Ecochain: A Layer‑2 Blockchain Approach to Cutting E‑commerce Transaction Fees

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**Abstract.** Rising payment‑gateway fees erode merchant margins and make micro‑transactions impractical for online retail. This study presents Ecochain, a Layer‑2, roll‑up‑enabled payment rail that batches e‑commerce orders off‑chain and settles them on Ethereum only once per block, thereby preserving security while minimising cost. A production‑grade gateway was integrated with Shopify and deployed on the Polygon PoS network. Under a 10,000-checkout stress test, Ecochain sustained 170 transactions ⁻s¹ on a single validator node and reduced the end‑to‑end settlement cost from USD 2.87 ± 0.14 on Ethereum main‑net to USD 0.021 ± 0.003 on Polygon a 99.3 % reduction with a median confirmation latency of 2.3 s. For a typical USD 50 basket, the total checkout fee falls from 3.1 % (Stripe card: 2.9 % + USD 0.30) to 0.12 %, and the system breaks even against traditional gateways at just USD 1.00. These results show that Layer‑2 cryptopayments can satisfy the cost and latency requirements of mainstream e‑commerce.

# iNTRODUCTION

Blockchain technology has emerged as a compelling alternative to traditional payment rails, offering programmable trust, global reach, and near‑instant settlement. Yet, its adoption in mainstream e‑commerce remains limited because Layer‑1 (L1) transaction fees and confirmation delays scale poorly for the small‑ticket, high‑volume checkouts that dominate online retail. A single Ethereum transfer can exceed USD 2–3 during network congestion, a cost that dwarfs the thin margins of many merchants and renders micro‑transactions (> USD 5) unviable [1]. Early attempts to build decentralised marketplaces such as OpenBazaar demonstrated technical feasibility. Still, they failed to gain traction primarily due to these cost and latency barriers and user experience (UX) gaps in wallet management. Payment‑service providers (PSPs) like Stripe have introduced crypto on‑ramps, yet they essentially replicate the fee structures of card networks (≈ 2.9 % + USD 0.30), offering little relief to merchants [2]. Consequently, a clear research gap persists: how can we leverage blockchain’s trust guarantees while matching or undercutting conventional gateways’ cost and UX benchmarks? Recent advances in Layer‑2 (L2) scaling technologies provide a new design space, particularly roll-ups. By aggregating thousands of off‑chain transactions into a single L1 proof, roll‑ups amortise gas costs, enabling sub‑cent fees without compromising security [3]. However, empirical evaluations of L2 payments in real e‑commerce settings are scarce, and questions remain about performance on commodity infrastructure, compliance with payment‑card industry (PCI) norms, and integration effort with existing storefronts.

This study addresses these gaps through the design and evaluation of Ecochain, an L2‑based payment gateway integrated with Shopify. We pursue the following research questions (RQs):

* **RQ1:** Can a roll‑up‑enabled gateway reduce the total checkout cost below 2 % and preferably below 0.5 % for baskets as small as USD 1?
* **RQ2:** What transaction‑per‑second (TPS) throughput and confirmation latency are attainable on low‑cost cloud instances (< USD 50 per month)?
* **RQ3:** How does the security posture of the proposed design compare with incumbent card networks and custodial PSPs?

To answer these questions, we implement Ecochain on the Polygon Proof‑of‑Stake network, conduct a 10,000-order stress test, and perform a security audit using Slither and MythX. Our results indicate a 99 % reduction in settlement cost and sub‑three‑second median latency, suggesting that L2 cryptopayments can meet, and often exceed, the economic and performance thresholds required for mass‑market adoption. The remainder of this paper is organised as follows: Section 2 surveys related work on blockchain payment systems and L2 scaling. Section 3 details Ecochain’s architecture and smart‑contract design. Section 4 describes the experimental setup and security‑audit methodology. Section 5 presents quantitative results and comparative analysis. Section 6 discusses regulatory and UX implications, limitations, and future work, and Section 7 concludes.

# lITERATURE rEVIEW

## Traditional Payment Gateways and Their Cost Structure

Card‑network‑based gateways such as Stripe, PayPal, and Authorize.Net remain the de‑facto standard for online checkout shown in FIGURE 1. Studies by Visa [4] and Bhat et al. [5] show average blended fees of 2.4-3.4 % plus a fixed component (USD 0.10-0.35) that disproportionately burdens low‑value baskets. While these works provide detailed fee breakdowns, they treat fees as exogenous and do not explore architectural alternatives capable of eliminating the intermediary rent. Conventional PSP research quantifies the problem as a high percentage and fixed fees but offers no design pathway to eradicate them. This gap motivates blockchain‑based approaches that can disintermediate acquirers and issuers.

A diagram of a payment process

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**FIGURE 1.** Current e-commerce processing model

**Layer‑1 Blockchain Payment Solutions and Layer‑2 Scaling Techniques for Payments**

Early decentralised marketplaces like OpenBazaar in 2016 [6] and token-based checkouts, Crypto‑Kitties in 2017, [7] demonstrated feasibility. Yet, empirical analyses by Earle et al.  [6] highlight average gas fees of USD 2–20 during congestion, rendering micro‑payments infeasible. Liya et al. [8] propose a smart‑contract escrow to reduce dispute risk but measure throughput only under a single-threaded Ganache test‑net, limiting external validity.  
L1 solutions inherit the fee‑latency trade-offs of their base chains. Therefore, an alternative scaling layer is needed to achieve cost parity with PSPs.

* **State Channels and Side‑Chains:** State channels (Lightning, Raiden) dominated the discourse before roll-ups. Saif  et al. [9] report sub-cent fees but note a 28 % failure rate for multi-hop payments. Side‑chains, such as Plasma Neiheiser et al. [10] improve capacity yet suffer from weaker security assumptions and complex exit games. Both approaches demand continuous online presence from users, a UX hurdle cited by Sikder et al. [11].
* **ZK‑ and Optimistic Roll-ups:** More recently, roll-ups aggregate thousands of transfers into a single L1 proof. Buterin’s canonical Gorzny [12] is refined by Optimism Tas et al. [13] and Chaliasos  et al. [14], who show 10–40× gas savings. However, their evaluations are synthetic deploying ERC‑20 transfers, not full checkout flows. Zero knowledge (ZK) roll ups push further. zkSync Era processed 10.2 M tx in February 2023 at ≈ USD 0.05 each Scroll reports EVM equivalence with 100 TPS on test net and compare prover time across circuits but ignore end-user latency, leaving open the question of real-world responsiveness [15].
* **Account Abstraction for UX:** ERC‑4337 account abstraction enables gas sponsorship and multi‑factor wallets, as analysed by Stoica et al. [16]. They demonstrate 40 % lower abandonment in a sandbox study, yet their cost analysis assumes static gas prices and omits L2 batching effects. Roll‑ups and account abstraction collectively promise sub‑cent fees and card‑like UX. Nonetheless, no study has integrated these primitives into a production storefront and measured both economic and performance outcomes under realistic load the focus of the present work.

**Security and Compliance Considerations with Identified Research Gap**

Security audits of payment smart contracts highlight re-entrancy and integer-overflow as primary risks, extending the analysis to roll-up bridges, identifying prover-timeout exploits. Regulatory papers [17]; Malaysia Securities Commission Malaysia (SC) 2024 [18] stress that custody rules and data‑privacy obligations are often sidelined in purely technical literature. While prior work catalogues technical and regulatory risks, little empirical data exist on whether L2 designs can satisfy PCI‑DSS-like controls or national payment regulations. Ecochain addresses this gap through an integrated security audit and compliance mapping.

The review reveals (i) *quantified cost pain points* in PSPs, (ii) *scalable but under-evaluated* L2 primitives, and (iii) *unresolved security/compliance* questions. No published study to date has experimentally verified that a roll-up‑driven gateway can deliver < 0.5 % fees, sub-three-second latency, and PCI-aligned security on commodity hardware. Ecochain is designed to fill this void and to answer the three research questions articulated in Section 1.

# METHODOLOGY

This paper outlines the methodology for implementing Ecochain, a blockchain-based solution aimed at reducing transaction costs in e-commerce. By leveraging Layer 2 blockchain technology, Ecochain addresses the inefficiencies and high fees inherent in traditional e-commerce platforms. These inefficiencies, often caused by multiple intermediaries in payment processing, impose significant costs on both small and large transactions.

## System Architecture and Smart Contract Development

Ecochain employs a four‑tier architecture FIGURE 2 that cleanly isolates user interaction, batching, settlement, and audit storage: the Storefront, built as a Shopify App Bridge plug‑in in TypeScript, captures order metadata, invokes WalletConnect for customer signatures, and streams the signed payloads to the Aggregator via a persistent submitOrder WebSocket while holding no private keys thus complying with PCI’s “no card data” rule; the Aggregator Service, a stateless Node.js micro‑service, buffers orders in memory, and every two seconds produces a Merkle root, generates a zkEVM proof, and submits a roll‑up transaction, exposing a REST callback for Storefront status polling; the Settlement Contracts, deployed on Polygon PoS, verify those proofs, update merchants’ on‑chain order books, and trigger USDC payouts, with an access‑controlled withdraw() for sweeping funds to cold storage; and finally the Data & Compliance layer pins order receipts to IPFS for transparency while logging hashed PANs and AVS flags to a VPC‑hosted PostgreSQL instance, leaving head‑room for regional modules such as GDPR “right to erasure.

The smart contract development focused on creating a secure and efficient transaction process. Key features include:

* **Payment Validation**: Ensures that transactions have a non-zero value and are not initiated by the store owner.
* **Fee Calculation**: Automatically calculates and deducts a fee from each transaction.
* **Sales Tracking**: Maintains a record of sales for each seller and the overall store.
* **Event Emission**: Emits events for sales and withdrawals to facilitate transparency and tracking.

## Experimental Environment

**Layer‑2 Network Selection:** In this research, three candidate networks are evaluated: Polygon PoS, Arbitrum One, and zkSync Era, against five criteria: average fee per 50 kB proof, confirmed TPS on public dashboards, EVM equivalence (tooling), DeFi ecosystem maturity, and fiat on‑ramp availability, as shown in TABLE 1. Polygon achieved the highest composite score, **justifying its selection** for all subsequent experiments. Where relevant, we report counter‑factual fees on Arbitrum and zkSync to demonstrate generalisability.

A diagram of a software flow

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**FIGURE 2.** System architecture of ecochain

**TABLE 1.** Presents the selection matrix; scores are normalised 1 (low)–5 (high)

|  |  |  |  |
| --- | --- | --- | --- |
| **Criterion** | **Polygon PoS** | **Arbitrum One** | **zkSync Era** |
| Avg. fee (USD) | 0.021 | 0.11 | 0.05 |
| Sustained TPS\* | 170 | 90 | 100 |
| Tooling maturity | 5 | 4 | 3 |
| Ecosystem TVL† | 5 | 4 | 2 |
| Fiat on‑ramp‡ | 4 | 3 | 2 |
| Composite score | 4.6 | 3.5 | 2.8 |

*\*Public stress‑test data, April 2025. †Total value locked from DeFi Llama snapshot 30 Apr 2025. ‡Direct credit‑card/ACH services.*

* **Load Generation and Metrics**

1. Hardware: AWS t3.medium (2 vCPU, 4 GB, USD 34 month⁻¹) hosts the Aggregator; the test client runs on a t3.small.
2. Dataset: 10 000 synthetic checkouts, basket sizes USD 1–100, Zipf(α = 1.2) distribution.
3. Metrics: settlement fee (USD), confirmation latency (P50/P95), throughput (TPS), CPU/memory footprint, and on‑chain gas usage. Each experiment is repeated five times; results are reported as mean ± SD.

* **Security Testing & Audit Plan**

1. To evaluate threats to validity we adopted a three‑stage audit pipeline:
2. Static Analysis – slither v0.10 detects reentrancy, integer overflow/underflow, and incorrect ERC‑20 allowances (0 critical, 3 medium, 2 informational findings).
3. Dynamic Fuzzing – Echidna runs 50,000 property‑based tests on the Settlement contract; no invariant violations observed.
4. Coverage & Differential Testing – Hardhat‑coverage reports 92 % branch coverage; MythX cross‑examines deployed byte‑code on Polygon Mumbai and finds no discrepancies.

* **Threats to Validity**

1. Gas‑price Volatility: Experiments were conducted when the base fee ≈ was 30 gwei; extreme congestion could raise costs, though batching reduces sensitivity by ~95 %.
2. Synthetic Workload Bias: While our Zipf distribution mirrors real Shopify data [20], genuine flash-sale spikes (burst > 1,000 TPS) require horizontal scaling of the Aggregator—future work.
3. Test‑net vs Main‑net: Production deployment may encounter higher MEV risk; we plan a guarded launch with circuit breakers and real‑time monitoring.

## Implementation Details

All source code, Dockerfiles, and Terraform scripts are bundled in the anonymous supplementary artefact supplied with this submission. The bundle includes a make benchmark target that reproduces every experiment; a permanent DOI will be minted after the review process. Deterministic builds ensure the results can be recreated on any machine that supports Docker 23 or later. As shown in TABLE 2.

**TABLE 2.** Build environment: tool versions and Docker image digests used to reproduce Ecochain’s results

|  |  |  |
| --- | --- | --- |
| **Component** | **Version** | **Docker/Img Digest** |
| Node.js | 20.7.0 | sha256:1b4be9b20f2b7d6f7c0…… |
| TypeScript | 5.4.2 | n/a |
| Solidity compiler | 0.8.23 (optimizer 20 000) | n/a |
| Hardhat | 2.21.0 | n/a |
| Foundry | 0.2.9 | sha256:afc19dcd7eaa1db6d4b59….. |
| Polygon zkEVM prover | 0.3.2 | sha256:7e12c1a4f9b3d6e2a….… |
| Terraform | 1.7.5 | n/a |

*\*The SHA‑256 digest is a content‑addressable fingerprint that guarantees the image is bit‑for‑bit identical across rebuilds. Nightly CI jobs re‑build every image and compare the resulting digest to the one pinned above; any mismatch triggers an alert, allowing us to detect* ***supply‑chain drift*** *before it affects reproducibility.*

## Deployment

The smart contracts were first deployed to Layer 2 test‑nets, specifically Polygon’s Mumbai and Arbitrum’s Goerli, to validate functionality and security before any main‑net launch. Deployment used Truffle, whose scripting and network‑management features were configured to target the chosen Layer 2 endpoints; this workflow is summarized in FIGURE 3. Integration with Layer 2 involved adding the relevant RPC URLs to the Truffle configuration, bridging assets between Layer 1 and Layer 2 when needed, and exploiting the reduced gas fees by batching transactions for off‑chain settlement. Throughout the process, extensive tests and verifications ensured the contracts performed correctly and efficiently in the Layer 2 environment.

**A diagram of a software process

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**FIGURE 3.** Deployment process flow diagram

# RESULTS AND ANALYSIS

This section answers RQ1 (cost), RQ2 (performance), and RQ3 (security). All benchmarks were run five times on an AWS t3.medium Aggregator; results are reported as mean ± SD unless indicated otherwise. For experimental Setup Dataset: 10 000 synthetic checkouts, basket USD 1–100, Zipf(α = 1.2). Hardware: Aggregator on AWS t3.medium (2 vCPU, 4 GB, USD 34 mo⁻¹). Metrics: settlement cost (USD), TPS, confirmation latency, CPU/mem, gas. Five independent runs; results reported mean ± SD. For cost reduction, FIGURE 4 compares the mean settlement fee across networks for basket sizes USD 1–100. Ecochain on Polygon reduces the cost from USD 2.87 ± 0.14 (Ethereum main‑net) to USD 0.021 ± 0.003 a 99.3 % saving. The break‑even basket versus Stripe (2.9 % + USD 0.30) occurs at USD 1.00, meeting the < 0.5 % micro-transaction target.

**TABLE 3.** Average settlement fee per checkout on each network and percentage reduction relative to Ethereum main‑net (USD)

|  |  |  |  |
| --- | --- | --- | --- |
| **Network** | **Mean Fee (USD)** | **SD** | **Reduction vs Main‑net** |
| Ethereum main‑net | 2.87 | 0.14 | - |
| Polygon PoS | 0.021 | 0.003 | 99.3% |
| Arbitrum One\* | 0.11 | 0.012 | 96.2% |
| zkSync Era\* | 0.05 | 0.009 | 98.3% |

*\*Single‑batch replay for comparability.*

*Polygon drives the total checkout fee on a USD 50 basket down to 0.12 %, beating the < 0.5 % target and breaking even against Stripe (2.9 % + USD 0.30) at USD 1.00. A one‑tailed t‑test (main‑net vs Polygon, n = 5) yields p < 0.001, confirming a statistically significant reduction.*

A graph of a graph

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**FIGURE 4.** Throughput and confirmation latency as a function of roll‑up batch size

For performance,FIGURE 4 plots throughput against batch size. The sweet spot is batch = 250, where Ecochain sustains 170 ± 4 TPS with a median latency of 2.3 ± 0.2 s (P95 = 3.1 s), comfortably exceeding the 100 TPS requirement for mid‑sized merchants. CPU utilisation peaks at 61 %, leaving ample headroom; cost per million checkouts is ≈ USD 57 (USD 36 compute + 21 Polygon gas).For security evaluation,Static analysis (Slither) and dynamic fuzzing (Echidna, 50,000 tests) reported no critical vulnerabilities; Hardhat‑coverage shows 92 % branch coverage, and MythX finds no byte‑code discrepancies on Polygon Mumbai. The audit, therefore, places Ecochain on par with, and in some vectors ahead of, incumbent custodial PSPs.

# Discussion

Batching check‑outs on Polygon slashes the mean settlement fee from USD 2.87 ± 0.14 on Ethereum to USD 0.021 ± 0.003 a 99.3 % saving that drives the cost of a USD 50 basket down to 0.12 %, comfortably below the < 0.5 % target and reaching fee‑parity with Stripe at just USD 1.00; meanwhile, on a single t3.medium (≈ USD 34 month⁻¹) Ecochain sustains 170 ± 4 TPS at batch = 250, with median confirmations of 2.3 ± 0.2 s and 61 % CPU utilization, showing that commodity hardware can support about 8 000 check‑outs per minute. A three‑layer audit static (Slither), dynamic (Echidna, 50,000 fuzz cases), and differential (MythX) found zero critical issues and 92 % branch coverage, satisfying PCI “no‑card‑data” rules and placing Ecochain on par with custodial PSPs while eliminating custody risk. Limitations remain: (i) gas‑price volatility (a 10× spike on the 30 gwei baseline would raise costs ≈ 5 %, partly offset by batching), (ii) synthetic workload bias (Zipf 1.2 traffic may under‑represent flash‑sale bursts > 1,000 TPS, for which horizontal aggregator sharding is planned), (iii) test‑net versus main‑net differences such as MEV, hence the guarded‑launch plan with on‑chain monitors and circuit breakers and (iv) wallet onboarding friction, which forthcoming ERC‑4337 smart accounts and fiat on‑ramps aim to ease. Even with these caveats, Ecochain’s sub‑cent fees reopen micro‑sales for music, gaming, and charity merchants, demonstrate to regulators that roll‑ups can meet PCI‑DSS logging and “no‑card‑data” mandates (supporting MiCA and Malaysia SC‑DAX compliance), and give payment‑gateway operators an open‑source aggregator that drops into Shopify or WooCommerce without disrupting existing flows.

# CONCLUSION

This study introduced Ecochain, a roll‑up enabled payment gateway that integrates natively with Shopify and lowers checkout fees by 99.3 % while achieving 170 TPS and < 3s median latency on commodity cloud hardware. These results confirm that Layer‑2 crypt payments can meet the economic (< 0.5 % fee) and usability (< 3s confirmation) thresholds of mainstream e‑commerce. In the future, we will work on Cross‑chain reach. Port Ecochain to BNB Chain and zkSync Era to broaden fiat on‑ramp coverage and resilience. Advanced ZK‑roll‑ups. Replace the current STARK prover with a Groth16 circuit to reduce proof size and speed finality. Account abstraction. Adopt ERC‑4337 smart wallets to remove seed‑phrase management for first‑time shoppers. We believe these extensions will further reduce barriers for small merchants and accelerate the transition toward decentralized retail at a global scale.

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