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Ai–Blockchain-Enabled Halal Traceability for Cross-Border Certification Harmonization: A Framework for Digital Halal Assurance

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ABSTRACT

This study addresses the increasing complexity of cross-border halal trade, where fragmented certification regimes and differing regulatory and fiqh-based approaches raise verification costs and weaken trust. The purpose of this research is to develop and evaluate a digital halal assurance framework that enables Artificial Intelligence (AI)–blockchain halal traceability to support cross-border certification harmonization by making compliance evidence interoperable, verifiable, and auditable. The study uses a qualitative multiple-case design involving regulators, certification bodies and auditors, manufacturers and suppliers, logistics providers, and laboratories. Data were collected through document analysis, semi-structured interviews, and expert review workshops, and analyzed using thematic analysis with cross-case synthesis to derive design requirements. Results show that harmonization relies on institutional arrangements for recognizing evidence; three outputs are pivotal: a shared minimum evidence baseline, a rule-based and updateable equivalence mapping, and a trust registry with accountability and revocation oversight. These elements also shape system architecture toward permissioned consortium governance. Interoperability is the main bottleneck because evidence is dispersed across heterogeneous formats; a minimum data set, selective disclosure, and a hybrid off-chain/on-chain architecture with standardized interfaces and schema versioning are needed to reduce manual reconciliation. Blockchain functions as an evidence engine that anchors audit trails, integrity proofs, and revocation-aware verification via smart contracts. The study concludes that harmonization requires aligning governance, data standards, and evidence mechanisms, and recommends phased implementation and support measures to avoid excluding small and medium enterprises.

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1. Introduction

In the period 2025–early 2026, the halal industry is moving from a "growing market" narrative to a high-value global ecosystem that simultaneously faces cross-border governance pressures, supply chain integrity demands, and value-based consumer preferences (ethics–sustainability). The State of the Global Islamic Economy (SGIE) 2024/25 report shows that Muslim consumer spending in the halal real economic sector (food, pharmaceuticals, cosmetics, fashion, travel, media) has reached around US$2.43 trillion in 2023 and is projected to increase in 2028, signaling the scale of the market that drives the need for a more reliable halal compliance and proving system (Sidarto et al., 2024). At the same time, the SGIE release emphasizes growth and opportunity signals that explicitly lead to digital-based halal verification as well as strengthening trade connectivity between countries (*SMIIC REPORT*, 2025).

Indonesia, the complexity of halal governance is also strengthening along with the phase of halal certification obligations which are affirmed starting October 18, 2024 for certain product groups that have a direct impact on business compliance and the need for more efficient audit/traceability infrastructure (BPJPH, 2024). Institutionally, the agenda for standardization is becoming increasingly urgent because disparities in standards/conformity assessment regimes have the potential to create double costs (re-certification) and trade frictions; SMIIC (OIC) places the harmonization of standards as a mechanism for reducing technical barriers to trade and increasing intra-OIC trade (*SMIIC REPORT*, 2025). Recent developments also show the strengthening of the joint recognition architecture through the SMIIC-IFHAB collaboration to encourage multilateral recognition arrangements (MRAs) so that halal-certified products can move across countries without re-certification (*SMIIC REPORT*, 2025).

The literature of the last 5–10 years has been grouped around several major themes. The first theme is blockchain-based digital assurance to lock data integrity and reduce the chance of manipulation in the halal supply chain; an empirical study in Malaysia, for example, proposes a sustainable blockchain framework to strengthen supply chain integrity and highlights implementation challenges that are typical for SMEs (Ali et al., 2021). This theme is in line with behavioral/adoption research that questions whether blockchain-based halal traceability will become a "hype or reality", by placing institutional factors and halal orientation strategies as determinants of stakeholder participation intentions (Sidarto et al., 2024). The second theme is the integration of AI–blockchain as a more operational compliance system: AI is positioned for anomaly/non-compliance detection and audit automation, while blockchain ensures immutability and audit trails. A holistic framework that combines AI, knowledge graphs, smart contracts, and blockchain points the way towards more efficient and auditable pre-certification screening (Sunmola et al., 2025). The strengthening of this integration agenda can also be seen in the AI-blockchain implementation framework to improve traceability, integrity, and certification processes in the halal supply chain (W. Khan & Nomani, 2020). The third theme emphasizes AI for halal authentication and traceability e.g. on ingredient/product authentication and fraud detection which is mapped as a "transformative slice" for the modern halal industry (Rabbani et al., 2021). Finally, there is a more technical and performance-oriented theme of system engineering, such as the Halal Chain model that combines blockchain, IoT, and smart contracts with performance evaluation (e.g., tamper detection and throughput) while containing the idea of jurisdiction-adaptive smart contracts to accommodate the diversity of standards (Yakubu et al., 2025).

Although the literature has confirmed the potential of technology as a key enabler of halal integrity, some knowledge gaps still stand out. First, much of the work still focuses on conceptual design/frameworks or limited technical testing, while discussions of how these digital solutions

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meet the cross-jurisdictional standardization regime are still relatively under-operational. This is crucial because the cross-border MRA agenda (e.g. SMIIC–IFHAB) explicitly targets the reduction of re-certification and the harmonization of conformity assessments—but there have been no studies linking the architecture design of the technology to the governance needs of the MRA (*SMIIC REPORT*, 2025). Second, adoption constraints such as cost, interoperability, and regulatory alignment are often recognized but have not been developed into implementation designs that test the readiness of certification institutions and business actors in the context of fast-moving policies (Sunmola et al., 2025). Third, the Industry 4.0 study on the halal meat supply chain emphasizes that the barriers to technology integration and regulatory alignment are still large and require a gradual implementation design; however, the integration of inter-actors (regulator–LPH/CB–industry–logistics) that is directly connected to harmonization demands has not been sufficiently proven through studies that combine technical and governance dimensions (Ellahi et al., 2025).

The novelty of this research is therefore directed at the development/assessment of an AI–blockchain implementation model for halal traceability that is explicitly aligned with the need for cross-border recognition (MRA) and policy realities (e.g. certification obligations), so that its contribution is not only technical, but also institutional and cross-jurisdictional (W. Khan & Nomani, 2020). This research aims to: (1) formulate and validate the framework for the implementation of an AI-blockchain-based halal traceability system that can strengthen data integrity, auditability, and automation of compliance checks; (2) analyze how the framework can be operationalized in ecosystems that are strengthening certification and supervision obligations (e.g. the Indonesian context), including their implications for business actors and related institutions (BPJPH, 2024; (3) review interoperability and governance prerequisites so that digital systems can support cross-border recognition (e.g. MRA schemes developed through SMIIC–IFHAB) so that the burden of re-certification can be reduced without diminishing the credibility of conformity assessments (COMCEC/SMIIC, 2024; SMIIC, n.d.; IFHAB, n.d.). (4) expanding the literature on AI–blockchain integration in halal supply chains by testing the suitability of framework design to certification needs that demand end-to-end assurance (Sunmola et al., 2025).

The central argument of this study is that strengthening the modern halal industry requires a combination of (a) standard governance and cross-jurisdictional recognition and (b) a digital proof infrastructure that is able to produce verifiable evidence from upstream to downstream. The literature suggests AI is increasingly relevant for authentication/monitoring and fraud detection, while blockchain and smart contracts can provide immutable records as well as automated verification—but their effectiveness is highly dependent on stakeholder interoperability and acceptance (Rabbani et al., 2021)). On the other hand, advanced system designs (e.g., blockchain–IoT and jurisdiction-adaptive smart contracts) promise performance and resilience to manipulation, but still need to be tested for compatibility with diverse certification regimes (Yakubu et al., 2025). Furthermore, the Industry 4.0 study on halal supply chains confirms that cost barriers, interoperability, and regulatory alignment are recurring implementation issues, so research that examines cross-actor implementation designs is relevant (Ellahi et al., 2025). Departing from these arguments, the method section will explain the research design and data collection strategy to assess feasibility, stakeholder acceptance, and governance needs so that the AI–blockchain model can function in the context of cross-border certification and harmonization.

The urgency of this study is strengthened as market reports confirm the growth of global halal spending and at the same time indicate that the next halal economic opportunities are accelerated by digitalization and verification innovations. At the governance level, cross-border harmonization and MRA initiatives (SMIIC–IFHAB) mark a policy shift from fragmented certification to a shared recognition ecosystem—one that demands infrastructure-ready evidence to maintain credibility . In the domestic context, the strengthening of halal certification obligations and post-certification supervision also increases the need for an efficient and scalable implementation model (BPJPH, 2024). Therefore, this research is relevant to bring together the agenda of harmonization of standards with the design of technology that can be operated in a dynamic policy ecosystem.

2. Literature Review

Harmonization of cross-border halal certification

Cross-border halal certification harmonization is generally understood as an effort to harmonize requirements, audit procedures, and recognition of conformity assessment results so that halal-certified products can be accepted in other jurisdictions without costly re-certification. However, the literature shows a difference in emphasis: some studies view harmonization as a standard convergence, while others emphasize equivalence-based mutual recognition without having to equate all fiqh methodologies and regulatory designs. The Indonesia-Malaysia study confirms that differences in regulatory approaches and certification body fiqh methodologies can create trade frictions and increase cross-border costs, so that harmonization is more realistically built through a map of equivalence of requirements and recognition protocols (Ramadhani & Mahomed, 2026a). A broader comparative perspective also shows institutional and procedural variation between countries (e.g. Indonesia–Malaysia–Mexico) that makes the "operational definition" of harmonization dependent on domestic governance (Putri & Rohmah, 2023). Meanwhile, the study of AI-blockchain implementation in halal supply chains places harmonization as an institutional–technical problem: digital systems must be able to translate cross-jurisdictional rules into verifiable evidence (Hussain et al., 2022).

In the literature, cross-border harmonization can be categorized into several forms: (a) harmonization of substantive standards (alignment of halal definitions, critical points, and material/process criteria), (b) procedural harmonization (audit, inspection, surveillance, and nonconformity handling), and (c) recognition-based harmonization (MRA) that emphasizes the equality of certification results. Ramadhani and Mahomed (2026) show that differences in fiqh methodologies have an effect on the determination of material and process criteria, so that harmonization is often more feasible at the procedural and recognition level than the full unification of substantive standards. On the supply chain side, blockchain-based halal frameworks and smart contracts have given rise to a new aspect: harmonization also concerns data standards and evidence interoperability (audit log format, chain-of-custody, and revocation status) so that they can be verified across borders (Hew et al., 2020). The next category is adoption-readiness-based harmonization: studies on participation intentions in blockchain-based halal traceability systems confirm that institutional pressures, regulatory legitimacy, and organizational halal orientation influence the adoption of cross-actor systems that are prerequisites for digital MRA (Soonsan et al., 2025).

Critically, harmonization studies often stop at the diagnosis of regulatory/methodological differences, but have not sufficiently explained how "cross-border recognition" can be operationalized into a cheap, fast, and auditable verification mechanism. The Indonesia-Malaysia study emphasizes the urgency of harmonization, but the next contribution space is to design governance artifacts (e.g. equity matrices) that are directly connected to the needs of digital proofing and MRA workflows (Ramadhani & Mahomed, 2026a). Other cross-country comparative studies show procedural and institutional variations, but the limitation is descriptive (SWOT) biases

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without examining the impact of such friction on the cost of cross-border verification or the design of certification data interoperability (Sidarto et al., 2024). On the technological side, the AI–blockchain framework for certification/traceability proposes technical integration, but the gap is the lack of testing of how it negotiates differences in fiqh/regulation rules between countries into a ruleset that can be verified across jurisdictions (Khan et al., 2025).

Blockchain-based halal traceability

Halal traceability refers to the ability to track the origin of ingredients, production processes, distribution, and halal compliance status end-to-end, so that halal claims can be proven through auditable evidence trails. Differences in definitions emerge in their focus: some studies emphasize traceability as a physical (chain-of-custody), while others emphasize traceability as the integrity of information (data provenance, immutability, and audit trail). Blockchain is positioned as a distributed record-keeping infrastructure that improves data integrity because records are difficult to change and can be verified across parties. A case study of Indonesian poultry shows that blockchain is able to strengthen the transparency of halal labels and process recording, overcoming the weaknesses of centralized systems that are vulnerable to manipulation (Sidarto et al., 2024). In the Malaysian context, blockchain-based frameworks derived from real-world implementation in multiple halal supply chains emphasize the role of smart contracts to lock in halal process compliance (Tan et al., 2020). Meanwhile, adoption studies highlight that blockchain traceability is not automatically accepted: participation intent is influenced by institutional legitimacy and organizational halal orientation strategies (Ramadhani & Mahomed, 2026b)

The categorization of blockchain-based halal traceability can be seen from: (a) blockchain type (permissionless vs permissioned/consortium), (b) data type (on-chain vs off-chain with hash), (c) tracking object (batch, lot, unit), and (d) verification mechanism (QR/RFID, IoT sensor, audit report). The "sustainable blockchain" framework for halal supply chains emphasizes realistic configurations for SMEs: a consortium model involving certification actors, manufacturers, and logistics, as well as an emphasis on cost challenges, technological readiness, and data access governance (Sidarto et al., 2024). Other models such as HalalChain highlight the categorization of functions: decentralized verification, real-time compliance, and automation of checks through smart contracts, with the aim of reducing the risk of fraud and data tampering (Yakubu et al., 2025). At the conceptual level of implementation, the framework of real implementation groups halal data points (materials, processes, certificates, audits) and formalizes process logging to close the gap of "fragmented information" between actors (Sunmola et al., 2025).

Critically, many blockchain-halal studies have been successful in demonstrating improved data integrity, but their limitations often lie in three areas: (1) wide-scale empirical validation across countries, (2) interoperability across systems and across certification bodies, and (3) data governance (who writes/certifies data, how conflicts are resolved). The Malaysian SME study emphasizes implementation challenges (cost, capability, and business model changes), but does not fully examine how consortium designs will interact with differences in cross-border certification regimes (Nawaz et al., 2025). The Indonesian poultry case study provides context-specific evidence that blockchain helps transparency, but its limitation is generalization: an effective design for a single commodity/company is not necessarily compatible with cross-border multi-actor structures (Hew et al., 2020). Meanwhile, models such as HalalChain emphasize real-time automation and compliance features, but the research gap is to test whether the rule engine and smart contracts can map variations in halal standards between jurisdictions without giving rise to veiled re-certification (Faiqoh, 2024).

AI–blockchain integration for "digital halal assurance" and harmonization

"Digital halal assurance" can be conceptualized as the ability of a system to produce evidence of halal compliance that can be verified digitally—sustainable, auditable, and selectively shareable across parties. AI–blockchain integration expands the meaning of assurance: blockchain provides immutability and trail audits, while AI provides analytical capabilities (anomaly detection, risk classification, document compliance checks) that support continuous assurance. The holistic AI–blockchain framework places AI as an automation engine for compliance checks and irregularity identification, while blockchain locks the trail of verification decisions/results so that they can be audited (Ali et al., 2021). AI studies for halal authentication and traceability show a wide range of applications (computer vision, NLP, ML) to detect fraud, validate composition, and improve supply chain transparency (Guest et al., 2006). On the management side, AI–blockchain integration is positioned as an innovation for religious compliance that must be translated into operational certification and traceability processes (Braun & Clarke, 2006).

The categorization of AI–blockchain integration in halal traceability generally includes: (a) AI functions (risk scoring, anomaly detection, document intelligence, supplier profiling), (b) blockchain functions (credentialing, provenance logging, revocation tracking), and (c) integration levels (partial at a certain point vs end-to-end). The AI–blockchain operational framework for halal supply chains maps integration on three goals: traceability, integrity, and improvement of the certification process; but emphasizes the need for a clear implementation design (actors, data flows, verification mechanisms) (Ramadhani & Mahomed, 2026b). Another holistic framework proposes a more "technical" integration through the merging of AI with blockchain for compliance checks and risk management, with the central issue of fragmented information and the difficulty of tracking provenance (Sunmola et al., 2025). From the domain side, AI reviews add categorization based on authentication objects (materials, processes, labels), data types (sensors, documents, images), and fraud scenarios, so that AI is understood as a contextual assurance amplifier, not just generic automation.

Critically, the AI–blockchain integration literature still faces a major gap: many studies emphasize the technical benefits, but have not adequately tested how the system becomes a cross-border "harmonization bridge"—that is, turning regulatory differences/standards into acceptable digital evidence through mutual recognition mechanisms. AI–blockchain frameworks for compliance offer an integration structure, but their limitations are often in the form of a lack of discussion of cross-jurisdictional standard mapping and governance of evidence acceptance (who is authorized to receive, when additional audits are needed). In the realm of AI, authentication reviews emphasize detection capabilities and transparency, but the gap is how AI results (risk/anomaly scores) translate into valid certification procedures and be accepted across countries without creating biases, false positives, or procedural conflicts (Rabbani et al., 2021). The study of AI–blockchain innovations for religious compliance underscores the need for an implementation framework, but the next research contribution space is to test interoperability + governance designs that explicitly lead to cross-border certification harmonization.

3. Methodology

This study adopts a qualitative approach using a multiple-case study design to examine how an AI–blockchain-enabled halal traceability framework can support cross-border halal certification harmonization. A multiple-case design is suitable because the phenomenon is socio-technical and context-dependent, shaped by interactions among regulatory regimes, certification practices, supply chain operations, and digital infrastructures. Case study methodology is particularly appropriate when investigating “how” questions in real-world settings where the boundaries between the

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phenomenon and context are not clearly evident (Yin, 2018). In addition, building insights across cases enables analytic generalization by identifying recurring patterns and boundary conditions rather than producing statistical generalization (Eisenhardt, 1989). The unit of analysis is the end-to-end halal traceability and verification process, including how compliance evidence is generated, shared, validated, and recognized across organizations and jurisdictions.

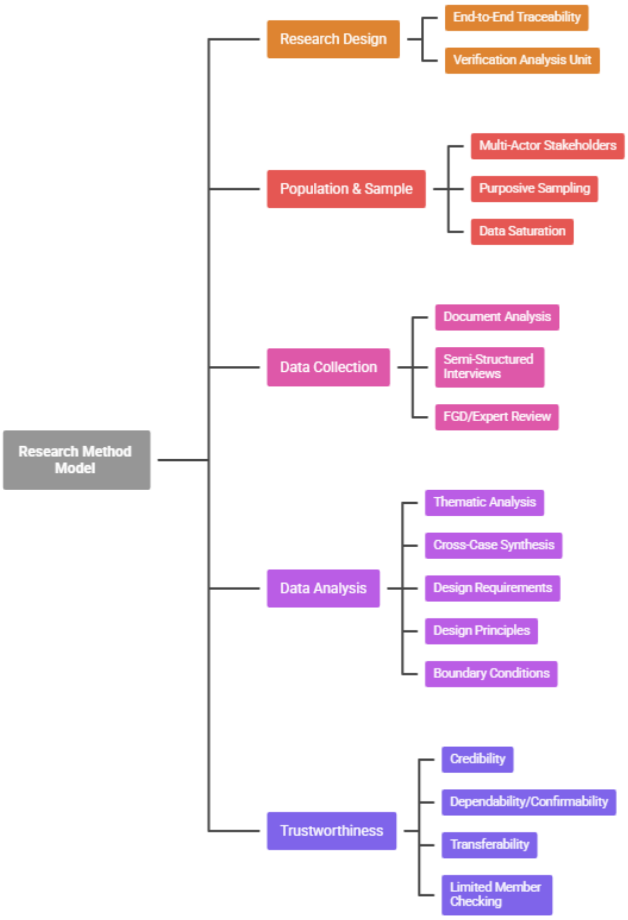

Figure 1. *Research methode model for Qualitative multiple-case study*

The study population comprises key stakeholders in the halal ecosystem who are directly involved in certification, auditing, traceability, and compliance assurance. These include: (1) halal regulators/authorities; (2) certification bodies/halal inspection institutions and auditors; (3) industry actors (manufacturers and critical ingredient suppliers); (4) logistics and distribution providers (including cold-chain operators where relevant); (5) testing laboratories and/or accreditation-related actors; and (6) technology providers or system integrators (optional) responsible for traceability, auditability, or digital assurance systems. A multi-actor population is necessary because halal assurance is enacted through interdependent practices across the supply chain and governance system, and qualitative inquiry is well suited for capturing such complexity (Ishtiaq, 2019) (Creswell & Poth, 2018).

Participants are selected using purposive sampling to ensure information-rich cases relevant to the research problem (Patton, 2015). Selection criteria include: (a) direct experience with halal certification, auditing, or halal supply chain governance; (b) involvement in traceability practices and evidence verification; and (c) decision-making or operational responsibility related to cross-organization or cross-border compliance processes. Sample size follows the principle of data saturation, meaning interviews continue until no substantively new themes emerge (Guest, Bunce, & Johnson, 2006). To ensure multi-actor coverage, the study targets approximately 12–20 informants distributed across stakeholder groups, with flexibility depending on saturation and access conditions.

Data are collected through three primary techniques to support triangulation and depth:

1. Document analysis of relevant regulations, certification guidelines, audit and surveillance procedures, certificate formats, and operational traceability documentation (e.g., SOPs, supplier records, laboratory reports, logistics logs). Documentary evidence is a core case study data source that strengthens contextual grounding and supports corroboration of interview claims (Yin, 2018).
2. Semi-structured interviews to elicit stakeholder perspectives on traceability practices, minimum evidence requirements, interoperability constraints, fraud risks, and time/cost drivers of cross-border verification and re-certification. Semi-structured formats balance comparability across participants with flexibility to probe emergent issues (Kvale & Brinkmann, 2009).
3. Focus group discussion (FGD) or expert review (optional) to validate the proposed framework and test the feasibility of equivalence rules and mutual recognition workflows through realistic cross-border scenarios. Group-based elicitation can surface shared assumptions, disagreements, and practical constraints relevant to governance and implementation (Kaiser et al., 2023).

Data are analyzed using thematic analysis, a flexible approach for identifying, analyzing, and reporting patterns (themes) within qualitative data (Braun & Clarke, 2006).The procedure involves: (1) transcription and familiarization; (2) initial coding guided by sensitizing concepts (traceability, evidence integrity, interoperability, certification governance, cross-jurisdiction recognition); (3) inductive refinement of codes and themes; (4) mapping relationships among themes; and (5) synthesizing findings into framework components (e.g., minimum data sets, digital evidence flows, AI-enabled anomaly/risk detection functions, and blockchain-enabled audit trails). For multiple cases, cross-case synthesis is applied to compare patterns across cases and derive transferable design principles and boundary conditions (Eisenhardt, 1989).

Trustworthiness is strengthened through established qualitative criteria: credibility, transferability, dependability, and confirmability (Ellahi et al., 2025). Credibility is enhanced via source triangulation (multiple stakeholder groups) and method triangulation (documents, interviews, and where applicable FGD/expert review). Limited member checking is used to confirm interpretations of key themes and sensitive inferences (Ellahi et al., 2025) Dependability and confirmability are supported by maintaining an audit trail documenting coding decisions, analytic memos, and iterative framework revisions (Ellahi et al., 2025). Transferability is addressed through "thick description" of context and explicit articulation of boundary conditions, consistent with analytic generalization principles (Yin, 2018).

4. Results And Discussion

Harmonized Governance Layer

The analysis indicates that the governance layer is the primary determinant of whether an AI–blockchain traceability system can meaningfully support cross-border certification harmonization. Across stakeholder groups, participants consistently described harmonization not as "one universal halal standard," but as an institutional arrangement for recognizing and validating evidence produced under different regulatory and fiqh-based frameworks. In practice, harmonization was perceived to hinge on three governance outputs: (1) a shared minimum evidence baseline, (2) a rule-based equivalence mechanism, and (3) a cross-border trust and accountability model. Regulators and certification bodies emphasized that without an agreed Minimum Assurance

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Requirements (MAR) package—covering critical control points, audit scope, laboratory evidence (where applicable), surveillance frequency, and revocation rules—digital traceability would merely accelerate the exchange of incompatible documents. This finding aligns with the idea that fragmentation of certification regimes drives inefficiency and re-certification costs, making harmonization increasingly urgent as trade grows (Guest et al., 2006).

A second result concerns the operational form of harmonization: stakeholders favored equivalence mapping over full standard unification. Equivalence mapping was described as a structured comparison between jurisdictions that classifies requirements into categories such as "fully equivalent," "equivalent with additional evidence," or "non-equivalent." Importantly, interviewees suggested that equivalence cannot be static; it must be versioned and updateable because certification policies, fatwas, and audit procedures change. This result supports the view that harmonization should be built as a living governance artifact rather than a one-time agreement. A third result is that cross-border governance requires a trust registry: a maintained list of recognized certification bodies, laboratories, and auditors, including scope, accreditation status, and revocation history. Participants argued that digital credentials only create trust if the issuer is recognized and continuously monitored—consistent with broader harmonization efforts that rely on formal recognition arrangements and standardized conformity assessment practices (*SMIIC REPORT*, 2025).

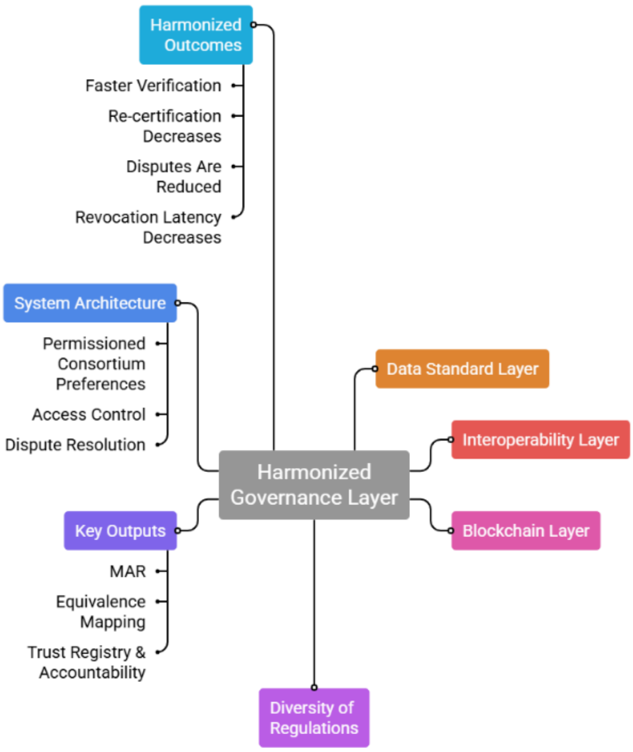

Figure 2. *Harmonized governance layer mechanism for cross-border halal certification harmonization.*

The figure visualizes the following mechanism flow:

1. Diversity of regulations and fiqh, triggers fragmentation of certification regimes and re-certification costs
2. This fragmentation drives the need for the Governance Layer as an "operating system" of harmonization

3. The Governance Layer produces 3 key outputs: MAR (Minimum Assurance Requirements), Equivalence Mapping (versioned & updateable), Trust Registry & Accountability
4. These three outputs allow for the creation of interoperable and credible evidence across jurisdictions
5. Governance also shapes the system architecture (permissioned consortium preferences, access control, dispute resolution)
6. The interoperable architecture and evidence then results in harmonized outcomes (faster verification, re-certification decreases, disputes are reduced, revocation latency decreases)

Finally, the findings show that governance requirements strongly shape system architecture. Stakeholders preferred a permissioned consortium model for the evidence layer because it better supports accountability, access control, and legal enforceability than public, permissionless designs. They also emphasized that governance must define roles and decision rights for dispute resolution (e.g., conflicting audit outcomes, contested non-conformance, revocation appeals), as well as rules for data access, confidentiality, and cross-border data transfer. These results suggest that the governance layer functions as the "operating system" of harmonization: it defines what counts as valid evidence, who can issue it, how it is verified, and how disagreements are settled.

These results advance a key argument: technology can enable harmonization only if governance first makes evidence interoperable. AI and blockchain can strengthen integrity, auditability, and continuous monitoring, but they cannot resolve foundational institutional differences unless translated into shared evidence semantics and accepted verification procedures. This supports a socio-technical interpretation of halal assurance in which traceability is not merely a data problem but a legitimacy problem—evidence must be recognized as authoritative across jurisdictions. The governance layer therefore contributes theoretically by clarifying the mechanism linking regulatory fragmentation to operational inefficiency: fragmentation increases the costs of verifying, translating, and re-performing assurance activities; governance reduces these costs by establishing an equivalence structure and a recognized issuer network.

The preference for equivalence mapping also has important implications. It suggests that the most realistic pathway to cross-border harmonization is not full convergence of halal standards, but managed diversity: jurisdictions retain doctrinal and regulatory autonomy while agreeing on a minimum baseline and a structured approach to "difference handling." This resonates with comparative insights that fiqh methodologies and regulatory designs differ in ways that make full unification difficult, yet still allow harmonization via agreed recognition mechanisms (N. Khan et al., 2025b). In this sense, the governance layer becomes a formal bridge between legal–religious plurality and supply chain efficiency.

The trust registry requirement further indicates that mutual recognition is not a one-off decision but an ongoing compliance relationship. Even with verifiable credentials and immutable logs, trust deteriorates if issuer oversight is weak, revocation is delayed, or surveillance is inconsistent. Governance must therefore incorporate revocation and surveillance protocols as first-class elements. A practical implication is that the AI–blockchain system should embed governance artifacts—such as MAR definitions, equivalence rules, and recognized issuer lists—as versioned, auditable, and updateable objects, ideally linked to decision logic (e.g., smart-contract-based rule checking). This directly addresses a common limitation in prior technology-focused frameworks: they propose digital traceability but under-specify how institutional recognition decisions are made and updated over time.

At the same time, the governance layer introduces constraints and trade-offs. Stronger harmonization governance can increase coordination costs upfront (negotiating MAR, equivalence matrices, and dispute mechanisms) and may face political and doctrinal resistance. In addition, a permissioned consortium model may raise concerns about power asymmetries (e.g., dominant

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jurisdictions setting baselines that disadvantage smaller exporters) and potential exclusion of SMEs due to compliance burdens. These tensions suggest future research directions: examining fairness and inclusivity in harmonization governance, testing different equivalence models (binary vs graded equivalence), and evaluating governance performance using measurable outcomes (re-certification reduction, verification time, dispute frequency, and revocation latency).

Overall, the governance layer is the critical bridge between institutional harmonization and digital assurance: it converts regulatory plurality into a structured recognition system, enabling AI–blockchain traceability to function as credible cross-border evidence rather than merely a faster documentation pipeline.

Data Standard Layer and Interoperability Layer

The results of the analysis show that the interoperability layer is the most technical and institutional "bottleneck" in realizing cross-border certification harmonization. Stakeholders tend to agree that the main problem is not the absence of data, but rather the misalignment of the structure, meaning, and quality of data exchanged between actors and between jurisdictions. Field findings indicate that evidence of halal compliance is often scattered in heterogeneous formats (certificates, audit reports, test results, logistics logs, supplier documents) and is difficult to consolidate into a single "data language" that can be verified consistently. As a result, the cross-border verification process relies heavily on manual interpretation, which triggers verification redundancy and increases the cost of re-certification. This pattern is consistent with the literature that highlights that blockchain-based halal traceability systems can fail to be a cross-border solution if they are not accompanied by data standardization and evidentiary interpretation rules (Jabeen et al., 2025).

The second outcome confirms the need for a minimum of cross-border agreed data sets as a prerequisite for interoperability. Stakeholders propose a relatively stable set of minimum data elements, including: product/batch identity, origin of materials and suppliers, process critical points (HCPs), audit results and nonconformity status, laboratory evidence (where relevant), certificate status (active/revoked), and chain-of-custody logistics. Interestingly, some informants emphasized that interoperability does not necessarily mean opening up all data; What is more important is the ability to selectively disclose the evidence needed according to the need for verification. These findings are in line with the direction of a holistic framework that places evidence interoperability at the core of "digital halal compliance" and demands data models that are able to link audits, provenance, and compliance status end-to-end (Nugraha et al., 2025).

The third outcome relates to the technical strategy considered the most feasible: stakeholders are more in favour of hybrid off-chain/on-chain architectures to overcome privacy constraints and storage burdens. Detailed data (e.g. full audit reports, COA labs, supplier documents) is stored off-chain in a managed repository, whereas blockchain stores hashes/metadata as proof of integrity and audit trails. At the same time, they emphasize that interoperability standards should define APIs and data schemas in order for cross-system evidence exchange to be automated and auditable. A number of technology actors mention the importance of schema governance (versioning, field changes, backward compatibility) to prevent "interoperability decay" when regulations or certification formats change. These findings are in line with blockchain-based traceability models that emphasize the need for structured data architectures and automated verification mechanisms (Jabeen et al., 2025).

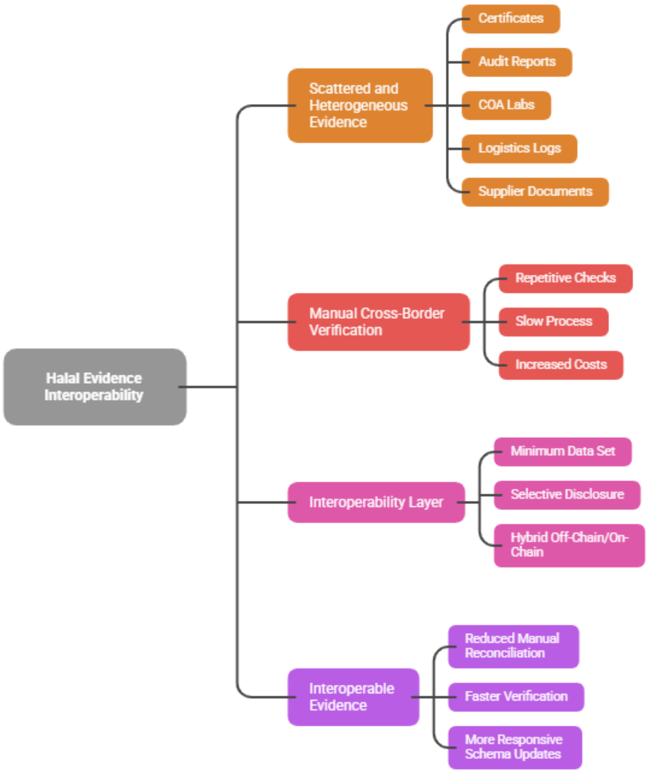

Figure 3. *Interoperability-layer mechanism for cross-border halal certification harmonization*

The image visualizes the following mechanism flow:

1. Halal evidence is scattered and heterogeneous (certificates, audit reports, COA labs, logistics logs, supplier documents) so that the structure–meaning–quality of data is not aligned between actors and between countries.
2. As a result, cross-border verification is still manual (interpretation & reconciliation of evidence), triggering repetitive checks, slowing down the process, and increasing the cost of re-certification.
3. The interoperability layer serves as a "translator" so that evidence can be read consistently across jurisdictions through 3 mechanisms:
    a. Minimum data set (minimum mandatory data for verification),
    b. Selective disclosure (for evidence that is necessary to maintain confidentiality),
    c. Hybrid off-chain/on-chain + API/schema governance (detail off-chain, hash/metadata on-chain, skema terstandar & versioning).

The output is interoperable evidence (standard semantics, auditable exchanges, auto-verify ready) resulting in reduced manual reconciliation, re-certification, disputes, as well as faster verification and more responsive schema updates.

The above findings make it clear that interoperability in the harmonization of halal certification is not just an issue of file format, but a matter of semantic evidence and equality of interpretation. In other words, the interoperability layer serves as a "translator" between the variation of certification regimes (rules, audit procedures, documentation practices) and the need for digital systems to perform consistent verification. If the governance layer establishes what is

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considered valid evidence, then the interoperability layer determines how that evidence is represented, exchanged, and understood across jurisdictions. Here, the emerging theoretical contribution is the mediation mechanism: the fragmentation of standards → inconsistency of the evidence data → the redundancy of verification → cross-border inefficiencies. Interoperability lowers transaction costs by converting evidence from local artifacts into "verification objects" that can be read across systems (Nurhayati et al., 2025).

The preference for minimum data sets and selective disclosure also points to an important compromise: cross-border harmonization requires transparency, but industry still requires protection of business confidentiality. Therefore, the most realistic approach is not to "open up all data", but to build verifiability through evidence summaries, standard metadata, and cryptographic integrity (e.g., hashes), and only sharing detailed data when necessary (e.g., additional audits or fraud investigations). These findings answer a weakness that often arises in blockchain-halal studies: focusing on immutability without adequately operationalizing privacy, data ownership, and cross-actor access rules (Ghalih et al., 2025). Thus, the interoperability layer becomes the meeting point between compliance demands and the reality of data governance.

However, the interoperability layer faces methodological and implementive risks. First, data standardization often leads to over-standardization: the scheme is too strict to accommodate differences in audit/fiqh procedures, or too loose to produce truly comparable evidence. Second, weak schema governance leads to version inconsistencies and lowers the reliability of cross-border verification. Third, cross-system integration (APIs, master data, actor identities, commodity codes) requires investment, which has the potential to burden SMEs and widen the adoption gap (Talib, 2024). Therefore, the study suggests evaluating the interoperability layer not only with technical indicators, but also institutional-operational indicators such as: reduction in re-certification, cross-border verification time, amount of manual reconciliation data, frequency of disputes due to interpretation of evidence, and latency of data schema updates as regulations change (Jabeen et al., 2025). Overall, the interoperability layer is a prerequisite for AI–blockchain traceability to work as a cross-border digital proof infrastructure, rather than just digitizing local documentation.

Blockchain as an "evidence & immutability layer"

The results of the analysis show that the blockchain layer is perceived not as a "repository of all halal data", but as an evidence engine that ensures that proof of compliance is not easily manipulated, can be traced back, and can be audited across actors. Stakeholders particularly certification bodies/auditors and industry parties value blockchain lies in the ability to create a consistent audit trail: who publishes evidence, when, against which batch, and how its status changes (e.g., active, suspended, revoked). These findings are consistent with the literature emphasizing blockchain to improve data integrity and transparency in halal supply chains, especially when evidence comes from various actors who do not fully trust each other (Hassan & Fernando, 2025).

The second result shows a strong consensus on hybrid off-chain/on-chain architecture. Detailed data (full audit reports, lab COAs, supplier documents, and sensitive operational records) is more feasible to store off-chain due to privacy, cost, and capacity considerations, while blockchain stores hashes, metadata, and pointers as "fingerprint" evidence to maintain integrity and non-repudiation. Practically, this pattern is considered more realistic for cross-border contexts because it allows for the selective exchange of evidence without sacrificing business confidentiality. These results are in line with a blockchain-based halal traceability framework that emphasizes the importance of architectural design that is able to balance transparency and confidentiality (N. Khan et al., 2025a).

The third result confirms the importance of smart contracts as a verification automation layer. Informants find smart contracts useful for: (1) recording the issuance of certificates/credentials in a standardized manner, (2) locking in the rules of proof validity (e.g., certificates are only valid if the issuer is in the trust registry), and (3) speeding up status checks (active/revoked) and preventing the use of expired or revoked certificates. In cross-actor discussions, revocation status is assessed as a tipping point, as delays in status updates can create reputational gaps and compliance risks. These findings are parallel to halal blockchain models that propose automated verification and real-time compliance as the key to reducing fraud and improving compliance assurance (Abdul et al., 2025).

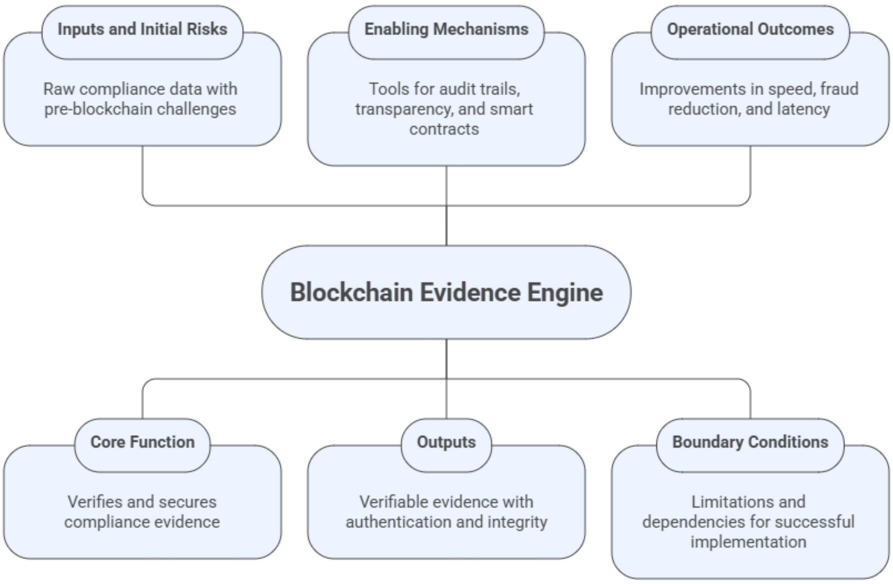

Figure 4. *Blokchain evidence-engine mechanism for halal tracebility and cross-border assurance*

The above findings make it clear that the role of blockchain in the AI–blockchain framework for halal traceability is primarily epistemic: blockchain transforms proof of compliance from mere administrative documents into artifacts that can be consistently verifiable across parties (Sidarto et al., 2024). If the governance layer establishes legitimacy (who is authorized to publish evidence and its acceptance rules), and the interoperability layer aligns the representation of evidence (data standards), then the evidence & immutability layer ensures that the evidence exchanged is authentic, intact, and has an auditable track of change. Theoretically, this reinforces the argument that cross-organizational "trust" can be shifted to evidence-based "verification", especially in ecosystems involving multiple actors and potential conflicts of interest (Jabeen et al., 2025).

The preference for hybrid off-chain/on-chain designs confirms a trade-off that is often overlooked in blockchain's popular narrative: total transparency is not the primary goal; What is more important is verifiability and auditability with controlled costs and risks. The hash+metadata strategy allows the system to prove the integrity of documents without exposing the contents of the document extensively in line with the industry's need to maintain supplier confidentiality, formulation, and processes. Thus, this layer serves as a mechanism of selective transparency: evidence can be cryptographically verified, while the disclosure of details can be limited to certain conditions (additional audits, anomaly investigations) (Hew et al., 2020).

However, the findings also point to important limitations that need to be anticipated. First, blockchain doesn't solve the "garbage in, garbage out" problem: if the initial data is wrong or the evidence is made uncrediblely, the blockchain simply locks in the error. Therefore, the evidence layer must be coupled with strict governance (evidence issuing authorities, accreditation,

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surveillance) and validation mechanisms (e.g. field audits, lab verification, or AI-based anomaly detection at other layers). Second, smart contracts bring the challenge of rule rigidity: if the verification rules are too rigid, the system can reject cases that are substantively compliant but have different procedures; If it is too loose, the system fails to be a safety. It demands documented rule versioning and exclusion procedures. Third, integration costs and technical capacity requirements can make it difficult for SMEs, as highlighted by halal blockchain implementation studies that emphasize barriers to adoption Therefore, evidence layer evaluation needs to include indicators that are not only technical (immutability, audit trail completeness), but also operational-institutional: latency of renewal status revocation, consistency of evidence issuance between institutions, reduction of document-based disputes, and reduction of the incidence of fraud/misalignment of cross-border evidence (Yakubu et al., 2025).

Overall, the blockchain layer as a "proof engine" is the foundation for cross-border harmonization to move from static document-based recognition to auditable digital proof, provided it is combined with data standards, issuer governance, and adaptive rule update mechanisms.

5. Conclusion

Overall, this study shows that the success of AI–blockchain-enabled halal traceability for cross-border certification harmonization depends on the system’s ability to transform “compliance documents” into interoperable, verifiable, and auditable digital evidence. Cross-stakeholder findings converge into three overarching themes. First, harmonization is not understood as the creation of one universal halal standard, but as an institutional arrangement for recognizing and validating evidence across jurisdictions with different regulatory and fiqh-based frameworks (*managed diversity*). In this arrangement, the governance layer functions as the “operating system” of harmonization through three core outputs: Minimum Assurance Requirements (MAR), equivalence mapping that is *versioned and updateable*, and a trust registry and accountability model to determine who is authorized to issue evidence and how that evidence is governed and monitored.

Second, the interoperability layer emerges as the most technical yet institutional bottleneck. The central problem is not a lack of data, but misalignment in the structure, meaning, and quality of data exchanged across actors and jurisdictions. This misalignment forces cross-border verification to rely on manual interpretation, producing redundant checks and increasing re-certification costs. Interoperability is enabled through a combination of a minimum data set, selective disclosure, and a hybrid data architecture supported by APIs, standardized schemas, and schema governance to ensure consistent interpretation while protecting business confidentiality. Third, the blockchain layer is positioned as an evidence engine, not a data warehouse. It provides immutability, audit trails, state tracking, and non-repudiation, especially through a hybrid off-chain/on-chain design and smart-contract verification for issuer validation, real-time status checking, and revocation management. Conceptually, the findings support a shift from trust-based compliance to verification-based compliance, where institutional legitimacy (governance) and evidence readability (interoperability) become prerequisites for blockchain to deliver credible cross-border assurance.

This study has several methodological and conceptual limitations that constrain the scope of its claims. First, the generalization is analytic rather than statistical; the models and themes describe mechanisms applicable to a “class of harmonization problems,” and their transferability depends on jurisdictional context, commodity type, and supply chain structure. Second, if artifact evaluation is primarily scenario-based or expert-validated, the evidence is strongest for conceptual feasibility, governance logic, and interoperability design, rather than for real-world system performance metrics (e.g., latency, throughput, or actual implementation costs). Third, restricted access to sensitive data (detailed audit reports, logistics records, lab data) may limit deep testing of evidence quality and integrity; consequently, the “garbage-in–garbage-out” risk cannot be fully mitigated through design alone. Fourth, smart-contract rules may introduce rigidity; without rule versioning and documented exception procedures, the system may reject cases that are substantively compliant but procedurally different. Finally, inclusion and fairness concerns—particularly adoption burdens for SMEs—require further empirical testing to ensure that digital harmonization does not create market exclusion.

Building on the findings and limitations, the research reconstruction advances three priority directions. First, future studies should develop and test a phased implementation model by piloting the framework in priority commodities and trade corridors, using measurable indicators such as re-certification reduction, cross-border verification time, frequency of document-based disputes, and revocation update latency. Second, institutional elements should be strengthened by operationalizing governance artifacts: a machine-readable equivalence matrix, a cross-border trust registry design, and integrated surveillance–revocation protocols linked to verification logic (e.g., smart-contract-aware policy checks). Third, on the data and technology side, future work should test evidence semantics (ontology/knowledge graphs), robust schema governance (versioning and backward compatibility), and secure selective disclosure mechanisms acceptable to regulators. To address "garbage-in–garbage-out," reconstruction also emphasizes coupling the evidence engine with validation mechanisms (audits/lab tests) and extending the framework with AI-based anomaly detection for continuous, risk-triggered assurance. Through these refinements, the contribution moves from a conceptual mechanism model toward an implementable framework that can be empirically validated across jurisdictions while extending the literature on evidence-driven halal certification harmonization.

Author contribution statement

Conceptualization, methodology, investigation, and writing—original draft: Ita Marianingsih. Literature review, data curation, and visualization: *Salim.* Formal analysis, writing—review & editing, and supervision: Sadiq Ibrahim Mijinyawa. All authors reviewed and approved the final manuscript.

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