



Governing halal integrity: Socio-technical pathways to digital transformation and innovation

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Abstract

Purpose – This study develops and field-tests an explainable Halal Integrity Risk Score (HIRS) to examine whether IoT-enabled and ledgered traceability can improve halal compliance, strengthen auditability, and support risk-based, maqāṣid-consistent oversight in halal logistics.

Methodology – Using an 18-month panel covering 118 halal-certified facilities and 1,247 product lines (dairy, ready-to-eat meals, confectionery, and frozen meats), this study evaluates a digital assurance system combining IoT sensors (temperature, humidity, proximity, GPS) and append-only traceability records with selective blockchain hashing. Causal effects were estimated through staggered difference-in-differences with event study diagnostics, while the HIRS was validated through logistic modelling, ROC-AUC, Brier score, and calibration assessment.

Findings – Relative to the controls, major non-compliance declined by 16.8%, first-attempt audit pass rates increased by 7.4 percentage points, and traceability completeness rose by 12.6 percentage points. The mechanisms include earlier detection, with temperature-excursion minutes declining by 28.3% and median time-to-intervention shortening from 56 to 19 min. The HIRS demonstrated strong predictive power (ROC-AUC 0.79, Brier score 0.142), confirming that risk features such as segregation proximity and route deviations can support calibrated compliance triage.

Implications – The results suggest that halal digital transformation is most effective when sensing, traceability, risk scoring, and alert governance are integrated into operational routines rather than being deployed as isolated technologies. This provides a roadmap for firms, certifiers, and regulators to transition to data-driven, measurable halal integrity governance.

Originality – This study contributes a field-validated, auditable halal risk metric and causal evaluation framework. This represents a significant step in translating digital traceability into a quantifiable governance tool that aligns technological capabilities with religious compliance requirements.

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Introduction

The halal industry intersects with moral aspirations, market scale, and regulatory complexity. Its animating commitments, namely lawful permissibility (ḥalāl), wholesomeness (ṭayyib), and consumer protection from harm, are realized not only through theological injunctions but also through the everyday mechanics of procurement, processing, logistics, certification, and audit. As value chains lengthen and diversify, these mechanics are increasingly mediated by digital infrastructures that sense, record, analyze, and automate the process. In this context, digital

transformation is not a superficial overlay of information technology or a narrow exercise in process automation. It is a strategic and organizational reconfiguration in which digital capabilities become constitutive of how halal values are created, assured, and communicated. In management research, digital transformation is understood as a firm-level transformation in which digital technologies reshape business models, organizational capabilities, and value creation processes (Verhoef et al., 2021). This view is consistent with broader digital transformation scholarship, which emphasizes that digital change affects not only technological infrastructure but also business strategy, organizational arrangements, and wider socio-economic relations (Kraus et al., 2021). Read in halal contexts, transformation redesigns core activities, rearticulates relationships among firms, certifiers, regulators, and consumers, and rebases trust on data-driven evidence alongside institutional reputation.

The halal domain intensifies these dynamics because assurance is inseparable from material flows. Integrity concerns ontological status, namely whether products have been kept free from prohibited inputs, cross contact, and process deviations. This condition imposes non negotiable requirements for segregation, identity preservation, traceability, and transparency across globally distributed networks. Halal supply chain management is therefore not reducible to downstream certification, since it requires the management of sourcing, handling, storage, transportation, and distribution in ways that preserve both halal and *ṭayyib* qualities until the point of consumption (Khan et al., 2018). Recent work on halal logistics further shows that physical segregation, process redesign, and operational control are central to preserving halal status, especially when halal products move through complex logistics environments that may also handle non halal goods (Ziegler et al., 2022). A review of halal supply chain research similarly identifies halal integrity, contamination prevention, limited adoption of halal logistics, and the need for more operationally rigorous models as persistent research concerns (Kurniawati & Cakravastia, 2023). Practically, this implies logistics architectures that continuously demonstrate control, not merely document it intermittently. These architectures rely on pervasive sensing to evidence conditions, automated identification to maintain chain of custody, and tamper evident data structures to strengthen provenance claims. Such capabilities shift assurance from episodic, paper based verification toward continuous, data centric validation.

Internet of Things technologies have therefore been promoted for food and pharmaceutical halal chains, particularly in temperature sensitive segments where *ṭayyib* requirements converge with safety regulation. IoT instrumentation compresses the epistemic distance between event and evidence. Conditions in containers, processing rooms, and retail coolers are rendered as time stamped telemetry and exception alerts, producing audit trails that support real time interventions and retrospective accountability. In supply chain management more broadly, IoT has been shown to support visibility, monitoring, coordination, and data driven decision making across major supply chain processes (Ben-Daya et al., 2019). In the halal food supply chain specifically, IoT applications are associated with traceability, certification monitoring, halal status authentication, livestock management, and improved operational efficiency, although their adoption is constrained by cost, technological maturity, regulation, and user acceptance (Rejeb et al., 2021). Cold chain monitoring research also demonstrates the relevance of RFID, wireless sensor networks, and temperature monitoring systems for reducing food safety risks and improving control over perishable products (Badia-Melis et al., 2018). When integrated with digital ledgers or robust event databases and certification systems, such monitoring can support continuous halal assurance rather than periodic certification snapshots. Blockchain based traceability frameworks are particularly relevant here because they strengthen the transparency and integrity of recorded events across food supply chains, although their effectiveness still depends on data quality, governance design, and adoption readiness (Ellahi et al., 2023; Gálvez et al., 2018; Kouhizadeh et al., 2021). These systems can also expose trade offs, such as those between cost minimizing consolidation and contamination risk in mixed load routing, that reshape managerial and regulatory priorities.

This study is theoretically grounded in three complementary lenses that clarify both design choices and governance implications. First, a socio technical systems view treats transformation as

the co design of processes, roles, and technologies, so that instrumentation and operating procedures evolve together rather than in isolation. This is important because digital halal assurance cannot rely on sensors, databases, or dashboards alone. It also depends on human routines, organizational accountability, certification procedures, and inter firm coordination. Second, risk based regulatory principles hold that oversight should be targeted to risk and proportionate to potential harm. The Organisation for Economic Co-operation and Development (OECD) regulatory enforcement framework stresses that inspection and enforcement should be risk focused and proportionate, with resources allocated according to the level of risk and the expected reduction of harm (Organisation for Economic Co-operation and Development, 2018). Third, value sensitive design aligns technical architectures with maqāṣid al-Sharī'ah concerns, including dignity, fairness, harm avoidance, and consumer protection. This alignment requires explainable scoring, auditable provenance, and the possibility to contest and correct model driven decisions. Value sensitive design is useful in this context because it treats values not as external ethical additions but as design requirements that shape technological systems from the outset (Hendry et al., 2021). For risk scoring, this also requires attention to calibration and interpretability, since poorly calibrated predictive systems may generate misleading risk estimates and produce disproportionate regulatory or managerial responses (van Calster et al., 2019). Together these lenses motivate the emphasis on explainability, calibration, and proportionality in halal digital assurance.

Despite the rapid diffusion of digital tools, two gaps persist in scholarship and practice. First, causal evidence linking specific digital investments, such as cold chain telemetry, electronic chain of custody, or machine vision inspection on slaughter lines, to halal integrity outcomes remains limited. Conceptual models, review articles, and case-oriented discussions have expanded the field, but there remains a need for stronger empirical designs capable of separating technology effects from contemporaneous shifts in management attention, product mix, or policy change. This gap is visible in halal supply chain research, where many studies still operate at the conceptual, strategic, or general supply chain levels, while fewer studies provide operational-level evidence on how digital technologies alter measurable integrity outcomes (Kurniawati & Cakravastia, 2023; Rejeb et al., 2021). Second, the integration of digital transformation research and normative frameworks that uniquely shape halal assurance remains underdeveloped. The maqāṣid al-Sharī'ah map naturally onto safety, transparency, and fairness in supply chain governance; however, design patterns that operationalize this alignment, including value-sensitive data governance, fairness by design in risk scoring, and grievance mechanisms for suppliers, are rarely specified for halal contexts. Without such integration, digital projects risk optimizing efficiency proxies while neglecting what counts for integrity, accountability, and social legitimacy.

The present study addresses these gaps by developing and empirically testing a theory of change in which digital traceability and real-time monitoring reduce integrity risk through improved detection and deterrence of deviations, faster corrective actions that limit the propagation of non-conforming lots, and organizational learning that designs risky configurations, such as mixed load routes without adequate separation. The analysis focuses on cold-chain-intensive halal food categories and certification-sensitive logistics operations, where failure modes are consequential for both ṭayyib and halal status and where digital instrumentation is sufficiently mature to support rigorous evaluation. To make the empirical strategy accountable, the evaluation is positioned within contemporary differences in differences scholarship that addresses staggered adoption, dynamic treatment effects, and heterogeneity across adoption cohorts (Callaway & Sant'Anna, 2021; Sun & Abraham, 2021). This methodological framing is important because digital adoption in supply chains rarely occurs simultaneously across facilities. It is usually phased, uneven, and shaped by the organization's readiness.

Accordingly, this study pursues three objectives and contributions. It introduces an explainable Halal Integrity Risk Score that aggregates telemetry and handling events into an auditable 0–100 index calibrated against independent audits. It estimates the causal impact of IoT-enabled operations on compliance outcomes via a staggered adoption difference in differences design with event study diagnostics. It also articulates a governance pathway that operationalizes risk-based and maqāṣid-consistent oversight through transparent scoring criteria and contestable

triggers. The expected outcomes include decision-grade evidence for managers, certifiers, and regulators, as well as a replicable blueprint for aligning operational sensing, organizational capability building, and proportionate regulation in halal supply chains. The following sections review the relevant literature and theoretical foundations, detail the empirical design, and present the results and implications.

Literature Review

Scholarship on the halal industry converges on a dual emphasis: the chain wide nature of integrity under Shariah and the role of digital technologies in operationalizing that integrity at scale. Integrity is not reducible to end product inspection, since it emerges from disciplined controls at every node, including procurement, storage, handling, transport, documentation, and communication among supply chain actors. In halal food industries, halal supply chain management has been shown to contribute directly to halal integrity assurance because integrity depends on coordinated practices that cover sourcing, production, logistics, and organizational control rather than certification as an isolated administrative event (Mohamed et al., 2021). A systematic review of halal supply chain research also indicates that the field has increasingly moved from general discussions of halal products toward questions of engagement, quality control assurance, production and distribution processes, operational support, and the institutional arrangements required to protect halal status across the whole supply chain (Indarti et al., 2021). The implication is that assurance must remain attached to the product through space and time rather than being asserted retrospectively at the point of audit. This chain property renders integrity a matter of both physical controls, including segregation, cleanliness, and temperature, and informational fidelity, including traceability, tamper resistant records, and chain of custody. These requirements make halal assurance dependent on architectures that synchronize material flows and data flows.

Digital transformation literature offers concepts and tools to structure these architectures while cautioning against treating technology as an overlay rather than a reconfiguration of core processes. Digital transformation is best understood as a process in which digital technologies disrupt existing value creation paths and require organizations to redesign their strategies, structures, and routines in response to these disruptions (Vial, 2019). This view is reinforced by organizational studies that describe digital transformation as a broader shift toward malleable organizational designs, continuous adaptation, and digitally mediated business ecosystems (Hanelt et al., 2021). Read in halal contexts, digital transformation points to assurance designed into logistics and quality operations through sensing, event logging, exception management, and accountable documentation, instead of an after-the-fact reporting layer. This also implies new accountabilities: when digital metrics inform certification surveillance or inspection targeting, the evidentiary basis for decisions must be auditable, explainable, and proportionate to risk. In short, transformation is best approached as the co-design of operational, informational, and governance systems that together make integrity legible and enforceable.

Within food and pharmaceutical value chains, IoT instrumentation has become central to continuous monitoring and real-time alerts, particularly where temperature, humidity, handling, and segregation must be controlled. Sensor networks compress the interval between events and evidence, enabling the prompt detection of deviations and the creation of credible audit trails. Cold chain research has long emphasized that temperature management is crucial for preserving the quality and safety of perishable products because even small failures in refrigerated storage and distribution can compromise product conditions before they reach consumers (Aung & Chang, 2014). For halal applications, these capabilities map onto critical control points: temperature telemetry substantiates *ṭayyib* conditions, door and proximity sensors can evidence segregation, and digital signatures at handover nodes support the chain of custody claims. When routinized into standard operating procedures, telemetry shifts organizations from reactive remediation toward preventive design by turning exception handling into a site of organizational learning.

Traceability research has also explored blockchain and distributed ledger technologies to secure provenance and deter opportunistic manipulation of records. In agriculture and food supply chains, blockchain has been studied as a technology that can improve transparency, traceability, and

information sharing across fragmented networks, although practical maturity, governance, interoperability, and adoption barriers remain significant concerns (Kamilaris et al., 2019). Supply chain scholarship similarly shows that blockchain and smart contracts may support transparency, security, and coordination in complex supply networks, but their value depends on organizational readiness, data quality, partner participation, and the alignment between technology design and supply chain objectives (Saberli et al., 2019). For halal assurance, these insights support a pragmatic position. Ledger based systems can strengthen provenance claims, but they cannot replace the need for reliable data capture at the point of production, storage, transport, and transfer. Consequently, halal digital assurance should not be imagined as a purely technological solution. It requires robust event databases, controlled access rights, audit protocols, and governance agreements that specify who records data, who verifies it, who may correct errors, and how disputes over halal status are resolved.

The regulatory science of risk based inspections adds a complementary pillar. Oversight resources are finite, and legitimacy depends on proportionality, meaning that supervisory attention should concentrate where the likelihood and consequences of harm are greatest. Risk based inspection literature shows that inspection frequency and monitoring intensity can be shaped by food business operators' compliance history, risk profile, food safety management systems, and the potential severity of hazards (van Asselt et al., 2021). Recent work on risk based monitoring further explains that risk ranking and surveillance design must be translated into practical monitoring plans that specify what should be inspected, how often inspection should occur, and how risk evidence should guide control priorities (Focker et al., 2023). In halal supervision, whether public or private, this implies a shift from uniform schedules to dynamic targeting guided by indicators such as historical non conformities, product vulnerability profiles, stable or unstable cold chain telemetry, completeness of handover records, and evidence of segregation. Proportionality further demands transparency about how risk is constructed and used so establishments can understand and correct the factors shaping inspection intensity.

These strands of literature also furnish the theoretical basis for the present study. A socio technical systems perspective explains why digital assurance must couple instrumentation with redesigned processes and roles, not merely attach sensors to existing routines. Risk based regulation provides the governance logic for allocating attention and sanction in proportion to measured integrity risk, aligning assurance with harm reduction. Ethical technology scholarship further warns that high level principles are insufficient unless they are translated into operational mechanisms, institutional responsibilities, and procedures for accountability (Mittelstadt, 2019). This point is especially important for halal digital assurance because risk scoring, automated alerts, and inspection targeting may affect suppliers, logistics providers, certifiers, and consumers. AI ethics research also identifies recurring principles such as transparency, justice, fairness, non maleficence, responsibility, and privacy, but shows that these principles often diverge in interpretation and implementation across domains (Jobin et al., 2019). In halal contexts, these concerns can be aligned with maqāṣid al Shari'ah by requiring explainable scoring, auditable provenance, proportionate intervention, privacy respecting data use, and channels through which suppliers or firms can contest and correct model driven decisions. Together, these lenses justify the study's emphasis on explainability, calibration, contestability, and proportionality in halal digital assurance.

Despite the convergence in the literature, two gaps persist. First, robust causal evidence remains thin: many accounts describe pilots, conceptual models, technological potential, or cross-sectional associations between digital adoption and compliance outcomes without identification strategies that isolate technology effects from contemporaneous changes in management attention, product mix, certification routines, or inspection intensity. Second, there is limited articulation of auditable halal-specific metrics that are both interpretable and useful for decision-making, such as measures of segregation proximity, unbroken chain of custody, temperature excursion risk, and deviation recurrence, which can be validated predictively and inspected by certifiers. Addressing these gaps requires domain-specific risk scores grounded in observable events and evaluation designs capable of producing decision-grade claims.

Taken together, the current research suggests that halal integrity is best protected by sociotechnical systems that generate reliable records, prioritize risk for targeted oversight, and

embody stakeholder values in their design. IoT sensing supplies the evidentiary substrate, traceability layers secure provenance across organizational boundaries, and risk-based supervision aligns enforcement with potential harm. The credibility of such systems rests on governance choices: transparent variable definitions, fair and contestable scoring, auditable records, and proportionate responses. Building on this synthesis, the present study proposes a halal-specific integrity risk score, sets hypotheses about its effect under IoT-enabled operations, and details an identification strategy suited to producing credible, decision-relevant evidence.

Hypotheses

Building on the problem of contamination and opaque handling in halal logistics, the theoretical logic for the study's propositions is as follows. Halal integrity hinges on preventing contact with non halal inputs and documenting process purity across nodes. This requirement cannot be reduced to final product certification because halal assurance depends on the coordinated management of sourcing, processing, storage, transportation, documentation, and logistics control throughout the supply chain (Mohamed et al., 2021). Risk scholarship in halal food supply chains also shows that contamination, raw material integrity, supplier compliance, traceability, and logistics handling are among the central vulnerabilities that may compromise halal status when they are not governed systematically (Khan et al., 2022). Real time sensing technologies are therefore relevant because they reduce the information gaps that enable integrity failures to remain unnoticed. In cold chain and other temperature sensitive contexts, temperature abuse has been identified as a recurring threat to food quality and safety, especially when products move through multiple storage and transport environments with uneven monitoring capacity (Ndraha et al., 2018). IoT based monitoring, RFID, wireless sensor networks, and related digital tools can improve visibility across these environments by converting handling conditions into time stamped data that support earlier detection and faster corrective action (Badia-Melis et al., 2018). When those device level observations are connected to traceability systems, auditability also improves because the product's movement, condition, and handling history can be reconstructed across supply chain actors. Food traceability research emphasizes that traceability is not merely a documentation function but a supply chain management capability that supports safety, quality assurance, recall management, and accountability (Aung & Chang, 2014). Blockchain and other data infrastructure can strengthen this capability by supporting transparent, distributed, and less manipulable records, although their effectiveness still depends on the quality of data entry, governance arrangements, and participation across the supply chain (Astill et al., 2019). On the public governance side, risk-based inspection strengthens the logic of digital traceability because oversight can be directed toward facilities, routes, products, or processes with higher likelihood and consequence of non compliance. Food safety inspection literature shows that risk-based approaches may use compliance history, company characteristics, historical monitoring data, and other risk indicators to determine inspection priorities and allocate limited supervisory resources more proportionately (van Asselt et al., 2021). In the halal context, this means that digital traceability and real time monitoring should not be treated simply as efficiency tools, but as governance instruments that help identify where integrity risk is concentrated and where corrective intervention is most urgent.

Research Methods

The study adopts a quantitative quasi experimental design to estimate the causal effect of digital transformation in halal supply chains on compliance and quality outcomes. Digital transformation is operationalized as the phased adoption of traceability platforms, cold chain IoT telemetry, and electronic certification workflows across logistics corridors. Because adoption occurs at different times across firms and corridors, the analysis uses a panel difference in differences design rather than a simple before and after comparison. This choice is important because staggered adoption can produce biased estimates when treatment timing and treatment effects vary across units, especially if conventional two way fixed effects models are applied without attention to heterogeneity (Goodman-Bacon, 2021; Imai & Kim, 2021). The panel covers 18 months and includes 118 halal

certified facilities distributed across processing plants, third party logistics depots, cross docks, and retail distribution centers. These facilities serve 1,247 product lines concentrated in dairy, ready to eat meals, chilled confectionery, and frozen meats. Treated corridors adopt the full IoT and traceability stack during the observation window, while comparison corridors maintain business as usual logging but are selected to share comparable geography, product mix, shipment volume, and pre adoption compliance trends. The unit of analysis is the corridor month, with inspections, shipments, telemetry events, and audit records mapped to this level. Data collection integrates sensor telemetry and administrative records, including temperature and humidity probes, door and proximity sensors, pallet level identifiers, GPS gateways, handling declarations, certificate identifiers, and audit outcomes. To strengthen reliability, audit outcomes follow a standardized non conformity codebook, a subsample of inspections is double coded, and discrepancies are reconciled before analysis, while commercially sensitive information is protected through anonymized facility identifiers, data minimization, and coarsened location data.

The main outcomes include audit non-conformities per inspection, halal recall rate per 10,000 SKUs, temperature excursion minutes in refrigerated logistics, and traceability completeness, defined as the share of batches with unbroken time-stamped provenance and certificate links. Treatment is defined as corridor-level exposure to the complete digital stack after adoption, while controls include product category share, route length, ambient temperature band, corridor type, and seasonal demand marker. Firm, corridor, and month fixed effects are used to absorb stable heterogeneity and common shocks that could otherwise confound the relationship between digital adoption and compliance. Since clustered panel data may understate uncertainty, inference uses cluster robust standard errors and wild cluster bootstrap checks to address the possibility of uneven cluster sizes and finite cluster bias (MacKinnon and Webb, 2017). Robustness checks include alternative comparison sets, placebo adoption dates, alternative event windows, and the exclusion of corridors with incomplete pre-adoption histories. Missing telemetry and audit fields were addressed using multiple imputation by chained equations when missingness was plausibly related to observed variables rather than being treated as random deletion from the analytical sample (White et al., 2011). As a complementary exercise, logistic regression and gradient boosting models were used to generate corridor month risk scores for non compliance. Predictive performance is assessed through discrimination, calibration, and transparent reporting principles, since risk scores used for inspection or compliance triage must be interpretable and reliable rather than merely accurate in aggregate (Collins et al., 2015; Steyerberg et al., 2010).

Results and Discussion

Digital observability and the governance of halal compliance

Across 118 halal-certified facilities, including processing plants, depots, cross docks, and retail distribution centers, and across 1,247 product lines observed for 18 months, the combined rollout of IoT temperature and humidity sensing, ledgered traceability, append-only documentation, selective blockchain hashing, and risk-scored audit workflows was associated with measurable improvements in halal integrity and compliance. Relative to staggered controls, the rate of major noncompliance per 10,000 shipments declined by 16.8 percent, with a 95 percent confidence interval from minus 22.4 to minus 11.1. First-attempt audit pass rates increased by 7.4 pp, while traceability completeness, measured as the share of batches with unbroken time-stamped provenance, rose by 12.6 pp. These effects are operationally meaningful because halal integrity is not only a matter of certification at the point of production but also a continuous supply chain condition that depends on segregation, documentation, supplier accountability, and the preservation of product status across multiple logistical nodes (Handayani et al., 2022). These results also align with recent studies on digital technology in halal supply chains, which identify blockchain, RFID, IoT, and traceability systems as key technologies for strengthening operational visibility and performance in halal logistics (Harsanto et al., 2024). In food cold chain management, RFID and IoT have been emphasized as technologies that improve traceability and operational efficiency, although practical implementation and human factors remain important unresolved challenges (Mustafa et al., 2024). Therefore, the improvement

observed in this study should not be read as a simple technological effect but as evidence that digital monitoring becomes consequential when it is embedded into the daily routines of custody, handling, audit preparation, and exception management.

The mechanism is clearest in the timing metrics and waste outcomes that improved once telemetry became part of routine operational governance. After deployment, the mean duration of temperature excursions greater than two degrees Celsius outside the target range fell by 28.3 percent per route, the median time to intervention shortened from 56 minutes to 19 minutes, and waste related write offs declined by 21 percent. These findings are consistent with cold chain studies showing that temperature abuse remains a recurrent weakness in commercial food distribution and that time temperature management is central to preserving safety and quality in perishable products (Mercier et al., 2017). The strongest marginal benefits appeared on multi stop urban routes and weekend dispatch windows, where congestion, staffing variance, and repeated door opening historically made compliance more fragile. In these contexts, telemetry transformed exception handling from retrospective explanation into early intervention. Alerts surfaced deviations sooner, supervisors could identify routes with recurring excursions, and maintenance could be targeted to vehicles whose cooling performance degraded under heat stress. This pattern is also consistent with empirical work on RFID and IoT based traceability systems, where sensor data on temperature and humidity can be integrated with product movement data to provide real time histories of perishable goods across distribution settings (Alfian et al., 2020). The point is especially significant for halal logistics because thermal control and halal segregation are not separate compliance domains. When chilled or frozen halal products move through shared warehouses, transport corridors, or consolidation points, temperature excursions, undocumented handovers, broken seals, and proximity to nonhalal pallets can become mutually reinforcing indicators of process vulnerability.

Effects varied by product category and logistics archetype, which strengthens the credibility of the findings. Dairy and chilled desserts, which operate within narrow thermal windows, recorded declines in major noncompliance of roughly 22 to 24 percent, while ready to eat lines registered declines of about 18 to 20 percent and frozen meats declined by 12 to 14 percent. Shelf stable categories showed little change, which is consistent with their lower sensitivity to thermal excursions. Facilities with mature HACCP programs but manual logging gained mainly through faster alerting and closure of exceptions, while sites with fragmented records benefited from stronger provenance and fewer documentation gaps. The traceability layer also extended benefits beyond temperature control. The share of batches with complete ingredient level attestations and immutable time stamps increased by 14.9 percentage points, and flagged instances of potential commingling in shared warehouses fell by 31 percent. Auditors cited machine readable certificates, append only event logs, and standardized handover signatures as reasons for faster close outs and fewer custody disputes. This supports the proposition that blockchain based and ledgered systems can improve food supply chain visibility, transaction transparency, and traceability when they are connected to verifiable operational events rather than treated as symbolic digital records (Li et al., 2023). In this sense, the traceability layer converted operational telemetry into cross organizational evidence that could be read by internal quality teams, regulators, and religious authorities.

The causal interpretation is supported by an event study design that is adapted for staggered adoption. Conventional two-way fixed effects models can be problematic when units adopt treatment at different times and treatment effects are heterogeneous because estimated coefficients may combine group period effects in ways that do not correspond to the intended causal estimand (de Chaisemartin & D'Haultfoeuille, 2020). Therefore, the analysis emphasizes estimators designed for staggered treatment adoption and heterogeneous effects and reports pre-adoption coefficients that cluster around zero within sampling variation. Robust event study approaches are particularly important in settings where treatment effects emerge dynamically after rollout and operational learning may change the magnitude of the effect over time (Borusyak et al., 2024). Flat pre-trends and consistent post-adoption declines support a causal interpretation over simple maturation or selection, while the timing of standard operating procedure updates suggests complementarity rather than confounding because analogous updates on control corridors did not produce

comparable drops in noncompliance. The Halal Integrity Risk Score adds a second layer of evidence. On a 20 percent hold-out sample, the model produced an area under the receiver operating characteristic curve of 0.79, a Brier score of 0.142, and an expected calibration error of 0.021. This is important because prediction tools used for inspection, recertification, and routing must not only rank risks but also provide calibrated probabilities that decision-makers can interpret responsibly (Wolff et al., 2019). Alert governance was equally decisive in this regard. An initial policy that notified staff of every anomaly raised short-term interventions but also increased overrides in high-throughput depots. After the logic was redesigned to prioritize severity and novelty, suppress repeated low-value alerts, and batch low-risk anomalies, compliance gains persisted while override rates returned to baseline. This pattern is consistent with research on alert fatigue, showing that repeated or low-value alerts can reduce user responsiveness, especially when alerts add complexity without improving decision relevance (Ancker et al., 2017). The findings suggest that digital observability creates the possibility of stronger halal governance, but sustained integrity depends on calibrated risk scoring, disciplined escalation rules, and organizational routines that convert signals into accountable actions.

Halal integrity as the organizing principle of digital transformation

The results show that digital transformation in halal value chains should not be understood as a narrow technology rollout but as a coordinated reconfiguration of strategy, data architecture, operational routines, and governance capabilities. The pattern observed in this study, where IoT telemetry, process automation, certificate validation, partner portals, and audit workflows improved together, indicates that the value of digitalization depends on complementarity rather than isolated tools. This interpretation is consistent with the argument that a digital business strategy is no longer merely a subordinate information technology function, as digital resources increasingly shape business scope, scale, speed, and value creation logic (Bharadwaj et al., 2013). In halal supply chains, such a strategic shift is especially consequential because value is produced not only through efficiency but also through the capacity to preserve religiously defined integrity across procurement, storage, processing, transportation, and certification. Digital infrastructure is important because it makes halal assurance more continuous, visible, and actionable. The strongest gains in the study appeared where firms did not simply install sensors or ledgers but reorganized work around the data produced by those systems. This supports a broader view of digital innovation as a layered architecture in which devices, networks, services, and content become loosely coupled yet mutually reinforcing components of organizational change (Yoo et al., 2010). This implies that halal digital transformation succeeds when technological layers are connected to accountable routines, not when digital tools are treated as decorative proof of modernization.

The distinctiveness of halal supply chains also explains why the measured effects concentrate around contamination interfaces, custody handovers, and temperature sensitive routes. Halal integrity is not equivalent to ordinary product quality because a product's permissibility can be compromised by contact, substitution, undocumented transfer, or uncertainty over process status. The halal supply chain model developed by Tieman et al. (2012) places particular emphasis on logistics business processes, product characteristics, market requirements, and halal control activities as determinants of halal supply chain performance. This framework helps explain why the results are strongest in multi node corridors where products move through shared depots, cross docks, and mixed traffic environments. The study's reduction in major noncompliance, increase in first attempt audit pass rates, and improvement in traceability completeness show that digital monitoring is most useful where halal risk is relational and mobile. A product may leave the plant with valid certification, but its integrity still has to be protected through transport, storage, repacking, and dispatch. The food supply chain integrity literature likewise argues that integrity requires attention beyond certification because raw material integrity, production integrity, service integrity, and information integrity must be coordinated across the chain (Ali et al., 2017a). In this sense, the findings support a domain specific proposition: digitalization creates the greatest halal value when it targets the points where physical contact, informational opacity, and institutional accountability intersect.

The operational improvements in temperature excursion duration, intervention time, and waste-related write-offs further suggest that digital assurance works by compressing the distance between events, evidence, and responses. Before telemetry, deviations were often entered into the audit record as retrospective explanations. After telemetry was routinized, deviations became actionable signals that could trigger corrective responses while the product was still in transit or storage. This is important because halal assurance depends not only on knowing that a violation has occurred but also on detecting conditions that could make violations more likely. Halal supply chain critical success factors include information technology, collaboration, certification, government support, logistics infrastructure, and human resource competence, which means that digital systems must be embedded in a broader organizational ecology rather than placed outside it (Ab Talib et al., 2015). The study's results demonstrate this ecology in practice. Temperature and humidity probes create visibility, pallet identifiers and handover signatures stabilize custody, certificate links reduce documentary ambiguity, and exception dashboards allow supervisors to direct attention to routes and facilities where integrity risk accumulates. The improvement in traceability completeness is particularly significant because halal traceability is not merely a consumer information device. It is an evidentiary structure that connects product identity, process history, supplier responsibility, and certification status to the final product. Earlier work on halal food supply chain integrity similarly identified certification, traceability, dedicated assets, trust among supply chain members, commitment, and the government's role as elements that strengthen integrity in complex trade environments (Zulfakar et al., 2014).

The traceability layer also clarifies why blockchains or ledgered records should be treated as trust amplifiers rather than trust substitutes. The observed improvement in recall efficiency and custody dispute resolution did not arise from immutability alone. It depends on disciplined master data, standardized handover events, certificate validation routines, and auditable exceptions. Food supply chain transparency research has shown that transparency requires intensified information exchange and integrated information systems across chain actors, particularly when stakeholders need to verify provenance, quality, and process attributes (Trienekens et al. 2012). Blockchain can support this transparency, but only when the data written into the system are accurate, timely, and institutionally meaningful. Research on blockchain traceability in food supply chains emphasizes that technical design is constrained by boundary conditions related to business incentives, regulation, quality assurance, and traceability practices (Behnke & Janssen, 2020). Therefore, the results caution against a simplistic belief that distributed ledgers automatically produce halal trust. If a warehouse worker records the wrong handover, if a certificate is not validated against the relevant authority, or if segregation events are not captured at the point of risk, the ledger may preserve the error rather than correct it. Blockchain improves halal assurance only when it is tied to verified off-chain controls and governed by clear responsibilities over data entry, correction, access, and dispute resolution.

The analytics component of this study extends this governance problem into the domain of risk scoring. The Halal Integrity Risk Score is useful because it organizes telemetry events, handover completeness, route deviations, commingling flags, and prior audit patterns into a decision aid for the triage. However, its value depends on interpretability and institutional accountability. Explainable artificial intelligence research stresses that explanation is crucial when machine learning models are used in contexts where decisions affect human organizations, legal accountability, privacy and trust (Arrieta et al., 2020). Halal assurance clearly belongs to this class of high-consequence decision environments because risk scores may affect inspection intensity, supplier credibility, routing decisions, recertification priorities, and consumer trust. Therefore, black-box optimization is insufficient. Rudin (2019) argues that high-stakes decisions should favor interpretable models where possible rather than relying on post hoc explanations for opaque systems. In halal governance, this means that certifiers and firms should be able to see why a route, batch, facility, or supplier is assigned a higher integrity risk score. The variables must have operational meaning, such as repeated temperature excursions, missing custody events, proximity to nonhalal pallets, delayed corrective action, or certificate mismatch. If the score cannot be

understood, contested, or corrected, it risks becoming another opaque authority rather than a tool for accountable assurance.

The human and organizational layers are equally important because the findings show that alert governance determines whether digital monitoring produces durable compliance or operational fatigue. Early anomaly based alerting increased interventions but also produced desensitization in high-throughput depots, while the later shift toward severity-based prioritization and suppression of repeated low-value alerts sustained gains without overwhelming staff. This supports a human-centered view of automation, in which reliable and trustworthy systems combine computational capability with meaningful human control (Shneiderman, 2020). In halal operations, human control does not imply returning to manual paper-based systems. This means designing digital systems so that operators, auditors, certifiers, and managers can understand the signal, act on it, and remain responsible for the decision. Data governance is central to this process. Data governance is commonly understood as the allocation of decision rights and accountabilities for data-related processes, which is precisely what halal digital assurance requires (Khatri & Brown, 2010). Firms must define who can create custody records, amend errors, validate certificates, receive alerts, override risk triggers, and audit such overrides. Without these rules, digitalization may increase the volume of information while leaving accountability fragmented.

The policy implication is that halal digital transformation should be organized around risk-responsive governance rather than uniform technological adoption. Risk-based regulation is valuable because it directs scarce supervisory resources toward activities and actors that pose higher potential harm. However, it must remain responsive to regulated firms' behavior, institutional capacity, internal control systems, and changing risk environments (Black & Baldwin, 2010). The evidence from this study supports this principle. Corridors with repeated excursions, fragmented custody records, or mixed warehouse interfaces require denser instrumentation and more frequent reviews, whereas consistently stable corridors can be monitored through lighter but still auditable routines. This differentiation does not weaken halal assurance. It is strengthened by aligning attention with risk. The managerial lesson is also clear: firms should map critical integrity points, allocate sensing and audit resources according to those points, and use platform-based data to make compliance visible across organizational boundaries. Digital innovation research emphasizes that digital technologies change innovation processes by increasing openness, generativity, and recombination across actors and artifacts (Nambisan et al., 2017). In halal value chains, this generativity becomes useful only when it is bounded by Shariah requirements, certification standards and auditable operating procedures. The issue is not how much technology is adopted but whether the adopted technology makes halal status more verifiable, governable, and resilient.

Therefore, the limitations of the results should be read as design guidance rather than as reasons to dismiss digital halal assurance. Some coefficient attenuation in highly instrumented sites may reflect the fact that these sites faced more complex risk environments before adoption. The variation across product categories also confirms that digital monitoring is not equally valuable everywhere. The shelf-stable categories showed smaller effects because their risk profiles are less dependent on thermal control, whereas dairy, chilled confectionery, and ready-to-eat meals gained more from continuous telemetry. The broader conclusion is that halal digital transformation should not pursue universal sensor saturation. It should pursue a fit among product vulnerability, logistics architecture, risk history, and governance capacity. This study reframes digital transformation in the halal industry as a governance project powered by technology rather than a technology project supplemented by governance. Digital infrastructure creates observability; traceability systems organize provenance; interpretable risk scores prioritize attention; and responsive governance converts those signals into proportionate actions. Taken together, these elements show that halal integrity can be operationalized as a living risk program in which religious requirements, supply chain discipline, and digital innovation reinforce each other.

Conclusion

This study demonstrates that digitally enabled halal logistics can strengthen integrity assurance when continuous sensing, tamper-evident traceability, calibrated risk scoring, and proportionate

oversight are integrated into a coherent governance system rather than deployed as isolated technological tools. The findings are consistent with the study's objectives: the Halal Integrity Risk Score provides an auditable mechanism for translating heterogeneous telemetry and handling records into risk-based decisions; IoT-enabled monitoring improves the timeliness of detection and correction in cold-chain and mixed-tenant logistics environments; and traceability infrastructure strengthens the evidentiary basis of halal certification, audit closure, and supply chain accountability. Theoretically, the study reframes halal digital transformation as a socio-technical and governance problem in which religious integrity, operational control, data architecture, and institutional trust must be designed together. Practically, the results suggest that firms and certifiers should prioritize instrumentation at high-risk integrity points, especially heat-exposed corridors, first-mile consolidation, multi-SKU cross-docking, undocumented handovers, and routes with recurring temperature excursions, while ensuring that risk scores remain explainable, thresholds are version-controlled, and alert systems are designed to prevent fatigue. The study is limited by its dependence on quasi-experimental assumptions, possible spillovers between treated and control corridors, telemetry gaps, sensor drift, audit measurement error, and contextual variation in climate, product mix, certification capacity, and logistics infrastructure. Future research should test the model through replication in other halal-sensitive sectors such as cosmetics, pharmaceuticals, and tourism logistics, compare alternative risk-scoring designs, examine interoperability across certification regimes, and explore vehicle-level or facility-level experimental designs that can sharpen causal attribution while preserving commercial confidentiality and role-appropriate privacy.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation and revision of this manuscript, the authors used generative AI and AI-assisted tools, including ChatGPT and Grammarly, for language refinement, structural editing, readability improvement, and consistency checking. These tools were not used to generate or fabricate research data, conduct statistical analyses, produce empirical findings, or replace the authors' scholarly judgment. All AI-assisted outputs were reviewed, verified, revised, and approved by the authors of this study. The authors take full responsibility for the accuracy, originality, integrity, and final content of this manuscript.

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