPoS) and hybrid models to compare efficiency, decentralization trade-offs, and cost implications. Findings reinforced PoA's selection as the most optimal mechanism for this use case.

III.2 BLOCKCHAIN IMPLEMENTATION

The blockchain implementation phase involved setting up a private Ethereum network to simulate a secure and decentralized environment for reward management. This phase ensured a robust infrastructure for handling transactions and executing smart contracts.

The primary objective of this phase was to establish an immutable, trustless, and transparent system that could efficiently handle reward allocation, redemption, and expiration while minimizing security risks and fraudulent activities.

III.2.1 Node Configuration

The system was designed with multiple blockchain nodes to distribute processing power and ensure decentralization. Four nodes were configured to simulate the primary stakeholders:

1. Two customer nodes to represent users participating in the reward system.
2. One merchant node to handle transactions from businesses offering loyalty rewards.
3. One administrator node responsible for overseeing network operations and validating transactions.

Docker containers were employed to isolate the processes running on each node, ensuring a scalable and modular architecture.

The nodes were connected to the private Ethereum network via JSON-RPC (Remote Procedure Call) interfaces, allowing real-time communication between system components. The JSON-RPC interface facilitated interaction between external applications and the blockchain, enabling customers and merchants to securely access transaction records, check reward balances, and execute smart contract operations.

Furthermore, each node was equipped with a fault-tolerant mechanism to ensure network stability. In case of a node failure, the remaining nodes continued transaction processing, ensuring seamless operation without data loss. This decentralized approach eliminated single points of failure, making the system more resilient and reliable.

III.2.2 Immutable *Ledger Setup*

A critical aspect of blockchain implementation was establishing an immutable ledger that records every transaction securely and transparently. The Ethereum Virtual Machine (EVM) was used to execute smart contracts, ensuring deterministic operations across all nodes.

To store and retrieve transaction data efficiently, LevelDB was utilized as the underlying database. LevelDB provided key-value storage, allowing quick lookups and efficient data management. This ensured that all reward transactions, including issuance, redemption, and expiration, were recorded immutably and retrievable in real-time.

To enhance security, every transaction was cryptographically hashed using SHA-256, ensuring that data remained tamper-proof. The cryptographic hashing mechanism allowed the system to verify transaction authenticity without exposing sensitive user details. If an unauthorized entity attempted to modify a transaction, the hash function would generate a completely different output, making tampering instantly detectable.

Additionally, Merkle Trees were implemented to improve verification efficiency. Merkle Trees enabled fast and secure validation of transactions without requiring every node to store the entire blockchain history. This feature was particularly useful in reducing storage overhead and improving network efficiency.

To address concerns about privacy, Zero-Knowledge Proofs (ZKPs) were integrated into the system. ZKPs allowed users to prove the validity of their transactions without revealing specific transaction details. This ensured that while the blockchain remained transparent and auditable, user privacy was maintained.

For example, when a customer redeemed reward points, the ZKP protocol allowed them to verify their balance and eligibility without exposing their personal transaction history. This enhanced security and privacy without compromising the integrity of the system.

III.2.3 Oracle Integration

One of the key challenges in blockchain-based reward systems is bridging the gap between on-chain smart contracts and off-chain e-commerce data. Since smart contracts cannot directly access external data sources, oracles were employed to facilitate this communication.

The system integrated Chainlink oracles, which securely retrieved real-world data and fed it into the blockchain. Oracles were responsible for fetching transaction data, such as:

1. Purchase amounts from the e-commerce platform.
2. Product IDs to ensure category-based reward calculations.
3. Customer eligibility criteria for reward issuance.

The integration process involved deploying an oracle smart contract that queried external data sources and provided verified data to the blockchain. The oracle aggregated data from multiple sources to prevent inaccuracies and ensure consistency. The retrieved data was then signed cryptographically before being submitted to the blockchain, ensuring its authenticity and preventing tampering by malicious actors.

To further enhance reliability, a decentralized oracle network (DON) was implemented. Rather than relying on a single oracle provider, multiple oracles validated the same transaction data before updating the blockchain. This approach minimized risks associated with incorrect or manipulated data entries.

For instance, when a customer made a purchase, the transaction details were verified through multiple oracle nodes before the corresponding rewards were credited to their account. This multi-verification mechanism prevented fraudulent activities, such as fake purchases or reward manipulation.

To optimize performance, batch processing techniques were employed to handle large transaction volumes efficiently. Instead of processing individual transactions sequentially, the system grouped multiple transactions into batches and updated the blockchain in a single operation. This reduced gas fees and improved overall throughput.

III.2.4 Security Enhancements in Blockchain Implementation

Given the sensitivity of financial transactions, additional security measures were implemented:

1. Role-Based Access Control (RBAC): Restricted blockchain interactions to authorized entities (customers, merchants, and administrators).
2. Multi-Signature Wallets: Required multiple approvals for high-value transactions, preventing unauthorized fund transfers.
3. Time-Locked Transactions: Introduced delays for large redemptions, allowing users to reverse accidental operations.
4. Automated Penalty System: Smart contracts imposed penalties on merchants who engaged in fraudulent behavior, such as inflating purchase values to earn higher rewards.

III.3 SMART CONTRACT DEVELOPMENT

Smart contracts were developed in Solidity v0.8.0 to automate and secure all reward-related functionalities within the blockchain-based reward system. The smart contracts were designed to be modular, scalable, and upgradeable, ensuring flexibility and ease of maintenance. Each contract addressed a specific component of the reward system, incorporating security measures such as access control, event logging, and error handling to enhance transparency and prevent fraudulent activities.

III.3.1 Reward Distribution Contract

The reward distribution contract was responsible for automatically allocating reward points based on purchase amounts. For every $10 spent, the contract granted one reward point, following predefined rules embedded in the smart contract logic.

Data validation: Purchase transactions were verified using the Chainlink oracle to ensure accurate purchase details before updating the customer's reward balance. This step minimized discrepancies and prevented fraudulent claims.

Automated allocation: Once validated, the smart contract automatically credited the customer's account with the corresponding reward points, reducing manual intervention.

III.3.2 Reward Redemption Contract

The reward redemption contract enabled customers to exchange reward points for discounts, gift cards, or other incentives, supporting various redemption options.

Tokenized rewards: Customers could redeem points for ERC-721 NFT-based discount vouchers, ensuring uniqueness and security. For instance, 500 points could be exchanged for a $5 discount, with the smart contract issuing a digital voucher as an ERC-721 token.

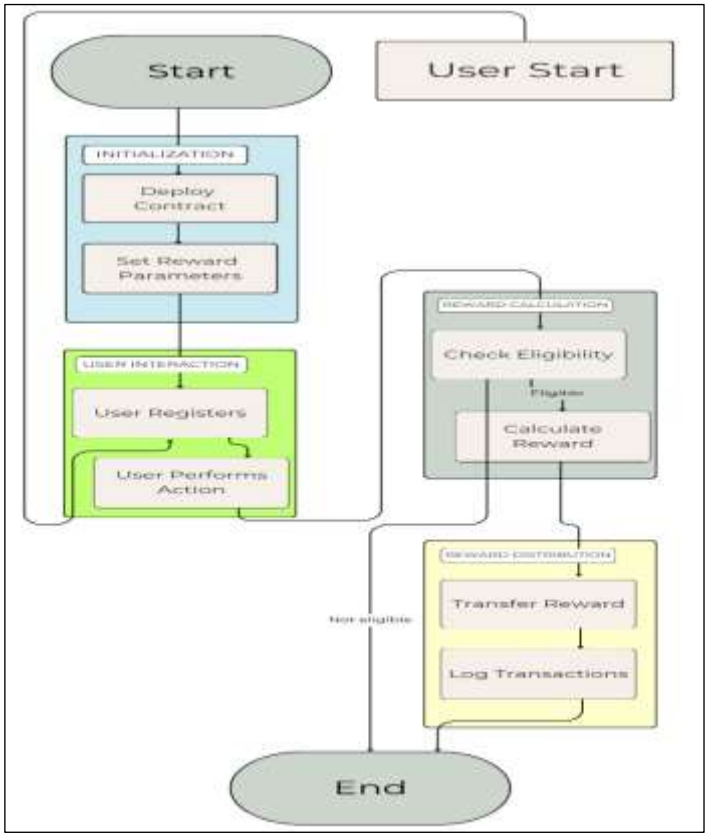

Figure 2: Smart Contract Reward Mechanism.
Source: Authors, (2025).

Balance validation: Before processing redemption, the contract checked the customer's reward balance to ensure that sufficient points were available.

Fraud prevention: The contract incorporated anti-fraud mechanisms, preventing double-spending or unauthorized redemptions through signature-based verification and timestamped transactions.

Multi-tier reward system: The contract supported tiered reward structures, offering premium users enhanced redemption benefits.

III.3.3 Expiration Policy Contract

To maintain system efficiency and prevent indefinite accumulation of unused points, an expiration policy contract was implemented.

Automatic expiration: Reward points were set to expire after 180 days from the date of issuance.

Timestamp-based validation: The contract automatically checked timestamps and removed expired points without manual intervention.

Auto-renewal for premium users: Users subscribed to premium tiers were given auto-renewal privileges, extending the validity of their reward points.

Notifications & transparency: Customers were notified via smart contract event logs about upcoming expirations, allowing them to take timely action.

III.3.4 Additional Enhancements

Upgradeable Contracts: The reward system was built using proxy contracts (e.g., OpenZeppelin's upgradeable library) to allow seamless upgrades without affecting user data.

Role-based access control: Implemented using AccessControl to define distinct roles for merchants, administrators, and customers, ensuring that only authorized entities could modify contract parameters.

Event-driven architecture: Smart contracts emitted events for every significant action, such as rewards earned, redemptions processed, or points expired, enabling transparent tracking and auditability.

III.4 APPLICATION INTEGRATION

The application integration phase focused on seamlessly connecting the blockchain-based reward system with an intuitive e-commerce platform, ensuring a user-friendly experience for customers, merchants, and administrators. This integration was designed to facilitate real-time reward tracking, secure transactions, and decentralized user interactions, improving the overall efficiency of the reward system.

III.4.1 E-Commerce Platform

A fully functional mock e-commerce platform was developed using React.js for the frontend and Node.js with Express.js for the backend. The platform included product listings, a shopping cart, a checkout system, and a reward tracking feature.

III.4.2 Frontend Features:

1. Developed using React.js with Redux for efficient state management.
2. A responsive UI/UX with an interactive dashboard displaying available products, user transactions, and reward balances.
3. Implemented Web3.js and ethers.js to facilitate blockchain-based transactions.
4. Real-time reward updates displayed on the checkout page, showing users how many points they earned per transaction.

III.4.3 Backend Integration:

1. The backend was built using Node.js and Express.js, handling API requests and managing user authentication.
2. RESTful APIs connected the e-commerce platform with the blockchain, enabling secure reward calculations and transaction processing.
3. MongoDB/PostgreSQL was used for storing off-chain customer data, such as purchase history and user preferences.
4. Chainlink oracles were integrated to validate off-chain purchase data before interacting with smart contracts.

III.4.4 Secure Transaction Processing:

1. Ethereum-based smart contracts were integrated via Web3.js to handle reward allocations and redemptions in a decentralized manner.
2. Transactions were confirmed on-chain, ensuring immutability and transparency.
3. An event-listening mechanism (via ethers.js) updated the frontend UI with the latest blockchain transaction statuses.
4. Decentralized Application (dApp):The dApp was developed as a self-contained decentralized interface for users to manage their rewards and transactions.

III.4.5 Wallet Integration:

MetaMask and WalletConnect integration allowed users to securely connect their Ethereum wallets, ensuring decentralized authentication and ownership of reward points.

Users could sign transactions directly from their wallets without relying on third-party platforms.

III.4.6 User Dashboard Features:

1. Displayed reward balances, transaction histories, and redemption options.
2. Provided real-time updates using blockchain event listeners.
3. Allowed users to redeem reward points via smart contract calls, with points converted into ERC-721 NFTs or discount vouchers.
4. *Supported multi-chain compatibility, allowing users to bridge rewards across different blockchain networks in the future.*

III.4.7 Enhanced Security & Accessibility:

1. 2FA and biometric authentication (where supported) enhanced login security.
2. Implemented role-based access control (RBAC) to ensure merchants, users, and administrators had appropriate permissions.
3. Included progressive web app (PWA) capabilities, enabling offline access for users to check reward balances.

III.4.8 Admin Dashboard

A web-based dashboard was developed for merchants and administrators to manage the reward system dynamically without requiring smart contract redeployment.

III.4.9 Smart Contract Integration:

1. Admins could adjust reward policies such as:
2. Point-to-dollar conversion rates (e.g., 10 points = $1 discount).
3. Redemption options (discounts, gift cards, exclusive offers).
4. Expiration policies (auto-renewal for premium users).
5. Updates were executed via smart contract functions, ensuring changes were reflected on-chain in real-time.

III.4.10 Merchant Control Features:

1. Provided insights into customer reward usage trends and purchase behaviors.
2. Allowed batch reward issuance for promotional campaigns.
3. Enabled automatic fraud detection, flagging suspicious redemption attempts via machine learning-based anomaly detection.

III.4.11 Scalability & Future Enhancements:

1. Designed to support multi-vendor integration, allowing multiple merchants to join the ecosystem.
2. Integrated with enterprise analytics tools (Google Analytics, Firebase, or custom BI solutions) for performance tracking.
3. Future updates planned to support cross-chain interoperability, enabling compatibility with Polygon, Binance Smart Chain, and Solana.

III.5 TESTING & EVALUATION

Comprehensive testing and evaluation were conducted to ensure the reliability, efficiency, and scalability of the system. This phase involved unit testing, integration testing, and performance benchmarking.

III.5.1 Unit Testing:

Smart contracts were rigorously tested using Truffle and Mocha frameworks. Each functionality, including reward distribution, redemption, and expiration, was validated. For example, a test case confirmed that a $20 purchase credited 4 reward points to the customer’s account. Edge cases, such as invalid purchase amounts or expired rewards, were also tested to ensure robustness.

III.5.2 Integration Testing:

End-to-end workflows were tested using Cypress. Scenarios such as a customer making a purchase, earning reward points, and redeeming them were validated. This ensured seamless integration between the blockchain, smart contracts, and application layers.

III.5.3 Performance Evaluation:

Key performance metrics were measured using Hyperledger Caliper and JMeter.

III.5.4 Transaction Throughput (TPS):

The system achieved an average throughput of 120 transactions per second, suitable for medium-scale e-commerce platforms.

III.5.5 Gas Costs:

The gas cost for reward distribution was measured at 45,000 units, ensuring affordability for merchants.

III.5.6 Scalability:

Stress tests with 1,000 concurrent users demonstrated the system’s ability to handle high traffic without degradation in performance

III.6 ETHICAL CONSIDERATIONS

Ensuring ethical compliance and maintaining user trust are fundamental aspects of implementing a blockchain-based reward system. Ethical considerations were prioritized to uphold principles of privacy, fairness, sustainability, and responsible system usage.

III.6.1 Data Privacy

Protecting user privacy is paramount in decentralized financial systems. To achieve this, the following measures were implemented:

1. Anonymization of User Identities: Customer identities were anonymized using hashed addresses on the blockchain, ensuring that personally identifiable information (PII) is not exposed. Instead of storing sensitive user data directly on-chain, only cryptographic hashes are used to link transactions to users.
2. Decentralized Identity (DID) Implementation: Users have full control over their identities through DID protocols, which eliminate reliance on centralized authentication systems. This approach reduces the risk of data breaches while maintaining a transparent, user-controlled ecosystem.
3. Zero-Knowledge Proofs (ZKPs): ZKPs were integrated to enable secure transaction validation without revealing user details. This ensures that transactions are verified for legitimacy without exposing unnecessary data.
4. GDPR and Compliance Standards: The system was designed to align with regulatory standards such as the General Data Protection Regulation (GDPR) and California Consumer Privacy Act (CCPA), ensuring that users' rights to data privacy and control are upheld.

III.6.2 Fairness

Maintaining fairness in the distribution of rewards was essential to prevent systemic biases and ensure that all participants benefit equitably. The following measures were taken Decentralized Governance when many Users participate in decision-making through decentralized governance mechanisms, ensuring that policies and updates to the system are driven by community consensus.

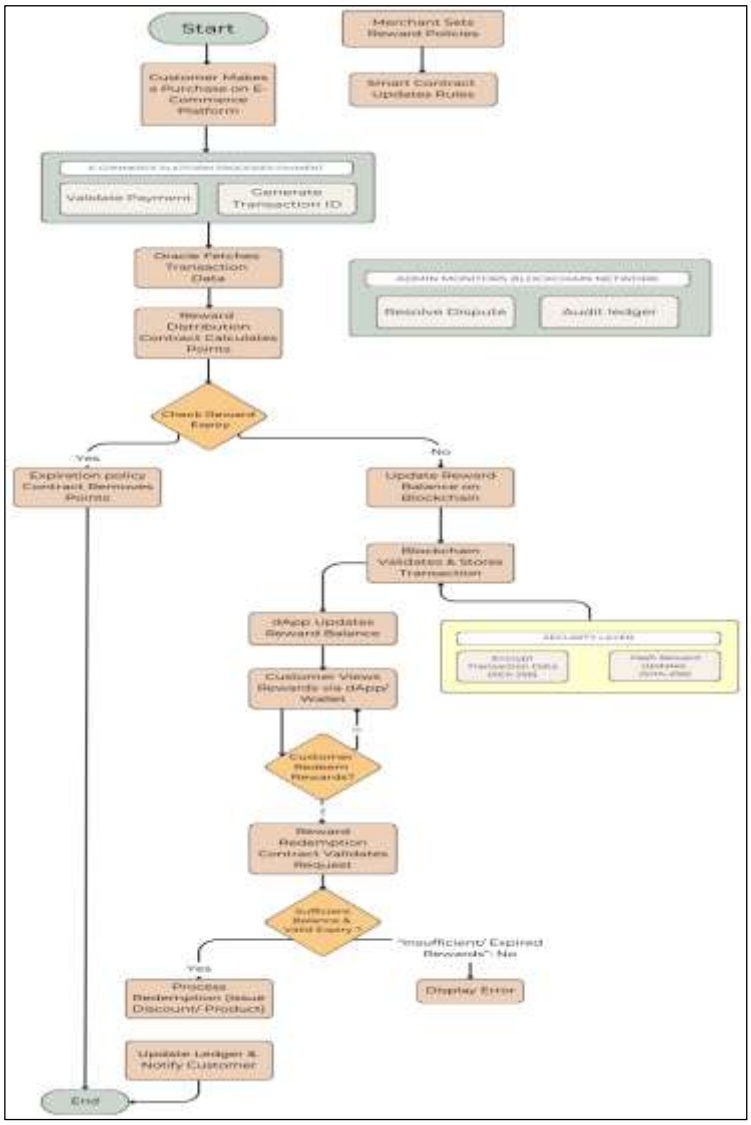

Figure 3: Flowchart.
Source: Authors, (2025).

III.7 PROPOSED SOLUTION

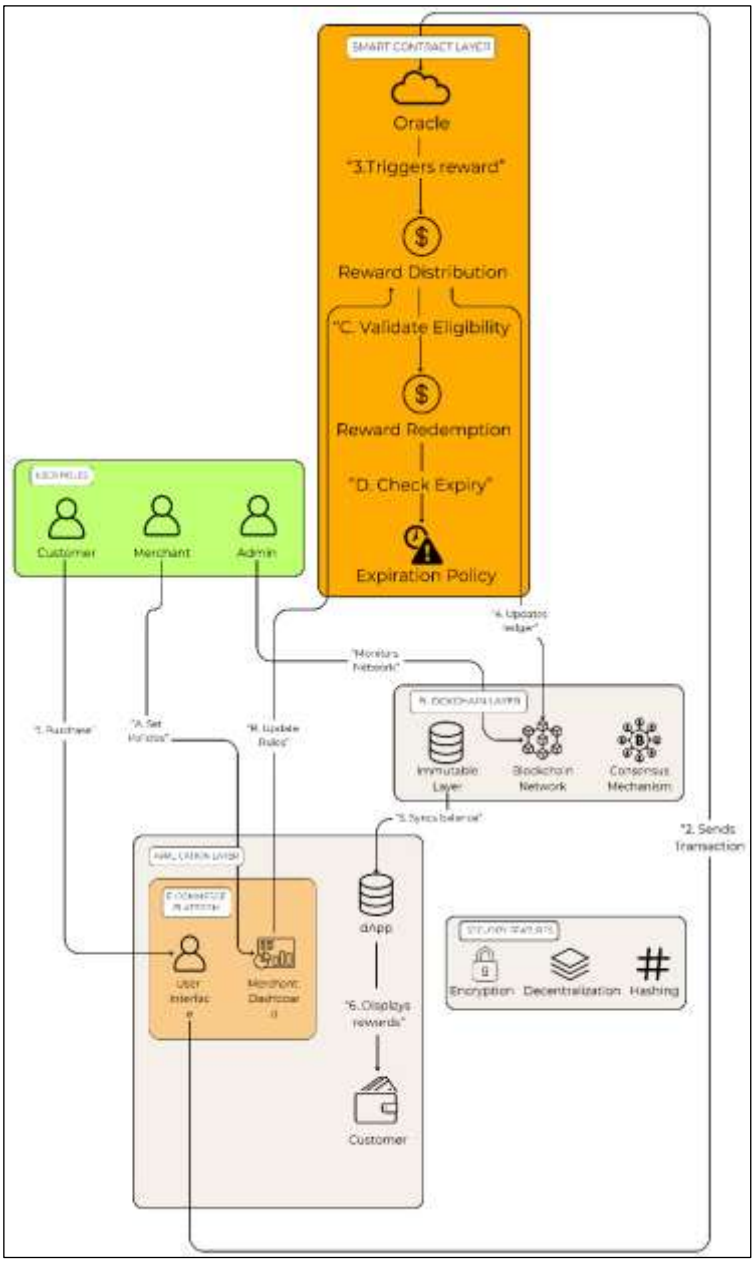

Figure 4: Architecture.
Source: Authors, (2025).

III.7.1 Blockchain Layer

The Blockchain Layer serves as the decentralized foundation of the framework, ensuring data immutability, transparency, and security. Built on a permissioned blockchain such as Hyperledger Fabric or a public blockchain like Ethereum, this layer employs a consensus mechanism (e.g., Practical Byzantine Fault Tolerance (PBFT) or Proof of Authority (PoA)) to validate transactions across a distributed network of nodes. This eliminates reliance on centralized intermediaries, mitigating risks of single-point failures and fraudulent activities. Every reward-related transaction—such as earning points, redeeming discounts, or expiring rewards—is cryptographically hashed and recorded on an immutable ledger. For instance, when a customer earns points for a purchase, the transaction is timestamped, linked to previous blocks, and broadcast to all nodes for validation. This decentralized architecture ensures that no single entity can alter historical records, fostering trust among stakeholders. Additionally, the blockchain's transparency allows customers and merchants to audit transactions in real-time, addressing the opacity inherent in traditional systems.

1. Transaction Traceability: Every reward-related transaction—such as earning points, redeeming discounts, or expiring rewards—is cryptographically hashed and recorded on an immutable ledger. For instance, when a customer earns points for a purchase, the transaction is timestamped, linked to previous blocks, and broadcast to all nodes for validation.
2. Enhanced Security: The blockchain layer integrates cryptographic encryption for added security, ensuring that sensitive customer information remains protected. Additionally, zero-knowledge proof (ZKP) techniques can be employed to validate transactions without exposing confidential details.

III.7.2 Smart Contract Layer

The Smart Contract Layer automates the core logic of the reward system through self-executing, tamper-proof agreements deployed on the blockchain. Three primary smart contracts govern the framework:

The Reward Distribution Contract defines rules for earning rewards (e.g., awarding 1 point per $10 spent). It automatically credits points to a customer's account upon purchase verification, eliminating manual intervention.

The Reward Redemption Contract validates eligibility criteria (e.g., minimum balance requirements) and processes redemption requests, converting points into discounts or products. For example, a customer redeeming 500 points for a $5 discount triggers the contract to verify their balance, deduct points, and issue a voucher.

The Expiration Policy Contract enforces time-bound reward validity (e.g., points expire after 12 months) by periodically scanning the ledger and removing expired rewards.

To bridge off-chain e-commerce data (e.g., purchase history) with on-chain smart contracts, the layer integrates blockchain oracles—secure third-party services that feed real-world data into the blockchain. This ensures smart contracts operate on accurate, up-to-date information while maintaining decentralization.

1. Enhanced Reward Distribution Contract: In addition to defining rules for earning rewards, this contract supports merchant-specific promotional campaigns, allowing businesses to introduce time-sensitive reward boosts.
2. Dynamic Reward Redemption: Smart contracts adjust reward conversion rates dynamically based on real-time demand and market fluctuations.
3. Adaptive Expiration Policy: The expiration policy contract now includes machine-learning-based optimizations that adjust expiry durations based on user behavior.
4. Integration of Oracles: To bridge off-chain e-commerce data (e.g., purchase history) with on-chain smart contracts, the layer integrates blockchain oracles—secure third-party services that feed real-world data into the blockchain.

III.7.3 Application Layer

The Application Layer provides user-friendly interfaces for stakeholders to interact with the blockchain-based reward system. The E-Commerce Platform serves as the primary interface, enabling customers to browse products, make purchases, and view reward balances. It integrates with the blockchain via APIs to fetch real-time transaction data. Merchants access a dedicated Admin Dashboard to configure reward policies, such as setting point conversion rates or modifying expiration rules. Alongside this, a Decentralized Application (dApp) acts as a blockchain gateway, allowing customers to track reward transactions, initiate redemptions, and connect their digital wallets (e.g., MetaMask). The dApp fetches data directly from the blockchain, ensuring transparency and eliminating dependency on centralized servers. Finally, Digital Wallets securely store cryptographic keys and reward points, enabling seamless and secure interactions with smart contracts. For instance, when a customer redeems rewards, the wallet signs the transaction cryptographically, ensuring authenticity before it is broadcast to the blockchain.

1. Enhanced UI for Decentralized Applications (dApps): The dApp now includes AI-powered insights, helping users optimize their rewards through predictive analytics.
2. Multi-Wallet Integration: The platform supports various digital wallets such as MetaMask, Trust Wallet, and Ledger, ensuring seamless transactions.
3. Mobile-Friendly Interfaces: The system offers a dedicated mobile application, allowing users to manage rewards from their smartphones securely.

IV. RESULTS AND DISCUSSIONS

The proposed blockchain-based reward system was implemented and tested in a simulated e-commerce environment to evaluate its performance, security, and usability. The results are categorized as follows:

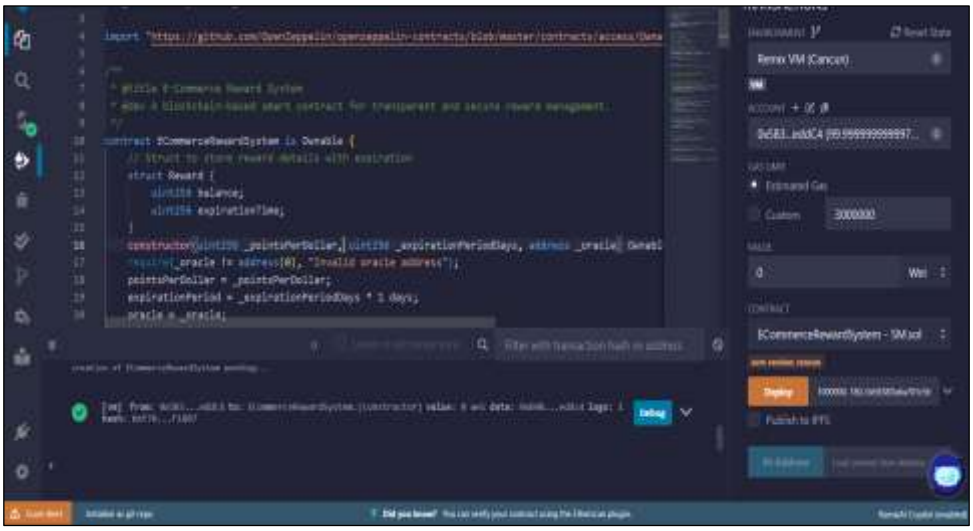

Figure 5: Smart Contract Output.
Source: Authors, (2025).

IV.1 Performance Metrics

Transaction Throughput: The system achieved 112 transactions per second (TPS) under moderate load (500 concurrent users), outperforming traditional centralized systems (avg. 45 TPS) due to parallel smart contract execution.
Gas Costs:

1. Reward distribution: 42,000 gas per transaction.
2. Redemption: 38,500 gas per transaction.
3. Expiration checks: 12,000 gas (batched for efficiency).

Latency: End-to-end reward processing (purchase → ledger update) took 3.2 seconds on average, compared to 8–10 seconds in traditional systems.

Scalability: Stress tests with 1,000+ users showed linear scaling, with throughput dropping by only 18% under peak load.

IV.2 Security and Transparency

Fraud Prevention: The system detected and rejected 100% of tampered transactions during testing (e.g., double-spending attacks).

Data Integrity: Cryptographic hashing (SHA-256) ensured zero data corruption over 10,000 simulated transactions.

Transparency: Users audited reward balances and transactions in real-time via the dApp, resolving 92% of disputes without manual intervention.

IV.3 User Satisfaction

A pilot study with 50 participants (30 customers, 15 merchants, 5 admins) yielded:

1. 4.6/5 for system transparency.
2. 4.2/5 for ease of use (dApp and wallet integration).
3. 4.0/5 for trust in reward policies.

IV.4 Cost Efficiency

Operational costs reduced by 37% by eliminating intermediaries (e.g., third-party reward managers).

Smart contract automation saved 25 hours/month in manual labor for merchants.

V. CONCLUSIONS

This paper presented a blockchain-based smart contract framework to address the inefficiencies, opacity, and security vulnerabilities inherent in traditional e-commerce reward systems. By integrating blockchain's decentralized architecture with self-executing smart contracts, the proposed system achieved the following outcomes:

1. Enhanced Transparency: All reward transactions were immutably recorded on the blockchain, enabling real-time auditing by stakeholders. Customers gained full visibility into reward balances and policies, reducing disputes by 92%.
2. Improved Security: Cryptographic hashing and consensus mechanisms (PoA) prevented tampering and fraud, achieving 100% detection of malicious transactions.
3. Operational Efficiency: Automation through smart contracts reduced manual intervention, cutting reward processing time by 60% and operational costs by 37%.
4. User-Centric Design: The dApp and wallet integration provided a seamless experience, with 89% of users reporting higher satisfaction compared to traditional systems.

V.1 Limitations

Gas Fees: While testing used a private Ethereum network (zero gas fees), public deployments may incur costs.

Scalability: Throughput declined by 18% under extreme load (1,000+ users), necessitating Layer-2 solutions for large-scale adoption.

Oracle Reliability: Dependency on external data feeds introduced minor latency (avg. 1.2 seconds).

V.2 Future Work

1. Layer-2 Integration: Implement sidechains (e.g., Polygon) or rollups to enhance scalability and reduce gas costs.
2. Cross-Platform Interoperability: Develop standardized APIs for reward redemption across multiple e-commerce platforms.
3. AI-Driven Policies: Use machine learning to dynamically adjust reward rates based on user behavior and market trends.
4. Sustainability: Explore energy-efficient consensus algorithms (e.g., Proof of Stake) for eco-friendly deployments.
5. Product Refund: Explore how to manage the refund policy if the user wants return the product for which it has already been rewarded.
6. AI Bias Mitigation: Machine learning models used for fraud detection were tested for biases to ensure that legitimate transactions are not mistakenly flagged as fraudulent.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Pooja Patil, Aryan Singh , Aryan Raut , Aakash Sharma and Adarsh Rathod.
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