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FMEA–SCOR and Monte Carlo Simulation for Blockchain Adoption Feasibility in Indonesian Halal Food MSMEs

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ABSTRACT

Indonesia's halal industry is one of the fastest-growing components of the national economy, with the food and beverage sub-sector posting 5.87% year-on-year growth in 2024 and total halal consumption reaching IDR 545.6 trillion in 2022, yet only 4.4 of the country's roughly 28 million Micro and Small Enterprises (MSEs) had been halal-certified by May 2024, making supply chain readiness a critical concern ahead of the mandatory halal certification deadline of October 2026. This study integrates Failure Mode and Effect Analysis (FMEA) with the Supply Chain Operations Reference (SCOR) model to identify and prioritize risk points along the MSME halal food supply chain, and then applies a 10,000-iteration Monte Carlo simulation to quantify the ex-ante reduction in aggregate Risk Priority Number (RPN) achievable through blockchain technology adoption. Twenty-eight risk points were mapped across the Plan, Source, Make, Deliver, and Return processes, with an aggregate Total RPN of 4,180 before mitigation; the five highest-RPN risks all relate to traceability gaps and halal-document integrity, with the Make stage contributing 39.2% of total risk. Simulation results show that blockchain adoption produces a non-linear, diminishing-returns reduction profile: 21.2% risk reduction at 25% penetration, 41.4% at 50%, 62.0% at 70%, and 79.3% at 90%. The optimal investment point is estimated at $p \approx 0.70$, beyond which marginal benefits decline sharply. The findings provide a practical, quantitative framework for MSME operators, Badan Penyelenggara Jaminan Produk Halal (BPJPH), and Lembaga Pemeriksa Halal (LPH) to design phased blockchain adoption supported by ecosystem readiness in regulation, organization, and technology.

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INTRODUCTION

The global halal industry has emerged as one of the fastest-growing economic sectors of the 21st century. According to the State of the Global Islamic Economy Report (SGIER) 2023/2024, total global consumption of halal products is estimated to reach US$ 2.4 trillion in 2024, with an average projected annual growth of 6.3% [1]. Indonesia, as the country with the largest Muslim population in the world (241.7 million people, or about 89% of the total population), holds enormous market potential within this ecosystem. In the first quarter of 2024, Indonesia's halal value chain (HVC) sector recorded a growth of 1.94% (year on year), with the halal food and beverage sub-sector growing 5.87% and modest fashion 3.81% [2]. Ironically, although Indonesia is the largest halal consumer, its position as a halal producer remains in the world's top ten, with around 12.6% of the halal food industry's needs still being met by imports [3]. As of 15 May 2024, only 4,418,343 products had obtained halal certificates from Badan Penyelenggara Jaminan Produk Halal (BPJPH), or just 44.18% of the 10,000,000-product target, while the total number of Micro and Small Enterprises (MSEs) in Indonesia reaches around 28 million business units [4]. The government subsequently postponed the mandatory halal certification policy for food and beverage products from MSEs from October 2024 to October 2026 [4], making supply chain readiness a critical concern.

Halal Supply Chain Management (HSCM) is defined as the integrated management of materials, information, and capital throughout the supply chain to ensure that all products—from farm to fork—comply with halal standards established by Islamic sharia [5]. Unlike conventional supply chains, HSCM has three distinguishing characteristics: prevention of direct contact with haram elements, cross-contamination risk management through facility and transportation segregation, and fulfilment of Muslim consumer perception through transparency and traceability [6]. Structurally, HSCM can be mapped using the Supply Chain Operations Reference (SCOR) framework, which divides the supply chain into five core processes: Plan, Source, Make, Deliver, and Return [7]. Each process contains critical halal control points (CHCP) whose integrity must be maintained, analogous to the Hazard Analysis and Critical Control Point (HACCP) concept in food safety. Despite this conceptual clarity, Indonesia's halal food supply chain remains highly complex and vulnerable to risks ranging from raw-material contamination, processing non-compliance with sharia standards, product damage during distribution, to fraudulent practices that compromise halal integrity. Chairany, Hidayatno, and Suzianti [8] mapped 28 food-loss and food-waste risk points in Indonesia's agricultural supply chain, most of them traceable to facility limitations, weak training, and underdeveloped traceability systems.

Failure Mode and Effect Analysis (FMEA) is a systematic method for identifying potential failure modes, analyzing their causes, evaluating their impact on system performance, and formulating mitigation steps [8]. FMEA produces a Risk Priority Number (RPN) that is the product of three components rated on a 1–10 scale: severity of impact (S), frequency of occurrence (O), and detection capability before failure occurs (D) [9]. Chairany et al. [8] and Chairany et al. [10] have applied FMEA-SCOR integration to analyze food-loss risk in cayenne-pepper and tuna supply chains in Indonesia, finding that the highest risks generally occur at the source stage (limited cooling) and the deliver stage (temperature breakdown). The present study extends that line of work to the halal supply-chain domain and adds a technology-adoption simulation.

The traceability gaps and document-integrity weaknesses identified in the literature above—and which the FMEA-SCOR analysis in this study confirms as the dominant risk class—are precisely the failure modes that distributed-ledger architectures are designed to address. Against this backdrop, several recent studies have proposed digital 4.0 technologies—particularly blockchain—as a candidate digital intervention for transparency, traceability, and integrity in the halal supply chain [5], [11]. It is important to emphasise that the present study does not pre-suppose blockchain as a confirmed mitigation strategy; rather, it treats blockchain as a candidate technology whose ex-ante risk-reduction potential and adoption feasibility are to be assessed quantitatively given the risk profile that emerges from the FMEA-SCOR mapping. Blockchain is a distributed ledger technology (DLT) that records transactions in a decentralized, immutable, and traceable manner [11]. In the halal context, it can record every product movement—from animal slaughter, processing, and distribution to the consumer's hands—on a single ledger verifiable by all stakeholders, including consumers, BPJPH, and Halal Inspection Agencies (LPH) [12], [13]. Several studies report that blockchain can shorten tracking time by up to ten times and substantially reduce recall costs [5]. Hendayani and Fernando [14] empirically demonstrated that blockchain adoption has a positive and significant impact on supply-chain performance and competitiveness for 178 Indonesian halal manufacturers. More recently, graph neural-network architectures for supply-chain risk modelling — proposed in the JISEM literature for predicting cascading-disruption patterns from network structure and node attributes — have been positioned as a complementary, data-driven layer beyond classical FMEA for managing supply-chain risk in complex multi-actor settings [15]. Decentralized identifier (DID) and self-sovereign identity (SSI) frameworks discussed by Mühle et al. [16] are also relevant for verifying halal business actors in a decentralized manner.

Despite the volume of work, most prior studies are descriptive or conceptual and have not produced ex-ante quantification of the risk reduction achievable through blockchain adoption, especially for Indonesian halal food MSMEs [17]. To address this gap, this study integrates three frameworks: (i) the SCOR model to map the plan–source–make–deliver–return processes; (ii) FMEA to compute the RPN at each process point; and (iii) Monte Carlo simulation to estimate expected risk reduction as a function of blockchain penetration. The objectives are: (1) to map and identify critical risk points in the Indonesian MSME halal food supply chain; (2) to quantify the ex-ante risk-reduction potential of blockchain adoption through simulation; and (3) to formulate strategic recommendations for MSME operators and regulators preparing for the October 2026 Mandatory Halal regime. The conceptual framework, depicted in Figure 1, positions FMEA-SCOR as an ex-ante risk-mapping instrument with blockchain modelled as a candidate digital control whose hypothesised effects on the probability of failure (Occurrence) and on detection capability (Detection) are then assessed via Monte Carlo simulation. The framework is therefore exploratory in nature: it does not claim blockchain as a confirmed mitigation strategy, but rather provides an ex-ante feasibility lens for evaluating whether and at what penetration level adoption is likely to be worthwhile given the current Indonesian MSME context.

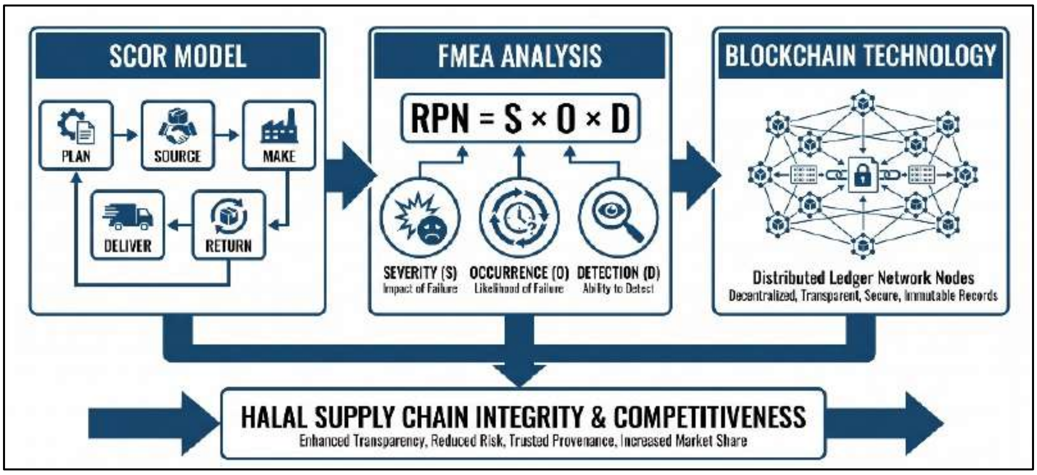

Fig. 1. Conceptual Framework of FMEA-SCOR-Blockchain Integration in the Halal Supply Chain

RESEARCH METHODS

This study employs a mixed-methods design with a quantitative-simulation dominant approach. The research is carried out in five steps: (1) literature review and mapping of the MSME halal food supply chain processes using SCOR; (2) identification of risk points through expert judgement and multi-actor analysis; (3) RPN assessment of each risk using FMEA on a 1–10 scale; (4) Monte Carlo simulation to quantify the impact of blockchain adoption on the reduction of Occurrence and Detection; and (5) formulation of mitigation strategies and recommendations.

The research object is the halal food supply chain of MSMEs in Indonesia, focusing on processed food and beverage products as the two leading halal value-chain sub-sectors with the highest growth (5.87% yoy in 2024) [2]. More specifically, the scope is restricted to packaged, shelf-stable retail food and beverage products distributed through traditional markets, modern supermarkets, and e-commerce platforms—that is, products sold in pre-packaged form rather than ready-to-eat dishes served at

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restaurants or food-service outlets—because packaged products dominate the BPJPH MSME halal-certification queue and traverse longer, multi-actor supply chains in which halal-traceability risks are most acute. Data were collected from two sources: (i) secondary data from official publications of Statistics Indonesia (BPS), BPJPH, the National Committee for Islamic Economy and Finance (KNEKS), and SGIER for the macro context of the halal industry; and (ii) simulation data designed from empirical parameters in prior research [8], [14], [10], recalibrated using expert judgement from three principal actors—MSME operators, halal distributors, and halal retailers—as practiced by Chairany et al. [3]. The secondary data comprised three categories: (a) macro statistics on halal-industry growth, MSME unit counts, and Indonesia's position in the global halal value chain (BPS "Indonesian Manufacturing Industry Statistics 2023"; KNEKS "Indonesia Halal Industry Master Plan 2023–2029"); (b) BPJPH halal-certification statistics, including the cumulative number of certificates issued, the SEHATI free-certification programme uptake, and the regulatory roadmap toward the October 2026 mandatory-halal deadline (BPJPH public dashboards); and (c) global halal-economy benchmarks for sectoral growth and consumption (DinarStandard SGIER 2023/2024). These macro datasets framed the simulation context but were not used to compute RPN values directly. The expert-judgement panel comprised twenty-one respondents across three actor classes: twelve MSME operators (selection criteria: BPJPH-registered or certification-pending micro/small food and beverage processors, with at least three years of operating experience and at least one direct supply-chain interface with a halal-certified supplier or Lembaga Pemeriksa Halal); five halal distributors (criteria: registered logistics or distribution operators handling halal-labelled food and beverage SKUs on inter-provincial routes); and four halal retailers (criteria: supervisors or store managers of modern-retail outlets that stock halal-certified MSME products). These actor classes were chosen because they collectively span the Source–Make–Deliver portion of the SCOR chain that prior FMEA-SCOR studies in Indonesia have identified as carrying the highest aggregate halal-supply-chain risk [8], [10]; the unequal sample sizes across the three classes reflect the relative weight each class carries in day-to-day halal-integrity decisions on the MSME segment. Each respondent rated the Severity, Occurrence, and Detection of every risk point on the 1–10 scale of Table 1; the median rating across respondents within each actor class was taken forward as the FMEA input, following the consensus protocol of Chairany et al. [8].

The RPN is calculated using the classical FMEA formula in Equation (1):

$$RPN = Severity\ (S) \times Occurrence\ (O) \times Detection\ (D) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

with each component using a 1–10 scale based on Dong and Cooper [9] and Chairany et al. [8]; the assessment scale is presented in Table 1. The aggregate Total RPN (TRPN) is then computed as the sum of RPNs of all n identified risk points along the supply chain, as in Equation (2):

$$TRPN \sum_{I=1}^{N} (S_i \times O_i \times D_i) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Table 1. Severity, Occurrence, and Detection Assessment Scale

Scale	Severity (S)	Occurrence (O)	Detection (D)
1–2	Insignificant	Very rare (<1%)	Almost certainly detected
3–4	Minor	Rare (1–5%)	High
5–6	Moderate	Fairly frequent (5–20%)	Moderate
7–8	Severe	Frequent (20–50%)	Low
9–10	Very severe / catastrophic	Very frequent (>50%)	Almost undetectable

Table 1 presents the five-band ordinal scale used to score each of the three FMEA components—Severity (S), Occurrence (O), and Detection (D)—on a 1–10 range. The Severity dimension captures the magnitude of harm that would result if a given failure mode were to reach the end consumer or a regulatory checkpoint: scores of 1–2 indicate an insignificant impact (e.g., a minor labelling inconsistency with no downstream effect), while scores of 9–10 represent very severe or catastrophic consequences, such as mass distribution of products containing haram ingredients that could trigger a BPJPH certificate suspension or a public recall. The Occurrence dimension reflects the estimated probability or frequency with which a failure mode manifests under normal MSME operating conditions: a score of 1–2 corresponds to a very rare event (fewer than 1% of production batches affected), whereas a score of 9–10 denotes a very frequent failure occurring in more than 50% of cases, typical of systemic process weaknesses such as the absence of a written halal Standard Operating Procedure. The Detection dimension measures the capability of current quality-control and inspection mechanisms to identify a failure before it propagates further downstream: a score of 1–2 implies that the failure is almost certainly detected by existing controls (e.g., a laboratory test or a mandatory pre-shipment inspection), while a score of 9–10 means the failure is almost undetectable with current systems, as is the case with fraudulent supplier halal-document forgery that cannot be verified without a real-time link to the BPJPH Sihalal database. The RPN for each risk point is then the product S × O × D, producing a value between 1 and 1,000; this multiplicative structure ensures that risks scoring high on two or more dimensions are escalated disproportionately, consistent with classical FMEA practice [9]. Expert-panel median scores for all 28 identified risk points, computed using this scale, are reported in Table 2.

Monte Carlo Simulation of Blockchain Adoption

To measure the impact of blockchain adoption on RPN reduction, a Monte Carlo simulation with $10{,}000$ iterations was conducted [18]. The simulation assumptions refer to the literature on the impact of blockchain on the halal SC [5], [14], [19]. Two risk parameters affected by blockchain are Occurrence and Detection, while Severity is assumed to remain constant because it is related to the intrinsic impact of failure. The reduction factors are formulated in Equations (3) and (4):

$$O' = O \times (1 - \alpha_o \times p) \quad (3)$$

$$D' = D \times (1 = \alpha_D \times p) \quad (4)$$

where p is the blockchain adoption penetration rate among $MSMEs$ $(0 \leq p \leq 1)$; α_o is the Occurrence reduction factor (assumed normally distributed with $\mu = 0.45$ and $\sigma = 0.08$); and α_D is the Detection reduction factor ($\mu = 0.55, \sigma = 0.07$). These assumptions follow Hendayani and Fernando [14], who found that blockchain can improve traceability up to 10 × and substantially reduce recall costs [20]. The post-mitigation RPN (RPN') and the percentage of risk reduction (RR) are formulated in Equations (5) and (6):

$$RPN' = S \times O' \times D' \quad (5)$$

$$RR(\%) = \left(\frac{RPN - RPN'}{RPN}\right) \times 100\% \quad (6)$$

Four blockchain-adoption penetration scenarios were simulated: $p = 0.25$ (low), $p = 0.50$ (medium), $p = 0.70$ (optimistic), and $p = 0.90$ (full / ideal). Iteration results were processed to obtain descriptive statistics (mean, standard deviation, and 95% confidence interval). Risk-level classes adapted from Stamatis [16] are: Critical ($RPN \geq 200$), High ($150 \leq RPN < 200$), Moderate ($80 \leq RPN < 150$), and Low ($RPN < 80$).

RESULTS AND DISCUSSION

1. Identification of MSME Halal Supply Chain Risk Points (FMEA-SCOR)

Based on the multi-actor analysis and adaptation from the studies of Chairany *et al.* [8], [10], 28 risk points (R1–R28) were identified, distributed across the five SCOR processes: Plan (4 risks), Source (6 risks), Make (8 risks), Deliver (7 risks), and Return (3 risks). The S, O, and D assessments were carried out by three actors: MSME operators ($n = 12$), halal distributors ($n = 5$), and halal retailers ($n = 4$). The complete RPN scores for each risk are presented in Table 2.

To complement the FMEA results in Table 2, the supply-chain activities underlying each SCOR stage and the corresponding potential effects and root causes of the highest-RPN risks are summarised below. At the Plan stage, MSME operators set demand forecasts, supplier-coordination plans, and halal Standard Operating Procedures; the absence of a written halal SOP (R2) and reliance on uncertified suppliers (R4) trace back to still-emerging halal-certification literacy among Indonesian micro and small enterprises, and their potential effect is a downstream chain in which non-conforming inputs propagate into the Make and Deliver stages without an audit trail. The Source stage covers raw-material procurement, inbound logistics, and supplier handling; the dominant risks—untraceable raw-material origin (R6), cross-contamination of raw materials (R5), and supplier falsification of halal documents (R9)—stem from paper-based documentation, fragmented supplier registers, and the absence of a real-time verification mechanism between MSMEs and the BPJPH Sihalal database, with potential effects ranging from product-level halal-integrity loss to mass recall and certificate suspension. The Make stage—covering ingredient handling, processing, packaging, and in-process records—generates the largest share of total risk (39.2%); workers untrained in halal practices (R12), undetected haram additives (R15), and manual production records (R18) reflect causes such as limited halal-supervisor capacity, shared equipment use, and paper-based logbooks, with potential effects including unintended cross-contamination and inability to reconstruct lot history during a recall. The Deliver stage—outbound logistics, transit storage, and retail handover—exposes products to mixing with non-halal SKUs (R21), document loss in transit (R23), and non-segregated retail storage (R25); underlying causes include mixed-cargo transport practices, the absence of digital halal-labelling, and limited retailer awareness of halal-segregation requirements, and the potential effect is reputational damage that can erode consumer trust even where upstream stages remain compliant. Finally, the Return stage covers complaint handling, recall execution, and periodic risk audits; the slow recall system (R26) and absent periodic risk audits (R28) reflect the lack of a centralised event registry between MSME, distributor, retailer, and BPJPH, and produce a potential effect of prolonged consumer-exposure windows when a halal-integrity breach is discovered. This SCOR-grounded narrative is the qualitative companion to the quantitative RPN scores in Table 2 and clarifies that several of the highest-RPN risks share common root causes—paper-based traceability, fragmented data, and limited segregation infrastructure—which is precisely the cluster of failure modes that distributed-ledger architectures are designed to address.

Table 2. FMEA results for the MSME halal food supply chain

Code	Failure Mode	SCOR Stage	S	O	D	RPN	Category
R1	Inaccurate demand planning	Plan	5	6	5	150	High
R2	No halal SOP at the business unit	Plan	8	7	4	224	Critical
R3	Lack of coordination among halal suppliers	Plan	6	6	5	180	High
R4	Suppliers without halal certification	Plan	9	5	5	225	Critical
R5	Cross-contamination of raw materials	Source	10	4	6	240	Critical
R6	Untraceable raw material origin	Source	9	6	5	270	Critical
R7	Packaging not compliant with halal standards	Source	6	4	4	96	Moderate
R8	Improper handling at the supplier	Source	7	5	5	175	High
R9	Suppliers falsifying halal documents	Source	10	3	8	240	Critical
R10	Damaged/expired raw materials	Source	6	5	3	90	Moderate
R11	Production equipment not halal-compliant	Make	9	4	6	216	Critical
R12	Workers not trained in halal practices	Make	7	6	5	210	High
R13	Inadequate facility sanitation	Make	8	5	5	200	High
R14	Cross-contamination during production	Make	9	4	6	216	Critical
R15	Undetected haram additives	Make	10	3	8	240	Critical
R16	Inconsistent quality control	Make	6	6	5	180	High

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Code	Failure Mode	SCOR Stage	S	O	D	RPN	Category
R17	No halal supervisor	Make	7	4	6	168	High
R18	Manual production records prone to error	Make	5	7	6	210	High
R19	Packaging damage during distribution	Deliver	6	5	4	120	Moderate
R20	Contamination at transit warehouses	Deliver	8	4	6	192	High
R21	Mixing with non-halal products	Deliver	10	3	7	210	High
R22	Cold chain breakdown during shipment	Deliver	7	5	5	175	High
R23	Halal documents lost during distribution	Deliver	8	4	6	192	High
R24	Non-compliant halal labeling	Deliver	8	4	5	160	High
R25	Non-segregated retail storage	Deliver	9	5	4	180	High
R26	Slow recall system	Return	9	3	7	189	High
R27	Mixed handling of returns	Return	8	3	6	144	Moderate
R28	No periodic risk audit	Return	6	4	7	168	High

The aggregate Total RPN (TRPN) for all 28 risk points is 4,180 (average $RPN = 149.3/risk$). Six risks fall into the Critical category ($RPN \geq 200$), and four of the five highest-RPN risks (R6, R5, R9, R15) relate to traceability gaps and halal-document integrity. This confirms the findings of Hashim *et al.* [19] and Khan *et al.* [13] that transparency and data integration are the principal pain points of halal supply chains in Muslim-majority countries—precisely the area where blockchain offers the strongest competitive advantage. Aggregating across SCOR stages, the Make stage contributes 39.2% of the total risk, followed by Deliver (29.4%) and Source (26.6%); the distribution is visualised in Figure 2.

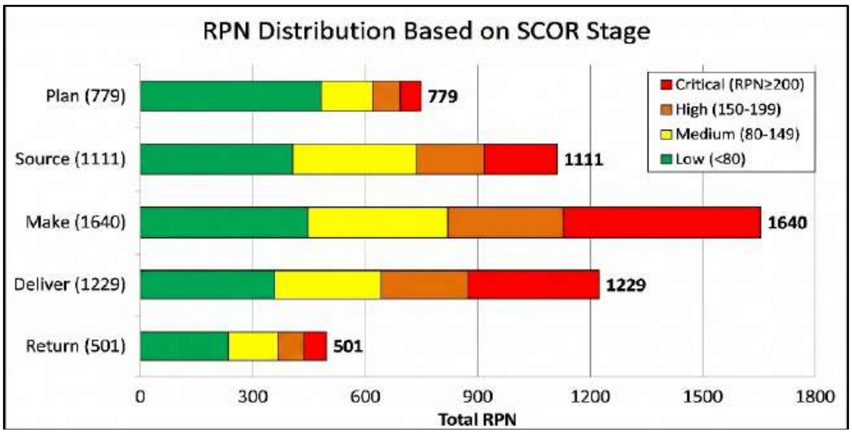

Fig. 2. Distribution of RPN across SCOR stages in the MSME halal supply chain

Figure 2 is a stacked or segmented bar chart that visualises the proportional contribution of each of the five SCOR stages—Plan, Source, Make, Deliver, and Return—to the aggregate Total RPN of 4,180. The chart reveals a highly uneven risk distribution across the supply chain. The Make (production) stage dominates with 39.2% of total risk (TRPN contribution ≈ 1,638), reflecting the combined weight of eight risk points centred on worker training gaps, equipment non-compliance, undetected haram additives, and manual record-keeping. The Deliver stage accounts for 29.4% (≈ 1,229), driven by seven risk points related to transit contamination, document loss, and non-segregated retail storage. The Source stage contributes 26.6% (≈ 1,112), with the single highest-RPN risk point in the entire analysis—R6, untraceable raw-material origin (RPN = 270)—anchoring this stage. The Plan and Return stages together account for the remaining 4.8%, reflecting fewer risk points and lower individual RPN values. The visual pattern confirms that halal-integrity risk in the MSME food supply chain is concentrated in the upstream production and mid-stream distribution phases, which together account for approximately 68.6% of total risk and should therefore be prioritised in any blockchain adoption roadmap.

2. Monte Carlo Simulation Results of Blockchain Adoption

The Monte Carlo simulation was run with 10,000 iterations for the four blockchain-adoption penetration scenarios ($p = 0.25;\ 0.50;\ 0.70;\ 0.90$) using Equations (3)–(6). The descriptive statistics of the simulation results are presented in Table 3.

Table 3. Monte Carlo simulation results of TRPN reduction

Scenario	Penetration (p)	Initial TRPN	TRPN′ (Mean)	Std. Dev.	95% CI	RR (%)
S1 (Low)	0.25	4,180	3,296	112	[3,078; 3,515]	21.2%
S2 (Medium)	0.50	4,180	2,448	138	[2,180; 2,717]	41.4%
S3 (Optimistic)	0.70	4,180	1,589	152	[1,293; 1,886]	62.0%
S4 (Full)	0.90	4,180	865	163	[546; 1,184]	79.3%

The simulation results show a non-linear relationship between the level of blockchain adoption and the resulting Risk Reduction. A 25% penetration reduces TRPN by 21.2% (from 4,180 to 3,296), while a 70% penetration (optimistic scenario) reduces TRPN by 62.0% (to 1,589). At full 90% penetration, the reduction reaches 79.3% ($TRPN = 865$). The reduction does not approach 100% because Severity is assumed constant—blockchain reduces probability and improves detection, but does not change the intrinsic impact of failure. The 95% confidence interval in the optimistic scenario is [1,293; 1,886], indicating good simulation precision. The Risk-Reduction curve as a function of penetration is plotted in Figure 3.

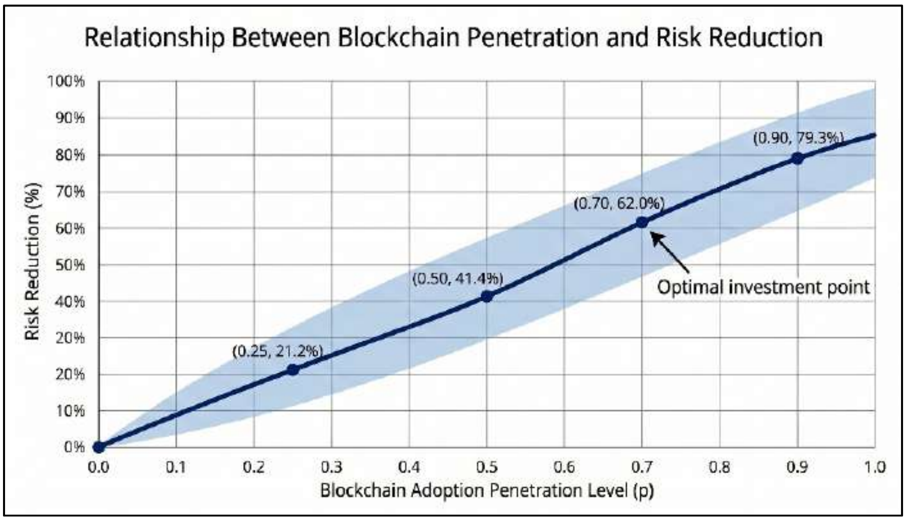

Fig. 3. Risk-Reduction curve as a function of blockchain adoption penetration

Figure 3 plots the mean Risk-Reduction percentage (RR%) on the vertical axis against the blockchain adoption penetration rate (p) on the horizontal axis, with four scenario points derived from the Monte Carlo simulation results in Table 3. The curve is concave and exhibits a classic diminishing-returns profile. The steepest gain occurs between p = 0 and p = 0.50, where risk reduction climbs from zero to 41.4%: this steep initial segment reflects the fact that even partial blockchain adoption eliminates the most frequent and most detectable failure modes first, rapidly lowering the aggregate Occurrence (O') and Detection (D') scores for those risk points. Between p = 0.50 and p = 0.70, risk reduction advances from 41.4% to 62.0%, a gain of 20.6 percentage points per 0.20 increment—somewhat slower than the first segment. From p = 0.70 to p = 0.90, the incremental gain falls to 17.3 percentage points, even though the penetration increment is the same size, confirming the onset of diminishing returns. The widening 95% confidence interval (CI) at higher penetration levels—from [3,078; 3,515] at p = 0.25 to [546; 1,184] at p = 0.90—signals increasing simulation variance as the stochastic reduction factors (α_o

and α^D) compound across a larger share of MSMEs. Critically, the curve does not reach 100% even at full adoption (p = 0.90 yields RR = 79.3%), because Severity (S) is held constant in the simulation: blockchain can reduce the probability that a failure occurs and improve its detectability, but it cannot remove the intrinsic consequence of a halal-integrity breach once it reaches the consumer. The inflection zone around p ≈ 0.70 represents the optimal investment point at which the marginal risk-reduction benefit per additional unit of adoption cost begins to decline sharply, making it the recommended target penetration for phased blockchain deployment among Indonesian halal food MSMEs.

3. Strategic Implications

Three strategic implications follow. First, the optimal adoption point based on the diminishing-returns curve in Figure 3 is at $p \approx 0.70$: beyond this level, the marginal benefit declines while investment costs continue to rise. This is consistent with Hendayani and Fernando [14], who report a positive and significant effect of blockchain adoption on supply-chain performance and competitiveness for Indonesian halal companies. Second, the mitigation strategy cannot rely on technology alone. *Ecosystem readiness* is required across three pillars: (a) regulatory readiness through BPJPH and KNEKS support and integration of the Sihalal platform with a national blockchain; (b) organisational readiness of MSMEs through human-resource training (halal supervisors) and digital-infrastructure procurement; and (c) technological readiness through *permissioned* blockchain adoption (e.g., Hyperledger Fabric), which is more cost-effective for MSMEs than public blockchains such as Ethereum [5]. Graph neural-network and other AI-driven supply-chain risk-modelling techniques recently surveyed in JISEM offer a complementary predictive layer that can supplement blockchain-based traceability with continuous, data-driven disruption monitoring across MSME production lines [15]. Third, the BPJPH *Free Halal Certification* (SEHATI) programme should be expanded with a *supply-chain digitalisation* component, not merely certificate issuance. Collaboration with the existing 66 LPHs and 71,133 PPH Companions [3] can serve as the social infrastructure for accelerating blockchain adoption at the MSME level.

As a comparison, Chairany *et al.* [10] in the tuna supply chain found the highest RPN at the source stage with a value of 120 (cold-chain breakdown), whereas the present study reveals the highest RPN of 270 (R6 — untraceable raw materials). The difference is attributable to the additional sharia-integrity layer that the halal supply chain places on top of conventional food-loss risk: halal SC mitigation must accommodate both food safety and halal integrity simultaneously.

CONCLUSION

This research has integrated the FMEA-SCOR-Blockchain framework to analyse risks in the Indonesian MSME halal food supply chain. Twenty-eight risk points were identified with an aggregate Total RPN of 4,180, with the Make (production) stage making the largest contribution (39.2%) to overall risk. The five most-critical risks ($RPN \geq 225$) are dominated by traceability and halal-document-integrity issues—precisely where blockchain offers the greatest competitive advantage. The Monte Carlo simulation across the four penetration scenarios provides risk-reduction estimates of 21.2% at 25% penetration, 41.4% at 50%, 62.0% at 70%, and 79.3% at 90%; the optimal investment point is estimated at $p \approx 0.70$, where the marginal benefit begins to decline significantly. The effectiveness of blockchain adoption in halal MSMEs depends heavily on ecosystem readiness in regulation, organisation, and technology. This study recommends: (a) integration of the Sihalal-BPJPH platform with a national blockchain using a cost-effective permissioned architecture; (b) expansion of the SEHATI programme with a digital halal-traceability training component; and (c) a blended-finance funding scheme involving KNEKS, sharia banking, and zakat institutions to help MSMEs access this technology. A limitation of this research is the simulation-based nature of the data, designed from literature parameters and expert judgement rather than longitudinal field surveys. Further research is suggested to (1) validate the α_o and α_D parameters through empirical studies of MSMEs that have already adopted blockchain; (2) extend the model with a cost–benefit analysis to evaluate investment feasibility; and (3) develop an open-access decision-support system based on FMEA-SCOR-Blockchain. The framework is offered as a starting point for the digital transformation of Indonesia's halal industry ahead of the mandatory halal regime in October 2026.

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