Mapping Security Risk Propagation in ERC Standards: From Specification Flaws to Implementation Deviations and Developer Knowledge Gaps

Abstract

The Ethereum Request for Comment (ERC) standards form the backbone of a $1.5+ trillion tokenized ecosystem, yet their security has been assessed only in isolation—ignoring how functional interdependencies between standards create systemic risks. This paper presents the holistic risk assessment of the ERC landscape, revealing vulnerabilities that emerge from the compositional nature of the standards themselves. We analyze over 100 ERC specifications to construct a functional dependency graph, deriving nine core categories that converge into four high-severity risk classes: Access Control, Transfer Integrity, Signature Mechanisms, and System Integration. We validate and explain these risks through structured surveys with 41 developers, quantifying a critical confidence–implementation gap: even widely used patterns are misunderstood and incorrectly applied, perpetuating vulnerabilities. Our findings culminate in an evidence-based security framework and actionable recommendations for standard authors, auditors, and developers. We provide a foundational methodology to proactively secure the protocol layer on which the future of decentralized finance and digital assets depends.

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1 Introduction

Ethereum Request for Comment (ERC) standards define how tokens behave on the Ethereum Virtual Machine (EVM) [1] compatible blockchains, forming the foundation of a multi-trillion dollar digital asset ecosystem [2]. These standards serve different purposes and audiences. **ERC-20**, the most widely adopted standard (millions of deployments), defines fungible tokens where each unit is identical—used for currencies, utility tokens, and stablecoins. **ERC-721** defines non-fungible tokens (NFTs), where each token is unique—used for digital art, collectibles, and ownership records. **ERC-1155** combines both capabilities in a single contract, enabling efficient batch transfers—popular in gaming and metaverse applications [3, 4]. Beyond these core standards, hundreds of extensions add functionality: ERC-2612 enables gasless approvals, ERC-2981 adds royalty information, ERC-4907 enables rental functionality. These extensions vary in adoption—some achieve prominence through integration with major platforms, while others remain experimental [5].

Problem: The evolution from simple tokens (ERC-20) to complex hybrids (ERC-1155) has enabled unprecedented functionality but outpaced security analysis [6]. Standards now form intricate dependency chains: ERC-721 requires ERC-165 for interface detection; ERC-1155 inherits patterns from both fungible and non-fungible paradigms; ERC-2612 depends on EIP-712 for cryptographic signatures. When potential risks, ambiguous specifications exist in base standards, they propagate through these chains to all dependent extensions. For instance, a risk in ERC-721's approval mechanism affects dozens of extensions (ERC-4907, ERC-2981, ERC-4494) [7]. Current research remains fragmented—studying individual standards [8], applying generic vulnerability checks [9], or measuring compliance without ecosystem context [10]. This approach potentially fails to capture how implementation challenges and dependencies (standards building upon each other) create systemic risks [11]. Consequently, the ecosystem lacks a holistic framework for identifying, assessing, and mitigating these interconnected security risks [5].

Research Motivation, Objectives and Approach: Motivation: With over $100B in assets relying on ERC standards, ecosystem-level risks threaten the entire token economy. Securing individual contracts is insufficient if base vulnerabilities silently propagate through inheritance chains. We are motivated to perform a deep security analysis of this innovative ecosystem. We believe that if security guarantees are addressed adequately, it will lead to greater adoption of the technology, which in turn should help society and the community build trusted decentralized systems. *Objectives*: We structure our assessment around four research questions: RQ1 analyzes specifications and respective contract implementations; RQ2 derives security risk categories; RQ3 investigates developer perceptions explaining why risks persist; and RQ4 synthesizes actionable recommendations.

Approach: By following the methodology (Section 2.3) , we aim to provide a pipeline [12] for understanding security risks in the ERC ecosystem. Our findings offer researchers, standard authors, tool developers, and practitioners a road map for improving Ethereum's security challenges.

We contribute the following:

(1) **Foundational Specification Framework:** Through manual curation of ERC standards, we developed a JSON specification database and dependency graph. This enabled us

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to analyze their functionalities and derive nine categories, providing a structured taxonomy for the ecosystem.

(2) **Large-scale Smart Contract Analysis:** We analyzed contracts across multiple EVM chains to identify gaps between specifications and actual developer implementation practices, which resulted in a notable partial compliance rate for ERC-1155.
(3) **Security Risk Assessment:** We provide a four-category security risk taxonomy—Access Control and Authorization, Transfer Operation Complexities, Signature Mechanism Vulnerabilities, and System Integration Challenges—derived from functional analysis, providing a holistic framework for ecosystem-level risk assessment (RQ2).
(4) **Validated Developer Insights:** Through 41 developer surveys, quantifying security risks, developer confidence implementation gaps and providing human-context explanations for why implementation practice inconsistencies lead to persistent vulnerabilities (RQ3).
(5) **Actionable Ecosystem Guidance:** We offer evidence based recommendations structured for developers (secure practices), tool builders (specification-aware analysis), and standard authors (security-first governance)—to mitigate identified ecosystem risks (RQ4).

Paper Organization: After reviewing related work (Section 2), we present: specification analysis (RQ1, Section 3), security risk assessment (RQ2, Section 4), developer validation (RQ3, Section 5), ecosystem recommendations (RQ4, Section 6), and conclusion (Section 7).

2 Background, Related Work and Methodology

2.1 Ethereum Standards and Token Ecosystem

ERC standards define how tokens behave on Ethereum—over 100 of them now exist, spanning DeFi, gaming, and digital ownership. These standards fall into three tiers. **Core standards** (ERC-20, ERC-721, ERC-1155) establish the basic token models. **Extensions** build on these with additional features: ERC-2612 enables gasless approvals, ERC-2981 adds royalty support. **Utility standards** handle supporting functions like interface detection (ERC-165) or off-chain metadata (ERC-1046). Adoption varies widely—core standards appear in millions of contracts, while specialized extensions see concentrated use in specific sectors like DeFi or gaming [13].

New standards go through the Ethereum Improvement Proposal (EIP) process [14], moving from Draft to Final status through community review. This open approach has enabled rapid innovation but also created complex dependency chains. ERC-721 requires ERC-165 for interface detection. ERC-1155 inherits behavior from both fungible and non-fungible parents. ERC-2612 depends on EIP-712 for cryptographic signing [7]. These relationships introduce real security challenges: optional requirements lead developers to ship partial implementations, ambiguous "SHOULD" clauses cause compatibility headaches, and vulnerabilities in base standards silently propagate to everything that depends on them [11]. Understanding the ecosystem means looking at how standards connect, not just what each one does alone.

2.2 Related Work

Existing security research on ERC tokens fails to address the ecosystem's systemic risks. Work on individual standards (e.g., ERC-20) catalogs implementation errors [8] but treats standards in isolation. Generic vulnerability detection tools [9, 15] operate in a semantic vacuum, missing standard-specific logic like signature validation flaws [16]. Ecosystem surveys [6, 17, 18] remain descriptive, while empirical analyses of deployed contracts often focus on generic vulnerabilities rather than standard-specific compliance [19].

Thus, a critical gap persists. Prior work has focused on *individual contracts* or *generic vulnerabilities*, but none provides a **specification-derived, ecosystem-wide risk framework validated by developer practice**. Existing approaches fail to connect the dots between the functional architecture of standards, the vulnerabilities they create, and the human factors that allow these vulnerabilities to persist in production.

This paper fills that gap. We present a **functionality-to-security risk assessment** framework that: (1) Derives risk categories (RQ2)from ERC specification architecture (RQ1), (2) Validates these risks through large-scale smart contract analysis across EVM chains (RQ1), and (3) explains their persistence through empirical developer insights (RQ3) and recommendations (RQ4). Our work shifts the paradigm from auditing isolated contracts [15, 20] to assessing and explaining the standardized ecosystem's vulnerabilities, building upon but fundamentally extending foundational smart contract security research [6, 18].

2.3 Methodology

This study employs a mixed-methods methodology (Figure 1) to assess security risks in the ERC ecosystem. Our five phase pipeline below (linking RQs in Section 1). **1. Specification Analysis and Data Curation (RQ1):** We analyze 100+ ERC standards, extracting function signatures, event definitions, and dependencies into a JSON knowledge base, alongside assembling a multi-chain dataset. → **2. Smart-Contract Analysis (RQ1):** Using selector signature matching on the bytecode dataset against our JSON specifications, we classify contracts by ERC footprint and assess developer implementations in practice and compliance levels, identifying inconsistent contracts and compliance gaps for further investigation. → **3. Security Risk Assessment (RQ2):** Building on data from Phase 1, we derive four security risk types through analysis of historical vulnerabilities and the functional taxonomy, applying threat modeling principles. → **4. Developer Validation (RQ3):** Through structured surveys with 41 practitioners, we *validate the risk categories* from Phase 3 and explain smart-contract implementation behaviors observed in Phase 2. → **5. Ecosystem Synthesis (RQ4):** We synthesize findings into evidence-based recommendations for specifications, tooling, and governance.

3 ERC Specification Implementation Analysis, Compliance and Categorization

We begin with the foundational work of our study, encompassing the creation of a ERC specification knowledge base, a large-scale empirical analysis of implementation compliance, and the derivation of a functional taxonomy. These elements collectively address ***RQ1: What are the structural and functional characteristics***

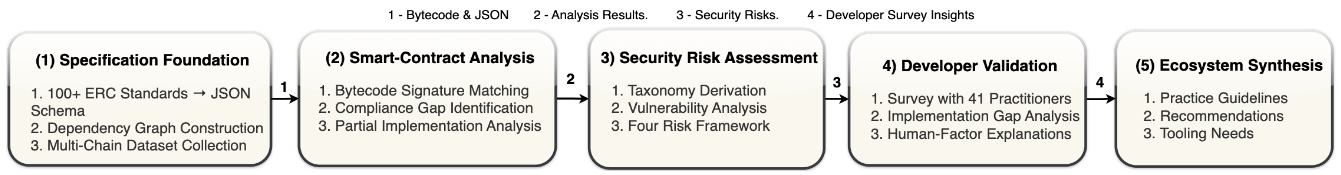
1 - Bytecode & JSON
2 - Analysis Results.
3 - Security Risks.
4 - Developer Survey Insights
(1) Specification Foundation
1. 100+ ERC Standards → JSON Schema
2. Dependency Graph Construction
3. Multi-Chain Dataset Collection
1
(2) Smart-Contract Analysis
1. Bytecode Signature Matching
2. Compliance Gap Identification
3. Partial Implementation Analysis
2
3) Security Risk Assessment
1. Taxonomy Derivation
2. Vulnerability Analysis
3. Four Risk Framework
3
4) Developer Validation
1. Survey with 41 Practitioners
2. Implementation Gap Analysis
3. Human-Factor Explanations
4
(5) Ecosystem Synthesis
1. Practice Guidelines
2. Recommendations
3. Tooling Needs

Figure 1: Research Workflow: From Specification Analysis to Ecosystem Recommendations

of the ERC ecosystem, and what compliance gaps emerge from deployed contracts?

3.1 Specification Extraction and Encoding

We conducted a manual analysis of 100+ ERC standards through an examination of Ethereum Improvement Proposals (EIPs [14]) to extract canonical specifications. For each standard, we identified: (1) mandatory functions with complete signatures and their four-byte selectors (keccak256 hash), (2) required events with 32-byte topic hashes, and (3) explicit dependency relationships declared in EIP documents. The curation process involved two researchers independently examining each EIP, with cross-validation to ensure accuracy—a necessity due to the heterogeneous formatting across EIPs that precluded fully automated extraction. Each ERC standard was encoded into structured JSON specifications:

- **Mandatory and Dependency Implementation:** Captures the mandatory functions and events required by the standard with dependent standards and adopted extensions. For instance, ERC-721's full configuration includes ERC-165 (*supportsInterface*) as a mandatory dependency, while ERC-2612 includes both ERC-20 and EIP-712 requirements.

Figure 3 illustrates our JSON schema for ERC-1155, showcasing function selectors, event topics, and semantic mappings. This knowledge base enables the subsequent empirical analysis. The JSON data curation file contents are publicly available[1].

3.2 Dependency Graph Construction

From the encoded specifications, we constructed a directed multigraph $G = (V, E)$ to model the ERC ecosystem. Nodes V represent individual ERC standards, categorized as *core* (ERC-20, ERC-721, ERC-1155) or *extensions* (ERC-2981, ERC-4907, etc.). Edges E represent two relationship types: *design-time dependencies* for formal inheritance/extensions declared in EIPs, and *conceptual linkages* for interoperability patterns identified through our analysis.

The resulting dependency network (Figure 2) reveals structural patterns:

- Three primary hubs anchor the ecosystem: ERC-20 (fungible core), ERC-721 (NFT nucleus with the deepest dependency chain), and ERC-1155 (hybrid bridge between paradigms).
- ERC-1155 [21] inherits from both fungible and non-fungible paradigms, concentrating security concerns from both.
- Signature-based standards like ERC-2612 demonstrate dependencies on external cryptographic specifications (EIP-712), creating subtle cross-chain replay risks [16].

3.3 Implementation Practice Analysis

To address RQ1's compliance gaps, we analyze smart contracts across four EVM chains using our specification database, identifying gaps that signal systemic risks.

3.3.1 Empirical Evidence of Implementation Inconsistencies.

Our pipeline processes contracts from four EVM chains, extracting function selectors and matching them against our JSON specifications to classify implementation completeness. We classify a contract as fully compliant if its bytecode implements all mandatory functions, events, and required dependencies for a given standard. Contracts missing any required element are classified as non-compliant (partially implemented).

Why This Analysis Matters: This large-scale analysis reveals an understudied problem: pervasive partial or non-compliant implementations among deployed contracts. As shown in Table 1, significant portions fail to implement mandatory functions or required dependencies.

The ERC-1155 Anomaly: Our analysis identifies ERC-1155 as a critical hotspot with highest partial compliance across all four chains. This anomaly cannot be explained by deployment volume alone—it points to inherent implementation challenges. We hypothesize that ERC-1155's high partial compliance rate stems from its unique position at the intersection of multiple functional paradigms (fungible, non-fungible, batch operations), which potentially creates disproportionate complexity for implementers. This finding serves as a key motivator for RQ2 and RQ3: to understand what risks such complexity creates, and why developers chose to implement it only partially.

Table 1: Implementation Compliance Across EVM Chains

Chain	Raw Contracts	Compliant Contracts (with Dependencies)
BNB Chain	2,308,899	1,602,719
Ethereum	1,114,861	631,220
Polygon	288,611	123,127
Avalanche	96,173	43,805
Total	**3,808,544**	**2,080,603**

3.3.2 From Empirical Patterns to Human Factors.

How This Analysis Motivates Developer survey: These quantitative findings present a puzzle: why do developers consistently deploy partially compliant contracts that risk interoperability failures and security vulnerabilities? The bytecode patterns alone cannot answer this question.

Our multi-chain compliance analysis serves two purposes for the study: 1. **Empirical Validation:** It quantifies the prevalence of

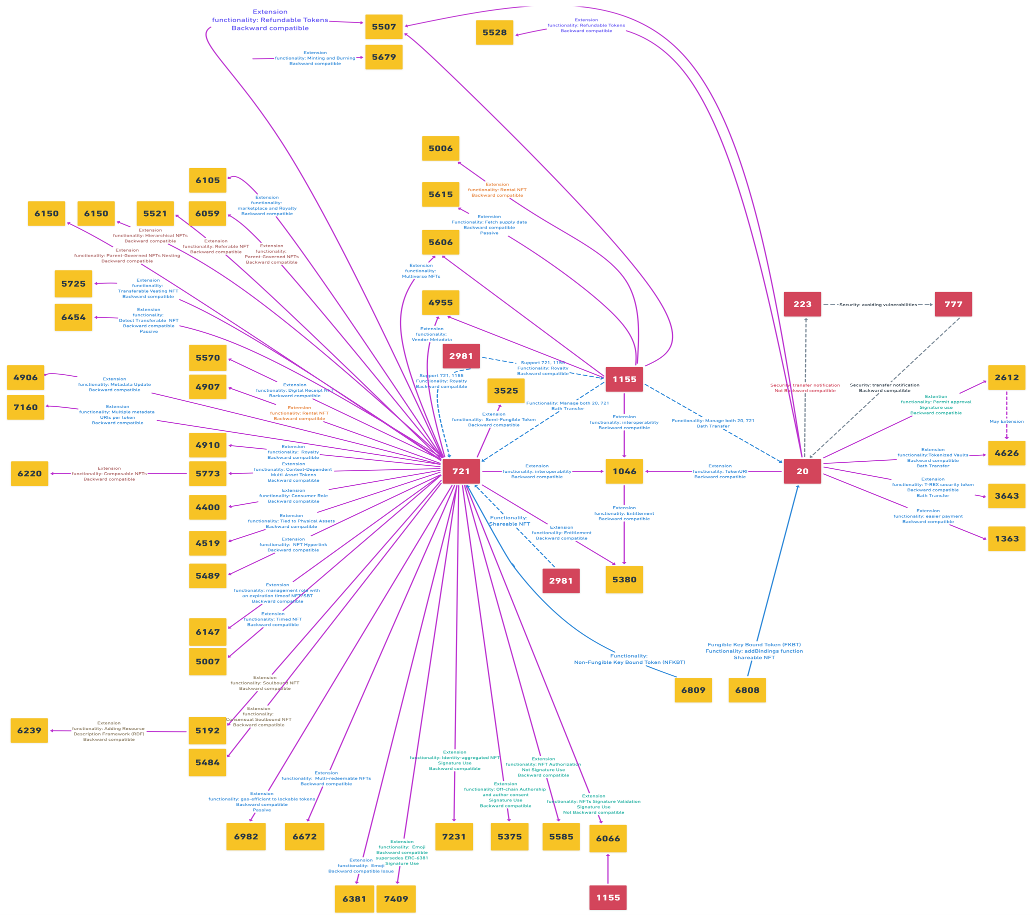

Figure 2: ERC standard dependency network illustrating inheritance chains and interoperability relationships.

real-world implementation discrepancies, compliance gaps that *motivate and inform* our security risk assessment in Section 4, providing evidence that these are not theoretical concerns but widespread ecosystem problems. 2. **Research Catalyst:** The identification of compliance gaps in complex standards like ERC-1155—creates precise, data-driven questions for our developer survey. We can now ask practitioners not just about general challenges, but about the specific implementation difficulties that lead to the observed patterns.

This empirical foundation ensures that our subsequent developer survey (Section 5) moves beyond general discussion to investigate the root causes behind quantifiable ecosystem problems, creating a connection between technical artifacts and human practices.

3.4 Categorization of ERC Standards

Synthesizing insights from the specification analysis, dependency graph, and compliance patterns, we derived nine categories that characterize the ERC ecosystem based on the their functionality (Table 2). These categories are defined by core operational characteristics and their associated security implications, providing the taxonomic foundation for our security risk assessment in Section 4.

The nine categories in Table 2 capture the spectrum of ERC functionality and their inherent security implications. However, these categories describe *what* standards do in isolation. The security question is: how do these functionalities interact and converge in real-world implementations to create vulnerabilities?

The observed patterns of partial implementations in complex standards like ERC-1155, which spans multiple categories provide empirical motivation for this next analytical step. In the following section, we analyze how combinations of these functional characteristics create distinct patterns of vulnerability. We distill the nine categories into four risk dimensions, establishing a framework that explains not just what standards do, but how their design leads to potential security failures.

4 Security Risk Assessment and Categorization

We now present our security risk assessment (***RQ2-What security risks can be derived from the analysis of ERC standards?***), deriving risks from the architecture established in Section 3. Our security risk framework is derived from the taxonomy shown in Table 2. We analyze how combinations of functional characteristics

[1]GitHub repository: https://github.com/BatchTransfer/BATCHAUDIT/blob/main/Specifications.json

Table 2: Categorization of ERC Standards

Category	Functionality	Standards	Primary Security Concern
Fungibility	Asset Type Specification	ERC-20, ERC-721, ERC-1155	Ownership and transfer permission models: Different fungibility types require distinct approval mechanisms, with NFT standards introducing blanket `setApprovalForAll` vulnerabilities.
Extension Patterns	Standard Enhancements	ERC-4907, ERC-2981, ERC-3525	Attack surface expansion through inheritance: Active extensions add state-changing functions that inherit insecure permission patterns from parent standards, propagating vulnerabilities.
Signature Usage	Cryptographic Authorization	ERC-2612, ERC-4494, ERC-5267	Cryptographic validation complexity: Externalizes signature verification to off-chain cryptographic proofs, creating implementation errors in domain construction and replay protection [16, 22].
Off-chain Operations	External Data Integration	ERC-1948, ERC-3668, ERC-5521	External trust assumptions and data integrity: Bridges on/off-chain data requiring proper cryptographic binding, where implementation errors create oracle dependency failures.
Multi-Token Operations	Batch Processing	ERC-1155, ERC-6150, ERC-1363	Atomic coordination of multiple transfers: Batch operations require perfect all-or-nothing execution, where partial failures create inconsistent states enabling selective theft [23].
Receiver Contracts	Interface Compliance	ERC-1155, ERC-777, ERC-1363	Interface compliance requirements: Mandatory callback interfaces create coordination dependencies; missing implementations cause token locking and interoperability failures.
Transfer Compatibility	Enhanced Transfer Mechanisms	ERC-223, ERC-777, ERC-1363	Backward compatibility breaks: New transfer patterns with callbacks may not be supported by existing wallets/exchanges, creating integration failures.
Security Resolvers	Recovery Mechanisms	ERC-20, ERC-777	Privileged access for recovery: Introduces centralized recovery mechanisms that conflict with decentralization principles and create new attack vectors.
Special Operations	Niche Functionality	ERC-4907, ERC-5006, ERC-5528, ERC-6059	Complex state management: Specialized functionality beyond basic transfers increases implementation complexity and creates unique coordination challenges.

create potential vulnerabilities, revealing how the nine categories converge into four risk dimensions. Unlike prior work that analyzes vulnerabilities in isolation [6, 18], we trace, map risks to their functionality, with Table 3 serving as our central explanatory device for this derivation.

4.1 Deriving Security Risks from Functional Analysis

We developed our security risk framework by analyzing ERC standard functionalities, from which we derived nine categories organized by core operational purpose. This derivation follows a three-step analytical process. First, we identified security risk patterns within each category by examining historical security incidents [6, 17, 18], implementation errors [24], and developer challenges. For instance, contract implementations in the Multi-Token Operations category exhibited atomicity failures during batch transfers [23][21]. Second, we traced these patterns to their architectural roots, finding that vulnerabilities often stemmed from design decisions inherent to the category—such as the choice of blanket approvals in NFT standards originating from the Fungibility category's ownership models. Third, we observed that security risks converged into four distinct risk dimensions based on shared root causes and exploitation mechanisms, rather than distributing uniformly across all nine categories.

This convergence is captured in Table 3, which shows how multiple categories combine to create each security risk dimension. The mapping reveals that security risks are not isolated to single functional characteristics but emerge from the interaction of complementary capabilities.

Table 3: Derivation of Risks from Functional Analysis

Risk	Categories	Derivation Rationale
AC	FUNG, EXT, SEC	Standards defining asset ownership (FUNG) establish permission models that, when extended (EXT), propagate insecure patterns like blanket approvals. Recovery mechanisms (SEC) add privileged overrides, creating authorization vulnerabilities.
TO	MTO, REC	Batch operations (MTO) require perfect atomic coordination, while interface mandates (REC) create hard dependencies. Their combination produces coordination failures where partial implementations lead to token loss or inconsistent states [25].
SM	SIG, OFF	Both categories externalize validation to cryptographic proofs, shifting security from on-chain execution to off-chain implementation. This creates subtle errors in domain construction, nonce management, and replay protection that evade conventional analysis [16, 22].
SI	REC, TC, SPE	Interface requirements (REC), compatibility breaks (TC), and specialized state (SPE) create complex interaction webs where single implementation failures compromise entire systems. This convergence produces system-level integration vulnerabilities.

Abbreviations: AC = Access Control and Authorization Risks, TO = Transfer Operation Complexities, SM = Signature Mechanism Vulnerabilities, SI = System Integration Challenges, FUNG = Fungibility, EXT = Extension Patterns, SEC = Security Resolvers, MTO = Multi-Token Operations, REC = Receiver Contracts, SIG = Signature Usage, OFF = Off-chain Operations, TC = Transfer Compatibility, SPE = Special Operations.

Implication: This convergence explains why security risks persist despite available security knowledge. For instance, ERC-1155's manifestation of all four risk types stems from its position at the intersection of multiple categories. This perspective reveals that securing individual implementations is insufficient—the standardization process itself must address these converging risk patterns.

This derivation establishes that the four security risk categories emerge from ERCs' functional architecture, explaining why vulnerabilities persist—some potentially inherent to specification standards rather than implementation errors. It is important to conduct cross-verification of standards to ensure all scenarios are covered for robust security. This shifts analysis from reactive detection to proactive assessment.

Derivation: The mapping reveals that security risks in the ERC ecosystem follow consistent patterns:

- **Access Control Risks** predominantly emerge from standards defining ownership models (Fungibility) that are extended through inheritance chains (Extension Patterns), creating vulnerabilities in approval mechanisms.
- **Transfer Complexities** concentrate in standards combining batch operations (Multi-Token Operations) with atomicity requirements, creating challenges that exceed typical implementation capabilities [26].
- **Signature Vulnerabilities** cluster in standards that externalize validation to cryptographic proofs (Signature Usage, Off-chain Operations), where implementation errors create security gaps that evade conventional analysis tools [16].
- **Integration Challenges** manifest in standards requiring coordination across multiple independent implementations (Receiver Contracts, Transfer Compatibility, Special Operations), where single failures compromise entire interaction chains.

This derivation provides the analytical foundation for our security risk framework, demonstrating that the four risk categories emerge from the functional characteristics of ERC standards rather than from arbitrary classification. The mapping also explains why certain standards exhibit multiple risk dimensions: ERC-1155, for example, spans three categories (Fungibility, Multi-Token Operations, Receiver Contracts) and consequently manifests all four security risk types.

4.2 Primary Security Risk Categories

For each risk category derived in Section 4.1, we examine representative high-risk functions: 1. *setApprovalForAll* (Access Control), 2. *safeBatchTransferFrom* (Transfer Complexities), 3. *permit* (Signature Vulnerabilities), and 4. *onBatchReceived* (System Integration).

4.2.1 Risk Quantification Framework. To assess the severity of each risk category, we employ a three-dimensional quantification framework:

- **Prevalence:** The percentage of contracts affected by the risk, derived from our multi-chain smart-contract implementations and risk analysis (Section 3.3). Prevalence is derived from our implementation compliance analysis. For instance, Access Control risks are highly prevalent because standards like ERC-721 and ERC-1155, which are widely deployed, inherently implement high-risk functions like *setApprovalForAll, safeTransferFrom (Batch).*
- **Impact:** The potential financial loss or system compromise severity. Signature Mechanism vulnerabilities [16, 27] have high impact due to unauthorized token transfers, while System Integration failures cause irreversible token locking.
- **Exploitability:** The technical difficulty for attackers to exploit [24] the vulnerability. Safe transfer and safe batch transfer operation complexities in ERC-721, ERC-1155, and ERC-6150 have a high chance of token loss or lock due to developer implementation errors, whereas access control phishing has high exploitability through social engineering by an attacker.

Overall, ERC-1155 emerges as particularly critical, scoring high across all three dimensions due to its hybrid nature and complex dependency requirements. This quantification builds upon existing vulnerability taxonomies [28, 29] while providing ERC-specific risk metrics. The validity and practical relevance of these risk categories were *empirically investigated* through our developer survey (Section 5), which examines whether developers recognize these risks and whether implementation gaps correlate with the risk categories we identified.

4.2.2 Access Control and Authorization Risks. Access control and authorization risks encompass vulnerabilities arising from granting excessive or inadequately scoped operational privileges. These security issues originate in the fundamental design of early ERC standards, where user convenience was prioritized over security. As shown in Table 3, this risk emerges from the intersection of Fungibility models (defining ownership) and Extension Patterns (adding permission layers). ERC-1155 is a prime offender, inheriting the high-risk ‘setApprovalForAll‘ pattern from ERC-721 while applying it to both fungible and non-fungible token types, thereby amplifying its attack surface.

The canonical implementation illustrates this risk:

```
function setApprovalForAll(address operator, bool approved)
     external {
    require(msg.sender != operator, " Self Approval Error");
    _operatorApprovals[msg.sender][operator] = approved;
    emit ApprovalForAll(msg.sender, operator, approved);
}
```

Listing 1: Approval mechanism of `setApprovalForAll`

When a token owner calls SETAPPROVALFORALL(OPERATOR, TRUE), they authorize that specific operator to transfer *any and all* tokens owned by that address without requiring further approval for individual transactions (Listing 1). This creates a powerful yet potentially dangerous authorization mechanism where: (1) authorization persists indefinitely unless explicitly revoked, (2) no token-level or quantity-based restrictions are possible, and (3) delegation chains enable secondary permissions where operators can further delegate access without the original owner’s knowledge.

Potential Security Risks: The architectural weaknesses in approval mechanisms enable several specific attack vectors. Malicious platforms exploit simplified approval interfaces to trick users into granting permanent permissions. Hacked marketplaces or services provide attackers with immediate access to drain entire NFT collections from all approved users [16][3]. Delegation chain vulnerabilities emerge where each additional operator represents a new attack surface. The lack of granularity, with no built-in mechanisms for time-bound authorizations or automatic expiration, creates persistent exposure windows.

As a result, these blanket approval mechanisms create systemic security risks that propagate across entire token ecosystems, rather than being confined to individual contracts. Standards most affected include ERC-721, ERC-1155, and their numerous extensions where blanket approval patterns propagate through inheritance chains, perpetuating security flaws across the token ecosystem. Our developer survey (Section 5) confirms this risk’s prevalence, with 60% of practitioners recognize phishing risks associated with setApprovalForAll but only 53% expressing confidence in implementing safe alternatives.

4.2.3 Transfer Operation Complexities. Transfer operation complexities encompass vulnerabilities arising from sophisticated asset movement logic that introduce novel failure modes absent in basic token transfers. This category, derived from the Multi-Token Operations and Receiver Contracts categories (Table 3), focuses on inherent risks of batch operations and interface coordination. ERC-1155’s ‘safeBatchTransferFrom‘ is the canonical example of this risk, arising precisely from its combination of these two functionalities: batch processing of multiple token types (Multi-Token Operations) with mandatory callback validation (Receiver Contracts).

The `safeBatchTransferFrom` function in ERC-1155 exemplifies this risk category:

```
function safeBatchTransferFrom(address from, address to, uint256[]
     calldata ids, uint256[] calldata amounts, bytes calldata data)
     external;
```

Listing 2: Batch token transfers

As defined in Listing 2, this function enables atomic transfers of multiple token types in a single transaction, where `ids[i]` maps to `amounts[i]` in equal-length arrays. The complexity stems from coordinating multiple token movements while ensuring all-or-nothing execution, demanding perfect implementation of atomicity across all transfers and proper validation of array lengths. The dependency analysis shows that when partially implemented, ERC-1155 can potentially lead to loss of tokens due to the receiver not being implemented, affecting atomicity and introducing unique coordination requirements.

Batch Atomicity Failures: Threat Vectors and Exploitation. Two specific failure modes enable attacks. **Partial State Updates** occur when some token transfers succeed while others fail within the same batch operation, creating dangerous inconsistencies where token ownership becomes ambiguous. Attackers exploit this by crafting batch operations that intentionally trigger failures for specific token IDs while allowing others to succeed, enabling selective theft while maintaining plausible transaction appearance. **Atomicity Violations** represent failures in the all-or-nothing guarantee, occurring through array length mismatches or incomplete error handling with missing revert condition checks. Exploitation involves designing transactions that exhaust gas or trigger revert conditions after partial state changes, allowing attackers to front-run legitimate batch transfers with gas-griefing attacks.

Standards most affected include ERC-1155 with its batch transfer mechanisms, ERC-6059 with hierarchical transfers, and ERC-1363 with callback-enabled transfers. These security risks demonstrates how functional sophistication often outpaces security implementation maturity, a finding corroborated by our developer survey where 64.3% recognized batch transfer risks but only 42.9% expressed implementation confidence, consistent with patterns observed in prior work on complex smart contract operations [23, 26].

4.2.4 Signature Mechanism Vulnerabilities. Signature mechanism vulnerabilities involve signature validation failures in ECDSA signature validation systems where implementation errors enable unauthorized operations and replay attacks. As shown in Table 3, this risk category emerges from the Signature Usage and Off-chain Operations functional domains, where standards externalize signature validation to cryptographic proofs. Smart-contracts implementing off-chain approvals, particularly ERC-2612 (fungible token permits) and ERC-4494 (NFT permits), are vulnerable to these attacks.

ERC-2612 introduces the `permit` function for gasless token approvals:

```
function permit(address owner, address spender, uint value, uint
     deadline, uint8 v, bytes32 r, bytes32 s) external;
```

Listing 3: Signature of ERC-2612 `permit` function

The `permit` function accepts an ECDSA signature composed of parameters `v`, `r`, and `s`, which must be verified against a signed message containing approval parameters (Listing 3). This introduces additional security requirements that also execute on-chain: whereas transaction validation checks stateful conditions (e.g., nonces, balances), signature-based approvals require precise verification to recover the signer's address. This demands correct construction of EIP-712 domain separators in the respective contracts—which are included in the message hash before signing, and proper validation of the recovered address against the expected approver.

Security Threats and Exploitation Vectors. Signature-based approvals introduce several specific failure modes that enable replay attacks and signature misuse. Chain ID mismatches occur when contracts use incorrect or hard-coded chain identifiers, allowing signatures valid on one network to be replayed on another. Domain separator omissions—where contracts fail to include salt, version, or contract address parameters in the EIP-712 domain—allow the same signature to remain valid across different applications or contract instances. Cross-contract replay becomes possible when signatures lack proper domain binding, enabling operations authorized for one contract to be executed against another. Nonce management failures, including hard-coded nonces, nonce reuse, or improper validation, enable signature replay. Deadline bypass occurs when missing or incorrect deadline validation allows expired signatures to remain valid indefinitely [16, 22] [27]. These violations result in signature misuse: a state where valid signatures authorize operations different from what the signer intended, effectively breaking the binding between signature, domain, and operation context.

At the wallet side, replay attacks become possible when signatures lack proper domain binding. The signature's mathematical verification succeeds, but the validation fails to ensure the signature was intended for the specific domain context: the chain ID, contract address, and version parameters that constitute the EIP-712 domain separator. These parameters are included in the message hash before signing, binding the signature to a specific contract instance and network. Contracts implementing off-chain approvals (ERC-2612, ERC-4494) are vulnerable to these attacks when domain binding is improperly implemented. The survey reveals a knowledge deficit: only 26.3% of developers report sufficient understanding of cryptographic constructs like DOMAIN_SEPARATOR to implement them correctly without expert assistance, underscoring the persistent challenge documented in smart contract security research [22, 27].

4.2.5 System Integration Challenges. System integration challenges capture vulnerabilities emerging from coordination failures between smart contracts, where security depends on consistent interface implementation. As shown in Table 3, this category emerges from the Receiver Contracts, Transfer Compatibility, and Special Operations domains. Both ERC-721 and ERC-1155 manifest this risk category in its most severe form. ERC-1155, in particular, requires receiving contracts to implement the IERC1155Receiver interface while also coordinating complex batch transfers—a combination that creates multiple points of integration failure.

Core Risk: Receiver Contract Compliance The mandatory requirement for receiver contracts to implement specific callback interfaces represents the primary attack surface. Standards like ERC-1155 and ERC-721 require receiving contracts to implement interfaces with callback functions, while ERC-777 mandates `tokensReceived` implementations. These create integration dependencies where single implementation failures can compromise entire interaction chains. The compliance check illustrates this coordination requirement:

```
require(IBatchReceiver(to).onBatchReceived(operator, from, ids,
     values, data) == ON_BATCH_ACCEPTED, "Invalid receiver");
```

Listing 4: Receiver contract compliance check

The compliance check in Listing 4 demonstrates Receiver Interface Implementation Failures: missing or incomplete receiver implementations lead to irreversible token loss (when tokens are sent to contracts that cannot handle them) and transaction failures (when callbacks revert). Absent callback functions cause permanent token locking when transfers revert. Partial implementations with incomplete function signatures or incorrect return values break expected

Table 4: Complete Summary: Security Risk Categories and Developer Insights

Risk Category	**Access Control**	**Transfer Operations**	**Signature Mechanisms**	**System Integration**
Description	Excessive/inadequately scoped permissions	Complex asset movement with atomicity requirements	Cryptographic validation failures in off-chain approvals	Coordination failures between contracts
Function	`setApprovalForAll`	`safeBatchTransferFrom`	`permit`, `DOMAIN_SEPARATOR`	Interfaces (`IERC1155Receiver`)
Affected Standards	ERC-721, ERC-1155, ERC-4907	ERC-1155, ERC-6059, ERC-1363	ERC-2612, ERC-4494	ERC-1155, ERC-777, ERC-223
Prevalence	HIGH (widespread in NFT standards)	MEDIUM (concentrated in multi-token)	MEDIUM (growing)	HIGH (all receiver-based standards)
Impact	HIGH (theft of entire collections)	HIGH (selective theft, locked assets)	HIGH (unauthorized transfers)	HIGH (irreversible token locking)
Exploitability	HIGH (Social engineering)	MEDIUM (requires crafted transactions)	MEDIUM (subtle crypto errors)	LOW (requires missing interface)
Developer Awareness	78.6% recognize phishing	64.3% recognize batch risks	26.3% understand crypto constructs	45.2% recognize receiver hooks
Implement Confidence	54.8% (safe alternatives)	42.9% (batch implementation)	52.4% (permit functions)	51.5% (integration)
Gap*	+23.8 pp	+21.4 pp	-14.3 pp (overconfidence)	-6.3 pp
Experience Gradient	9.1% vs 78.3% accept responsibility	16.7% vs 70.0% aware	30.8% vs 18.2% understand crypto*	22.2% vs 60.8% aware
Key Practice Gap	Risks from secondary approvals	Only 37.1% verify dependencies	71.4% rely on templates	Only 28.6% employ adequate testing
Primary Root Cause	Perpetual approvals without expiry	Atomicity, dependency complexities	Cryptographic knowledge deficit	Cross-standard interface confusion
Attack Vectors	Phishing, hacked marketplaces, delegation chains	Partial state updates, atomicity violations, gas griefing	Chain ID mismatches, nonce failures, deadline bypass	Missing callbacks, partial implementations, return value errors
Priority	MEDIUM (7.1 pp gap)	MEDIUM (9.9 pp gap)	CRITICAL (-20.7 pp gap)	LOW (-1.5 pp gap)

Note: *Inverse relationship—crypto understanding does not improve with experience. ERC-1155 critical across multiple categories. Gap* = Awareness - Confidence.

behaviors. Return value errors with incorrect success/failure indicators cause unexpected transaction outcomes. Cross-standard variation exacerbates these challenges: developers familiar with ERC-721's `onERC721Received` often fail to implement ERC-1155's `onERC1155BatchReceived`, creating silent interoperability failures.

Standards most affected include ERC-1155 (with mandatory receiver interfaces), ERC-777 (with callback requirements), and ERC-223 (with compatibility breaks). These security risks highlight the fundamental challenge: security emerges not from individual component correctness but from perfect coordination across multiple independent implementations. Our survey confirmed this integration gap, with only 45.2% recognizing mandatory receiver hook requirements and just 28.6% employing adequate testing methodologies for these interfaces.

5 Developer Survey: The Human Factors Behind ERC Security Risks

To understand why these risks manifest in practice, we investigate the human factors through developer surveys , we now investigate the human factors that determine whether these risks manifest in practice. This section addresses ***RQ3: How do developers perceive, navigate the implementation challenges?***. Our structured survey with 41 practitioners moves beyond technical analysis to provide an empirical explanation for the compliance gaps observed in RQ1 and the persistence of the vulnerabilities cataloged in RQ2.

We do not merely seek to validate our risk taxonomy; we use it as a precise analytical lens to investigate developer awareness, confidence, and implementation practices. By connecting quantitative survey data to our specific technical findings, we bridge the gap between abstract risk and concrete developer behavior [30]. This approach allows us to measure *awareness-implementation gaps* and identify root causes—such as specification ambiguity, tooling deficiencies, and knowledge fragmentation—that sustain the ecosystem's vulnerability landscape. The insights from this human-context validation are essential for formulating actionable, evidence-based recommendations to address these security risks in RQ4.

5.1 Research Design and Methodology

We designed a *structured survey instrument* with 47 questions to allow for deeper exploration of complex topics. The study received institutional ethics approval. Surveys achieved an 84% response rate, with follow-ups conducted to address potential non-response bias (Appendix D).

This mixed approach ensured quantitative data collection while capturing qualitative insights about implementation challenges with four thematic blocks corresponding to RQ4's core dimensions: (1) Background, Experience and Specification Understanding, (2) Implementation Practices and Challenges, (3) Security Risk Assessment, and (4) Tooling Needs and Ecosystem Future outlook and Adaptation. Participants were recruited through professional networks, developer forums, and blockchain conferences to ensure representation across experience levels.

Connecting Technical Patterns to Human Factors: This survey serves as the bridge between our technical findings in RQ1-RQ2 and actionable recommendations in RQ4. We specifically investigate: (1) whether developers recognize the four security risk categories we derived from functional analysis, (2) what implementation challenges explain the patterns observed in our multi-chain analysis, and (3) what tooling and specification improvements would most effectively address these gaps. By quantifying confidence-implementation gaps across security risk categories, we move from identifying *what* security risks exist to explaining *why* they persist.

5.2 Developer Background and Specification Understanding

Our 41 survey participants included 15 beginners (<1 year, primarily ERC-20), 13 intermediate (1-2 years, ERC-20/721/1155), 12 experienced (2-5 years, multiple standards), and 1 expert (>5 years, complex standards). A majority (68.3%) have 2 years or less experience, indicating a rapidly growing but inexperienced ecosystem. This distribution correlates with implementation behaviors: beginners predominantly implement only ERC-20, while experienced developers handle complex standards like ERC-2612 and multiple standard compositions.

Specification comprehension varies significantly across experience levels. While 48.8% of participants find ERC specifications "clear and easy to implement," this perception increases with experience: only 33.3% of novices (<1 year) report clarity versus 63.6% of experienced developers (2-5 years). This gradient explains observed implementation behaviors—less experienced developers demonstrate higher template dependency (64.3% prefer following existing contracts) and greater difficulty with cryptographic concepts (38.1% struggle with DOMAIN_SEPARATOR construction). This background establishes that security implementation challenges are not uniformly distributed but correlate with developer experience and specification comprehension.

5.3 The Human Dimension of Access Control Risks

Our survey reveals a nuanced but concerning landscape for "setApprovalForAll" risks, the cornerstone of Access Control vulnerabilities. Three patterns emerge that explain why these risks persist despite available knowledge.

High Recognition but Implementation Barriers: A strong majority of developers (60.0%) recognize phishing risks, and over half (52.9%) support time-bound approvals as mitigation, creating only a **7.1 percentage-point awareness-implementation gap**. This suggests developers understand the problem and solution but face practical barriers—primarily marketplace compatibility constraints and implementation complexity.

Experience-Dependent Responsibility Gap: The most striking finding is the dramatic experience divide in responsibility acceptance. While 78.3% of experienced developers accept responsibility for implementing safeguards, only **9.1% of novices do so** ($p<0.001$). This 69.2 percentage-point responsibility gap reveals that ecosystem solutions cannot assume uniform developer accountability. Developers predominantly view this as a serious issue—57.6% consider it 'critical and widespread,' and 44.1% see it as a protocol-level flaw. Yet implementation remains at the individual level, creating a disconnect between problem scale and solution scope.

Connecting to RQ1/RQ2: These findings validate access control as a risk category, but reveal it persists not from ignorance but from *implementation ecosystem constraints*. The moderate awareness gap (7.1 pp) coupled with severe responsibility gaps (69.2 pp novice-experienced difference) suggests solutions must address both technical implementation and developer maturity progression.

5.4 Developer Struggles with Transfer Operation Complexities

Transfer operation complexities represent the most direct correlation between developer capability gaps and observed compliance failures. Our survey reveals why ERC-1155 exhibits the highest partial compliance rate among major standards.

Moderate Gap with Severe Implementation Consequences: The **9.9 percentage-point awareness-implementation gap** (47.1% awareness vs 37.1% confidence) may appear modest, but in the context of atomic batch operations, even minor implementation errors create catastrophic failures. This gap explains the selective theft vulnerabilities observed in deployed contracts.

Experience Progression Masks Knowledge Deficits: Awareness shows strong positive correlation with experience: 16.7% (novices) $\rightarrow$ 54.5% (intermediate) $\rightarrow$ 70.0% (experienced). However, confidence remains low across all levels (37.1% overall), indicating that experience increases risk recognition but not necessarily implementation capability.

Dependency Verification Crisis: Only 37.1% of developers consistently verify dependencies before deployment—a potential failure for standards like ERC-1155 with complex dependency chains. This connects to our RQ1 finding of 33.7% partial compliance; developers aren't omitting functionality intentionally but due to unclear dependency relationships.

The Atomicity-Complexity Trap: Batch operations require atomicity—all-or-nothing execution—a concept that exceeds typical developer mental models, explaining why only 37.1% of developers express confidence implementing these operations correctly. The combination of atomicity complexity (conceptual) and dependency ambiguity (practical) creates a "perfect storm" where even aware developers struggle with correct implementation.

Synthesis: Transfer operation vulnerabilities stem from a *capability implementation mismatch*: developers recognize risks (47.1%) but lack the conceptual understanding and practical tooling for correct atomic implementation, leading to the partial compliance patterns observed in RQ1.

5.5 Cryptographic Knowledge Deficits and Signature Risks

The Signature Mechanism Vulnerabilities risk category stems from contracts implementing off-chain signatures—a mechanism where ERC specifications like ERC-2612 provide interface requirements but delegate critical security decisions to developers. Our survey reveals profound knowledge deficits that explain persistent implementation errors

Cryptographic Knowledge Gap: Only 26.3% of developers report sufficient understanding of cryptographic constructs like *"Signature (ECDSA)"*, *"Nonce"*, *"Deadline"*, and "*DOMAIN_SEPARATOR*" to implement them correctly without expert assistance. This represents the most severe knowledge gap across all risk categories and creates a **negative 20.7 percentage-point gap** where implementation confidence (47.1%) exceeds actual understanding (26.3%). Contrary to typical learning patterns, cryptographic understanding shows an inverse relationship with experience: 30.8% of novice developers (<1 year) understand crypto terms versus 30.8% of intermediate developers (1-2 years) and only 18.2% of experienced developers (2-5 years). This counterintuitive finding suggests that cryptographic complexity may overwhelm developers regardless of experience, or that developers learn to work around rather than understand cryptographic requirements.

Over-Reliance on Tooling Masks Knowledge Gaps: The negative awareness-confidence gap (Table 5) indicates that developers may be implementing signature-based approvals without fully understanding them, relying on templates that provide potentially false confidence. This suggest that signature-related vulnerabilities often stem from subtle implementation errors—such as those documented in [16] when generating signatures using the "permit" method from ERC-2612—that evade conventional analysis tools [22, 27].

Connecting to RQ2: These knowledge deficits explain why Signature Mechanism Vulnerabilities persist despite available documentation (OpenZeppelin implementations) and tooling. When only 26.3% of practitioners understand the cryptographic constructs required for signature-based approvals, protocol-level specifications for digital signatures potentially lead to insecure deployments. This suggests signature mechanism as a distinct and critical risk category requiring specialized educational interventions.

5.6 Tooling and Specification Gaps as Enablers

Beyond category-specific gaps, our survey reveals cross-cutting deficiencies that enable all risk categories. Contrary to expectations, specification clarity is relatively high, but tooling gaps create dangerous implementation shortcuts.

Specification Clarity vs. Implementation Guidance: A majority of developers (65.8%) find ERC specifications "clear and easy to implement," but only 34.2% encounter compatibility issues from differing interpretations. This suggests specifications are reasonably clear *conceptually* but lack *practical implementation guidance*, particularly for complex operations.

The Template Dependency Crisis: Despite reasonable specification clarity, 64.3% of developers prefer following existing contracts rather than implementing from specifications. This template dependency, combined with low confidence in key areas (37.1% for dependency verification), creates widespread propagation of initial implementation errors.

Targeted Analysis Demand vs. Generic Tooling: An overwhelming 80.2% of developers value targeted analysis of specific high-risk functions over generic vulnerability scans. However, current tooling operates in a semantic vacuum, failing to understand ERC-specific requirements and creating both false positives and dangerous false negatives.

Impact: This creates a self-reinforcing cycle: Developers with reasonable specification understanding default to template implementation—driven by convenience (64.3% preference) and tooling gaps that fail to support secure signature mechanism implementation. Vulnerabilities become entrenched as flawed templates propagate. The cycle explains why individual educational interventions may fail—developers lack the tooling infrastructure to translate specification understanding into secure implementation.

Table 5: Implementation Confidence Across Risk Categories

Security Risk Category	Awareness Rate	Confidence	Gap
Access Control	60.0%	52.9%	7.1 pp
Transfer Operations	47.1%	37.1%	9.9 pp
Signature Mechanisms	26.3%	47.1%	-20.7 pp
System Integration	50.0%	51.5%	-1.5 pp

Note: Gap = Awareness - Confidence in percentage points (pp). For Signature Mechanisms, the negative gap indicates implementation needs actual understanding.

The Risk Category Gradient: Our confidence gap analysis (Table 5) reveals a risk gradient that prioritizes intervention strategies: 1. Critical Priority (Signature Mechanisms): -20.7 pp gap suggests immediate educational intervention for developers and revised guidance for standard authors. 2. Medium Priority (Transfer Operations): 9.9 pp gap reveals the sufficient confidence and need for dependency tooling and contract implementations that follow the ERC dependency structure. 3. Medium Priority (Access Control): a positive 7.1 pp gap suggests secure smart contract development and marketplace coordination. 4. Low Priority (System Integration): -1.5 pp near-balance suggests current understanding is adequate. This gradient provides empirical guidance for resource allocation: education on signature validation requirements deserves disproportionate investment given the knowledge deficit and dangerous over-confidence pattern.

5.7 Synthesis: The Socio-Technical Cycle of Risk

Our survey shows that ERC security risks are sustained by a self-reinforcing socio-technical cycle, not just individual mistakes. This cycle has five key components: (1) developers struggle with signature mechanism requirements (only 26.3% understand it fully without expert assistance) (2) responsibility varies dramatically by experience—novices accept little responsibility (9.1%) while experienced developers accept much more (78.3%); (3) despite clear specifications (65.8% find them clear), developers heavily rely on templates (64.3%) due to inadequate tooling; (4) dangerously, developers are over-confident in cryptography, implementing features they don't fully understand; and (5) there's strong demand for better tools (80.2%) that current generic solutions don't meet.

6 Ecosystem Recommendations

We recommend targeted interventions to address ***RQ4: What recommendations to developers, potential improvements to specifications, tooling, and governance can mitigate the identified security risks?***. This section translates our empirical findings into actionable recommendations to address the identified security risks, structured by stakeholder responsibility: standard authors must address specification ambiguities, developers must implement secure patterns for high-risk functions, and the ecosystem must provide supporting tooling and education. Each recommendation is grounded in our survey evidence and risk taxonomy, creating a cohesive framework for ecosystem improvement.

6.1 Recommendations for Standard Specifications and Governance

Our survey reveals that specification ambiguity and governance gaps fundamentally enable the socio-technical risk cycle. With 57.1% of developers encountering compatibility issues from ambiguous requirements and 71.4% supporting stricter security reviews, the standardization process itself requires reform. These recommendations target the root causes identified in our functional analysis, where design decisions in specifications (e.g., approvals without expiry) propagate vulnerabilities across implementations

6.1.1 Time-Bounded Approval Semantics for NFT Standards. The `setApprovalForAll` pattern exemplifies how specification design creates vulnerabilities. Our survey shows nuanced risk-mitigation alignment: 60.0% of developers recognize phishing risks associated with `setApprovalForAll`, and 52.9% support time-bound approval implementations. However, implementation barriers persist due to marketplace constraints and implementation complexity.

We recommend amending ERC-721 and ERC-1155 standards to replace `setApprovalForAll(bool)` with `setApprovalForAll(address,uint256 expiry)`. For existing deployments, this would require a new function to maintain ***backward compatibility*** while enabling time-bound approvals for new integrations.

6.1.2 6.1.2 Standardized Security Risk Profiling.

Developers currently lack guidance on where to focus security efforts, despite 80.2% valuing targeted analysis over generic scans. Our security risk taxonomy provides the conceptual framework, but this knowledge must be integrated into the standardization process itself.

We propose auditing tools to include a mandatory "SECURITY-RISK-PROFILE" section categorizing risk exposure using our four-category framework. For ERC-1155, this would indicate HIGH risk across three categories: Access Control (via `setApprovalForAll`), Transfer Operation Complexity (via `safeBatchTransferFrom`), and System Integration (via receiver interface requirements). This profiling enables risk-aware development, where security effort is allocated proportionally to threat exposure.

6.2 Recommendations for Secure Implementation Practices

Our survey reveals a 9.9 percentage-point awareness-implementation gap for transfer operations, where 47.1% recognize batch transfer risks but only 37.1% confidently implement dependency verification practices.

6.2.1 Atomicity Guarantees for Batch Transfer Operations.

The `safeBatchTransferFrom` function in ERC-1155 exemplifies the Transfer Operation Complexity risk category, where atomicity failures enable selective theft through partial execution. Our analysis shows ERC-1155 has the highest partial compliance among major standards, correlating with developer confidence deficits.

Secure implementation requires enforcing the all-or-nothing invariant: either all transfers in a batch succeed or the entire transaction reverts. This is achieved through pre-validation of all conditions before state modification—checking array length equality, token ID validity, and balance sufficiency for all items before modifying any balances. The implementation must maintain the invariant that the sum of token balances remains constant across the batch, with no intermediate states where some transfers succeed while others fail, as emphasized in batch operation security [26].

6.2.2 Cryptographic Validation for Signature-Based Standards.

Our survey reveals severe cryptographic knowledge deficits, with only 26.% of developers reporting sufficient understanding of cryptographic constructs like `DOMAIN_SEPARATOR`—both how to construct them correctly and how to use them in signature validation. This knowledge gap explains why signature validation vulnerabilities persist despite available documentation. Secure implementation requires defense-in-depth across three validation layers. First, domain separator construction must use dynamic `block.chainid` rather than hard-coded values, preventing cross-chain replay attacks [16]. Second, signature validation must check malleability conditions (s-value bounds), deadline expiration, and nonce sequencing [22]. Third, implementations must test edge cases: expired signatures and cross-contract replay attempts, as demonstrated in formal verification approaches.

6.2.3 Mandatory Interface Compliance Verification.

System integration failures occur when contracts implement standards partially, missing mandatory interfaces required for interoperability. Only 45.2% of developers recognize that receiving contracts must implement specific callback interfaces, explaining widespread token locking incidents.

Secure implementation requires proactive interface management. Before deployment, contracts must verify implementation of all mandatory interfaces declared in standards: `IERC1155Receiver` for ERC-1155 token reception, `IERC721Receiver` for ERC-721, and `IERC777TokensRecipient` for ERC-777. This verification should use ERC-165's `supportsInterface` for runtime compatibility checking, not just compile-time assumptions.

For callback implementations, the checks-effects-interactions pattern is non-negotiable. Functions must validate all inputs and update internal state before making external calls, preventing reentrancy attacks that exploit the callback mechanism. This disciplined approach to interface compliance transforms integration from an afterthought to a core design consideration, addressing the coordination failures that characterize system integration risks.

6.3 Recommendations for Tooling and Educational Infrastructure

Tooling and educational gaps enable the socio-technical risk cycle by failing to catch implementation errors or build developer capability. Survey data shows 80.2% demand targeted analysis tools over generic scanners, while knowledge progression remains experience-dependent: novices show only 22.2% awareness of mandatory interfaces versus 60.8% among experienced developers. These gaps require integrated solutions that combine semantic tooling with structured education.

6.3.1 Specification-Aware Security Analysis Tools.

Current security tools operate in a semantic vacuum, applying generic patterns without understanding ERC-specific requirements [9]. We propose developing security scanners that consume structured specification data—such as our JSON database from Section 3.1—to perform semantic validation. These tools would verify function selector compatibility, check dependency compliance using our mapped relationships, validate cryptographic implementations against EIP templates, and detect partial implementations by comparing deployed contracts against mandatory requirement lists. By understanding ERC semantics rather than applying generic patterns, such tools would address the 80.2% demand for targeted analysis while catching the implementation errors that current tools miss.

6.3.2 Structured Learning Pathways Based on Risk Progression.

The experience-dependent knowledge gaps revealed in our survey indicate that current learning resources fail to support developers through the complexity progression. With 57.1% of developers having <2 years experience, the ecosystem needs structured pathways that build capability systematically

We recommend creating tiered learning pathways organized around our risk taxonomy. The novice pathway would focus on core standards (ERC-20/721) with emphasis on Access Control and System Integration fundamentals. The intermediate pathway would address complex standards (ERC-1155, ERC-2612) covering Transfer Operation atomicity and Signature Mechanism cryptography. The advanced pathway would teach cross-standard dependency analysis and security assessment using our taxonomy as an analytical framework. Each pathway must integrate practical testing requirements, addressing the gap where 71.4% recognize risks but only 28.6% employ adequate testing.

6.3.3 Verified Reference Implementation Catalog. Template dependent development (64.3% of developers prefer existing contracts, Q10) propagates vulnerabilities when templates are insecure. Rather than discouraging this natural developer behavior, the ecosystem should provide vetted alternatives.

We propose maintaining a curated catalog of secure implementations, each including: production-ready code for common standard combinations, integrated test suites with fuzzing configurations for high-risk functions, security analysis mapped to our risk taxonomy, and gas optimization trade-offs with security implications. This catalog would transform insecure copy-paste behavior into guided, verified implementation while serving as an educational resource that demonstrates secure patterns in practice.

The recommendations above form an interconnected framework for addressing the socio-technical cycle of ERC security risks. This approach recognizes that security in standardized ecosystems requires coordinated action across specifications, practices, and infrastructure. By addressing all components of the socio-technical cycle simultaneously, the ecosystem can transition from reactive vulnerability patching to proactive risk management, creating a foundation where security emerges from clear specifications, competent implementation, and supportive tooling rather than heroic individual effort.

7 Discussion and Conclusion

We provide a comprehensive security risk assessment of the Ethereum ERC ecosystem through an integrated methodology. We establish that security risks are systemic, emerging from the functional architecture of interdependent standards (RQ1-RQ2), and are sustained by measurable gaps in developer knowledge and tooling (RQ3).

Limitations and Future Work: Our study has several limitations that suggest directions for future research. First, while our survey sample (n=41) provides rich qualitative insights, larger-scale quantitative studies would strengthen generalizability. Second, our analysis focuses primarily on EVM-compatible chains; future work should explore whether similar patterns exist in non-EVM blockchain ecosystems. Third, our dependency graph captures declared relationships in EIPs but may miss implicit dependencies in real-world implementations. Future work should develop automated dependency extraction from deployed contract bytecode. Finally, we plan to implement the specification-aware security tools recommended in Section 6.3, building upon our JSON database and dependency graph to create practical solutions for developers.

Conclusion: Our study establishes a causal understanding of ERC ecosystem security: (1) Functional complexity and compositional dependencies (RQ1) create inherent systemic risk categories (RQ2); (2) These risks persist due to measurable gaps in developer awareness, cryptographic understanding, and tooling support (RQ3); (3) Addressing this socio-technical cycle requires coordinated interventions across specifications, implementation practices, and tooling infrastructure (RQ4). By integrating technical analysis with human-factors research, we provide both a framework for understanding ERC security risks and an evidence-based roadmap for ecosystem improvement—essential foundations for securing Ethereum's multi-trillion dollar token ecosystem.

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A Ethical Considerations and Data Handling

This study received institutional review board approval (IRB-25-232-A187(1125)). All 41 survey participants provided informed consent; no personally identifiable information was collected. Responses were encrypted, stored securely, and will be retained for five years then destroyed. Blockchain analysis used only public data from official RPC endpoints and explorers. No private keys or address clustering were accessed.

B Research Transparency

All research materials are publicly available at (anonymized GitHub repository): JSON specification database (107 ERC standards with function selectors, event topics, dependencies), analysis pipeline scripts (Python), complete survey instrument (47 questions), and dependency graph data. See Figure 3 for example JSON format. These resources enable independent verification and future research.

By making both our processed data and analysis tools available, we enable independent verification of our findings and lower barriers for future ERC ecosystem research.

- **Complete specification database:** JSON files encoding 107 ERC standards with function selectors (keccak256 hashes), event topics, dependency graphs, and categorization metadata. Example JSON shown in Figure 3. We also provide a Comprehensive ERC Security Analysis in Table 6

Figure 3: Example JSON specification for the ERC-1155.

```
{
 "ERC1155": {
  "selectors": ["01ffc9a7","f242432a","2eb2c2d6","00fdd58e","4e1273f4","a22cb465","e985e9c5"],
  "topics": ["c3d58168c5ae7397...", "4a39dc06d4c0dbc6...","17307eab39ab6107...",
          "6bb7ff708619ba06..."],
  "functions": {
         "supportsInterface(bytes4)": "01ffc9a7",
         "safeTransferFrom(address,address,uint256,uint256,bytes)": "f242432a",
         "safeBatchTransferFrom(address,address,uint256[],uint256[],bytes)": "2eb2c2d6",
         "balanceOf(address,uint256)": "00fdd58e",
         "balanceOfBatch(address[],uint256[])": "4e1273f4",
         "setApprovalForAll(address,bool)": "a22cb465",
         "isApprovedForAll(address,address)": "e985e9c5"
  }, "events": { /* Event mappings omitted for brevity */ }}}
```

- **Analysis pipeline:** Python scripts for multi-chain bytecode processing, function selector extraction, compliance classification, and dependency graph generation (requires: web3.py, pandas, networkx).
- **Survey instrument:** Full questionnaire with 47 questions including branching logic, response options, and administration instructions.

C Threats to Validity

Internal validity: Survey participants self-selected, potentially over-representing developers with strong security opinions. Self-reported proficiency introduces subjectivity. External validity: Four major EVM chains may not represent smaller platforms. Construct validity: Compliance classification captures interface implementation not logical correctness; risk taxonomy represents one possible framework. Mitigations included stratified sampling, pilot testing, and transparent methodology.

D Selection Validity and Bias Acknowledgment

We conducted pilot testing with 3 senior developers to refine question clarity and added examples for complex concepts. Participants were recruited through professional networks, forums, and conferences with stratified sampling by experience. While this may bias toward professionally engaged developers, it precisely targets practitioners most relevant to ERC implementation.

E Statistical Analysis Approach

We used descriptive statistics (percentages, means) and inferential methods with 95% confidence intervals (Wilson score). Experience group comparisons used chi-square and t-tests; correlations used Pearson coefficients with p-values. All analyses used R 4.2.1 (stats package). Reported CIs provide population parameter context given sample size.

Table 6: Comprehensive ERC Security Analysis: Functions, Implementation Insights, and Security Risks

Type & Target Function(s)	ERC Standard	Functional Insights	Analysis Insights & Potential Security Risks
Access Control Related (Approval)			
`setApprovalForAll`, `isApprovedForAll`, `setApprovalForAllForAssets`, `isApprovedForAllForAssets`	ERC-721, ERC-1155, ERC-5773	Authorization enabling **operators** to manage all user tokens. Provides convenience for NFT marketplaces and multi-token platforms.	**Secondory Permits** : Permitted operator grants further permissions without the knowledge of the actual owner **Malicious Operators**: Platforms trick users into granting permanent approvals. **Asset theft**: Compromised operator contracts can drain entire NFT collections. **Lack of granularity**: No scope or time limitations on approvals.
`approveAndCall`, `transferFromAndCall`	ERC-1363	Extends ERC-20 with post-transfer callbacks for atomic operations. Enables complex DeFi interactions in single transactions.	**Unvalidated receivers**: Missing `onTransferReceived` implementations cause token loss. **Front-running**: Authorization signatures can be intercepted.
`_approve(to, tokenId[i])`	ERC-4910	Batch approval mechanism for multiple NFTs. Reduces transaction costs for bulk operations.	**Ownership ambiguity**: Complex hierarchies create unclear ownership states. **Unauthorized transfers**: Missing individual approval checks enable token theft.
Transfer Operations			
`safeBatchTransferFrom`, `safeTransferFrom`, `batchTransfer`	ERC-1155, ERC-721, ERC-6150	Multi-token batch operations enabling atomic transfers of fungible/non-fungible tokens. Critical for gaming and NFT platforms.	**Atomic transfer failures**: Single bug affects all tokens in batch (cascading effect). **Array manipulation**: Incorrect array length validation enables under/overflow attacks. **Receiver bypass**: Missing `ERC1155TokenReceiver` implementations cause irreversible transfers. **Gas exhaustion**: Large batch operations can exceed block limits.
`transfer`, `transferFrom`	ERC-20, ERC-875, ERC-1363	Core token transfer logic with varying safety levels. ERC-20 lacks return values, ERC-223 adds data parameter, ERC-1363 includes callbacks.	**Reentrancy**: Callback-enabled transfers vulnerable to recursive attacks. **Token locking**: Missing receiver implementations trap tokens. **Interface confusion**: Inconsistent implementations break interoperability.
`batchTransferParent`, `batchRefundExtension`	ERC-6150, ERC-5507	Complex UI handling for hierarchical batch operations. Requires synchronized management of token arrays and approvals.	**Array desynchronization**: UI/contract state mismatches cause failed transfers. **Approval confusion**: Complex approval hierarchies create user errors. **Gas estimation errors**: Batch operations unpredictable gas costs.
`nestTransferFrom`	ERC-6059	Enables hierarchical NFT transfers where parent NFTs contain child NFTs. Supports complex ownership structures.	**Recursive depth attacks**: Deep nesting can exceed stack limits. **Circular dependencies**: Infinite transfer loops possible.
`share`, `gift`, `safeMint`	ERC-4907, ERC-5006, ERC-5023	Temporal ownership and specialized transfer mechanisms. Enables NFT rentals, time-limited sharing, and conditional transfers.	**Expiry bypass**: Missing timestamp validation enables indefinite access. **Ownership confusion**: Multiple simultaneous owners create security ambiguities. **Access control flaws**: Missing role checks enable unauthorized sharing.
Signature Mechanisms			
`permit`, `DOMAIN_SEPARATOR`	ERC-2612, ERC-4494, ERC-5267, ERC-4626	Off-chain signature approvals for structured data signing for cross-chain approvals. Domain separators prevent cross-contract signature replay.	**Replay attacks**: Cross-chain signature reuse if domain separators mismatched. **Parameter tampering**: Malicious front-ends can modify signed data. **Nonce manipulation**: Predictable or reused nonces compromise security. **Domain manipulation**: Incorrect chainId or contract address enables cross-chain replay. **Parameter encoding**: Mismatched struct hashes create invalid signatures. **Salt collisions**: Predictable salt values compromise uniqueness.
`_signEdition`, `claim(...)`	ERC-3440, ERC-3135	Complex signature verification for edition-based NFTs and claim mechanisms. Supports limited edition drops and gated access.	**Verification DoS**: Expensive signature checks enable gas exhaustion attacks. **Epoch manipulation**: Time-based signature validation vulnerable to timestamp attacks. **Signature forgery**: Weak randomness in signature generation.
`isValidSignature`, `verifyIdentitiesBinding`	ERC-6066, ERC-6492, ERC-7231	Contract-based signature validation enabling smart contract wallets and revocable signatures. Supports account abstraction.	**Domain inconsistency**: Cross-contract signature validation with mismatched domains. **Revocation bypass**: Delayed or missing revocation checks. **Interface confusion**: Multiple signature standards create implementation errors.
`keccak256(abi.encode)`	ERC-6381, ERC-7409	Custom domain hashing implementations for specialized use cases. Enables gas optimization and application-specific signing.	**Encoding errors**: Incorrect ABI encoding produces invalid hashes. **Deadline bypass**: Missing expiration checks enable stale signature use. **Field omission**: Missing required domain fields compromise security.
System Integration Challenges			
Front-End Implementation Complexity :			
User interaction layer support for-(`eth_sign`, `personal_sign`, `eth_signTypedData_v1` through v4)	ERC-712, ERC-191, ERC-1195	Secondary integration challenges exist at the user interaction layer, where DApp developers face difficulties in correctly implementing signing interfaces.	creates confusion that can lead to API misuse and reintroduce risks like replay attack. signing interface between users and smart contracts.
`Front-end support for permit`, `DOMAIN_SEPARATOR`	ERC-2612, ERC-4494	Front-end must correctly serialize permit structures for wallet presentation. Requires precise parameter alignment with backend.	**UI deception**: Malicious front-ends modify signing data without user awareness. **Wallet incompatibility**: Different wallet implementations break signature validation. **User confusion**: Complex signing messages reduce security awareness.
`transfer(addrs,uint,bytes)`	ERC-223	Non-standard transfer with data parameter breaks ERC-20 compatibility. Requires specialized wallet support.	**Token locking**: Wallets without ERC-223 support cannot receive tokens. **Data corruption**: Incorrect calldata encoding causes failed transfers. **User experience**: Breaks established wallet interfaces and patterns.
Back-End Implementation Complexity :			
`ERC1155TokenReceiver`, `ERC721TokenReceiver`	ERC-1155, ERC-721	Full interface implementation required for contract receivers. Supports batch operations and complex token interactions.	**Interface omission**: Partial implementations cause reverted transfers and locked assets. **Batch failure**: Single failed receiver cancels entire batch. **Gas optimization**: Complex implementations increase contract size and costs.
`tokensReceived`, `onTransferReceived`	ERC-777, ERC-223, ERC-1363	Mandatory receiver callbacks requiring full interface implementation. Enables reactive contract behavior to incoming transfers.	**Token loss**: Missing receiver implementations trap tokens permanently. **Reentrancy gates**: Callback functions must follow CEI patterns. **Registry dependency**: ERC-1820 registry adds deployment complexity.
`hashEIP712Domain(Domain memory)`	ERC-5267	Precise domain hashing requiring all EIP-712 fields. Ensures signature uniqueness across applications.	**Field omission**: Missing salt or version fields create colliding domains. **Chain confusion**: Incorrect chainId enables cross-chain replay. **Upgrade incompatibility**: Domain changes break existing signatures.
`vaultInitialize`, `mint`, `burn`	ERC-4626	Vault operations with complex access control and validation logic. Supports yield-bearing token wrappers.	**Unauthorized minting**: Weak `_beforeTokenTransfer` hooks enable supply manipulation. **Ownership bypass**: Missing role checks in administrative functions. **Cap manipulation**: Incorrect limit enforcement enables inflation attacks.
On-chain data integration	ERC-1948	Direct on-chain data storage/retrieval requiring real-time synchronization. Enables dynamic NFT metadata.	**Data tampering**: Off-chain data sources vulnerable to manipulation. **Synchronization failures**: Front-end/back-end state mismatches. **Gas optimization**: Expensive storage operations enable DoS attacks.