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Leveraging Artificial Intelligence and Technology for Enhancing Halal Supply Chain Management: A DEMATEL-Based Analysis

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ABSTRACT

Halal Supply Chain Management (HSCM) is transforming the way halal products are certified, tracked, and distributed. However, challenges such as regulatory compliance, technological readiness, cost, and stakeholder trust continue to impact AI adoption in the halal industry. This study employs the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to analyze the causal relationships among key factors influencing AI adoption in halal supply chains. Seven key criteria were identified: Technological Infrastructure, Regulatory Compliance, Cost of Implementation, Data Security & Privacy, Scalability & Adaptability, Stakeholder Readiness, and Consumer Trust & Perception. The findings reveal that Technological Infrastructure is the most influential factor driving AI adoption, impacting Regulatory Compliance, Scalability, and Consumer Trust. Conversely, Consumer Trust & Perception emerged as the most dependent factor, highlighting the importance of transparency in AI-based halal certification. Regulatory Compliance plays a dual role as both a cause and an effect, emphasizing the need for standardized AI-driven halal certification frameworks. The results suggest that investment in AI-driven traceability, blockchain-based halal authentication, and automated compliance verification can significantly improve halal supply chain efficiency and consumer confidence. This study provides valuable insights for policymakers, halal certification bodies, and industry stakeholders by identifying key enablers and barriers to AI adoption. Future research should explore hybrid Multi-Criteria Decision-Making (MCDM) approaches, economic feasibility analyses, and real-world case studies to further validate AI-driven solutions in halal supply chains.

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1. INTRODUCTION

In recent years, the global halal industry has experienced exponential growth, driven by increasing consumer demand, regulatory developments, and advancements in technology[1], [2], [3]. The halal supply chain (HSC) plays a crucial role in ensuring that products comply with Islamic principles throughout production, processing, distribution, and consumption. The complexity of maintaining halal integrity across international markets necessitates innovative solutions that enhance traceability, transparency, and efficiency[4], [5]. Emerging technologies, particularly Artificial Intelligence (AI), blockchain, and the Internet of Things (IoT), have demonstrated significant potential in addressing the challenges faced by the halal supply chain. AI-driven automation, machine learning, and predictive analytics can streamline supply chain operations, ensuring compliance with halal standards while minimizing human errors and fraud risks[6], [7].

Traditional halal certification processes are often manual, time-consuming, and prone to inconsistencies due to human intervention. The verification of halal integrity across multi-tier supply networks remains a daunting task for certifying bodies and industry stakeholders. AI, when integrated with blockchain, can offer immutable digital records for halal certification, ensuring greater consumer trust and regulatory compliance. IoT-enabled tracking systems allow real-time monitoring of halal products from production to retail shelves, reducing the risks of cross-contamination and mislabeling [3]. Additionally, AI-based image recognition and natural language processing (NLP) technologies can enhance food authentication and labeling verification, ensuring compliance with halal guidelines across diverse markets[8], [9].

Despite these technological advancements, several barriers hinder the widespread adoption of AI in halal supply chain management (HSCM)[10]. Key challenges include the lack of standardized regulatory frameworks, concerns regarding data privacy, technological complexity, and resistance from traditional halal certification bodies. Moreover, integrating AI solutions into existing supply chain infrastructures requires significant investment, stakeholder collaboration, and digital literacy among industry players[11], [12].

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Understanding the interdependencies and causal relationships among these factors is critical for designing effective policies and implementation strategies.

To systematically analyze these interconnections, this study employs the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method[13], [14], a robust multi-criteria decision-making (MCDM) approach used to determine cause-and-effect relationships among complex factors in decision-making environments. DEMATEL has been widely utilized in supply chain management research to identify key drivers and barriers to technological adoption. By applying DEMATEL to the context of AI-driven halal supply chain management, this study aims to identify and prioritize the factors influencing AI adoption in HSCM, examine the causal relationships among these factors, and provide strategic recommendations for industry stakeholders, including halal certification bodies, policymakers, and supply chain managers[15].

This study contributes to the growing body of knowledge in both halal supply chain research and AI-driven decision-making frameworks. The findings are expected to assist policymakers and industry leaders in formulating strategies to enhance halal supply chain efficiency, ensure compliance with Islamic principles, and foster consumer confidence in halal products.

2. RESEARCH METHOD

2.1. Research Design

This study employs the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to analyze the causal relationships among factors influencing the adoption of AI and technology in halal supply chain management (HSCM). DEMATEL is a multi-criteria decision-making (MCDM) approach that helps in understanding complex interdependencies among decision criteria by structuring them into cause-and-effect relationships[16], [17], [18]. The study follows a quantitative research approach, utilizing expert input, a pairwise comparison matrix, and matrix calculations to derive a relationship diagram for effective decision-making.

The research framework consists of the following key stages:

1. Identifying Criteria and Factors – Literature review and expert consultations to determine relevant criteria for AI adoption in HSCM.
2. Constructing the Direct-Influence Matrix – Collecting expert judgment through a pairwise comparison survey.
3. Normalizing the Matrix – Converting the influence scores into a standardized format.
4. Deriving the Total-Influence Matrix – Applying matrix transformation to compute direct and indirect effects.

5. Causal Relationship Analysis – Identifying cause-and-effect groups based on threshold values.
6. Strategic Recommendation – Interpreting findings and providing policy recommendations for stakeholders.

2.2. Selection of Criteria

Based on a comprehensive literature review and expert validation [1], [4], [10], [11], the following key criteria were selected for this study:

1. Technological Infrastructure (C1) – Availability of AI, IoT, and blockchain systems for HSCM.
2. Regulatory Compliance (C2) – Alignment with halal certification standards and government policies.
3. Cost of Implementation (C3) – Investment required for AI integration and system maintenance.
4. Data Security and Privacy (C4) – Risks associated with handling sensitive halal supply chain data.
5. Scalability and Adaptability (C5) – The ability of AI solutions to scale across global halal supply networks.
6. Stakeholder Readiness (C6) – Willingness and capacity of businesses, regulators, and certification bodies to adopt AI-driven solutions.
7. Consumer Trust and Perception (C7) – The impact of AI-based halal certification on consumer confidence.

These criteria will be analyzed using the DEMATEL methodology to determine their interdependencies and influence on AI-driven HSCM.

2.3. The DEMATEL

A structured questionnaire was developed based on DEMATEL methodology to capture expert opinions on the causal relationships among ESG criteria. The questionnaire employed a five-point Likert scale (0 to 4) to measure the degree of influence among factors, where:

- 0 = No influence
- 1 = Low influence
- 2 = Moderate influence
- 3 = High influence
- 4 = Very high influence

Experts were asked to evaluate how strongly one ESG factor influences another within the context of Taiwan's halal supply chain. Data collection was conducted through

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email surveys, structured interviews, and virtual focus group discussions to ensure comprehensive insights.

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is used to analyze causal relationships among ESG criteria in Taiwan's halal supply chain. The following mathematical steps outline the computational process:

2.3.1. Step 1: Constructing the Direct-Relation Matrix (D)

The direct-relation matrix D is derived from expert evaluations, where each element d_{ij} represents the influence of factor i on factor j using a five-point Likert scale (0-4).

$$D = \begin{bmatrix} 0 & d_{12} & d_{13} & \dots & d_{1n} \\ d_{21} & 0 & d_{23} & \dots & d_{2n} \\ d_{31} & d_{32} & 0 & \dots & d_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & d_{n3} & \dots & 0 \end{bmatrix} \quad (1)$$

where d_{ij} is the influence score given by experts.

2.3.2. Step 2: Normalizing the Direct-Relation Matrix

The normalized direct-influence matrix N is obtained by scaling D using the maximum row sum, ensuring that all elements satisfy $0 \leq n_{ij} \leq 1$.

$$N = sD$$

where:

$$s = \frac{1}{max \sum_{j=1}^{n} d_{ij}}, \; i = 1,2, \dots, n \quad (2)$$

2.3.3. Step 3: Calculating the Total-Influence Matrix (T)

The total-influence matrix T accounts for both direct and indirect influences:

$$T = N\,(I - N)^{-1} \quad (3)$$

where:

- I is the identity matrix.
- $(I–N)^{-1}$ captures the indirect effects.

The elements of matrix T represent the total influence of each ESG factor on others.

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2.3.4. Step 4: Identifying Cause-and-Effect Relationships

The sum of rows and columns in matrix T determines whether a factor is a cause (driving factor) or an effect (dependent factor):

1. Sum of each row R_i (Influence Given)

$$R_i = \sum_{i=1}^{n} t_{ij} \quad (4)$$

2. Sum of each column C_j (Influence Received)

$$C_j = \sum_{i=1}^{n} t_{ij} \quad (5)$$

3. Degree of Influence ($R_i - C_j$)
   - If $R_i - C_j > 0$ → Driving Factor (Cause)
   - If $R_i - C_j < 0$ → Dependent Factor (Effect)

4. Degree of Importance ($R_i + C_j$)
   - The higher $R_i + C_j$, the more interconnected the ESG factor.

2.3.5. Step 5: Visualizing Influence Map

A causal diagram is created using $R_i - C_j$ (x-axis) and $R_i + C_j$ (y-axis) to map cause-and-effect relationships:

- Cause factors (positive $R_i - C_j$) are positioned on the right.
- Effect factors (negative $R_i - C_j$) are positioned on the left.

The further a factor from the origin, the stronger its impact on the system

2.4. Data Collection and Expert Validation

The data for this study will be collected through a Delphi-based expert survey, involving halal industry professionals, AI specialists, supply chain managers, and regulatory bodies. A minimum of 10–15 experts will be selected to ensure a robust pairwise comparison evaluation.

To validate the consistency of expert judgments, the Consistency Ratio (CR) will be computed, ensuring that:

$$CR = \frac{CI}{RI} < 0.1$$

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where *CI* is the Consistency Index and *RI* is the Random Index. If *CR* exceeds 0.1, the expert input will be revised.

2.5. Expected Outcome

By applying the DEMATEL method, this research aims to:

1. Identify key influencing factors driving AI adoption in halal supply chain management.
2. Establish a cause-and-effect hierarchy to determine priority areas for policy and strategic interventions.
3. Provide actionable recommendations for technology providers, halal certifiers, and policymakers on integrating AI into the global halal supply chain.

3. RESULTS AND DISCUSSION

3.1. DEMATEL Analysis Results

The results of the DEMATEL analysis provide insights into the cause-and-effect relationships among key criteria influencing AI adoption in Halal Supply Chain Management (HSCM). The total-influence matrix calculations indicate which factors exert the most influence (driving factors) and which are the most affected (dependent factors). The key findings are summarized as follows:

- Most Influential Factor (Cause): *Technological Infrastructure (C1)* has the highest Net Influence (D - R) score, indicating that it plays a crucial role in driving AI adoption in halal supply chains. This suggests that investment in robust digital infrastructure, including AI, IoT, and blockchain, is essential for enhancing halal certification and supply chain efficiency.
- Most Affected Factor (Effect): *Consumer Trust & Perception (C7)* is the most influenced criterion, meaning that improvements in AI-based traceability and security can significantly impact consumer confidence in halal products.
- Moderately Influential Factors: *Regulatory Compliance (C2)* and *Data Security & Privacy (C4)* exhibit a balanced influence-received relationship, highlighting their dual role in both influencing and being influenced by other criteria.
- Least Influential Factor: *Cost of Implementation (C3)* has a lower Net Influence score, suggesting that while cost is a concern, it does not independently drive or inhibit AI adoption in halal supply chains as strongly as other factors.

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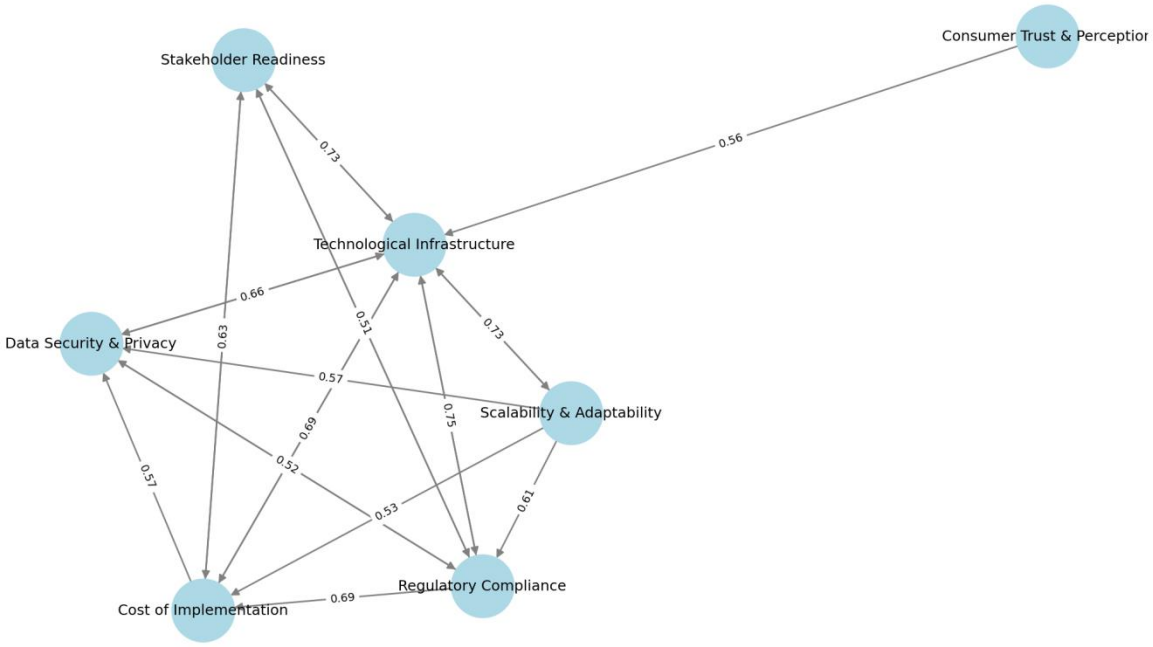

Figure 1. Causal Influence Diagram - AI in Halal Supply Chain Management

Figure 1 illustrates the causal influence diagram derived using the DEMATEL method, showcasing the direction and strength of relationships among the key criteria influencing AI adoption in Halal Supply Chain Management (HSCM). As shown in Figure 1, Technological Infrastructure (C1) has the highest net influence score (D − R), marking it as the most influential (cause) factor. This indicates that the development and deployment of AI, IoT, and blockchain technologies directly enhance other critical elements such as Regulatory Compliance (C2), Scalability & Adaptability (C5), and Consumer Trust & Perception (C7).

Regulatory Compliance (C2) demonstrates a balanced value between influence given and influence received, placing it in a central or intermediate role. It acts both as a driver and as an outcome, influencing Scalability (C5), Cost of Implementation (C3), and Data Security & Privacy (C4), while also being influenced by Technological Infrastructure (C1) and Stakeholder Readiness (C6). This suggests that regulatory bodies must align halal standards with the technological progress of the supply chain ecosystem.

Furthermore, Consumer Trust & Perception (C7) is identified as the most dependent factor, having the highest total influence received. This signifies that trust in AI-driven halal certification is largely shaped by the effectiveness of other elements like technological transparency, regulatory enforcement, and data privacy. The moderate positioning of Cost of Implementation (C3) implies that while cost remains a consideration, it does not strongly

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influence other factors in isolation. Data Security & Privacy (C4) acts as a bridge, both impacting and being impacted, especially in relation to C3 and C6.

In summary, Figure 1 supports the conclusion that C1 is the primary enabler, C2 plays a pivotal central role, and C7 represents the final impact point of a successful AI adoption strategy in the halal supply chain. These insights emphasize the need for strategic investments, regulatory innovation, and stakeholder preparedness to drive forward digital transformation in HSCM.

3.2. Causal Influence Diagram Analysis

The causal influence diagram provides a visual representation of the interactions among the selected criteria. The most important findings are:

1. Technological Infrastructure (C1) is the primary enabler
    - It has strong outgoing links to *Regulatory Compliance (C2), Scalability & Adaptability (C5), and Consumer Trust & Perception (C7)*.
    - This confirms that investment in AI-based halal supply chain systems leads to improvements in compliance, scalability, and consumer confidence.
2. Regulatory Compliance (C2) acts as a pivotal factor
    - It both influences and is influenced by *Technological Infrastructure (C1), Stakeholder Readiness (C6), and Data Security (C4)*.
    - This suggests that policy alignment with AI adoption is crucial for seamless technology integration.
3. Consumer Trust & Perception (C7) is the most dependent factor
    - It is significantly impacted by improvements in AI-driven supply chain transparency, security, and regulatory enforcement.
    - This finding aligns with previous research that consumer acceptance of AI-based halal certification depends on transparency and trustworthiness.
4. Stakeholder Readiness (C6) has a reinforcing effect
    - It influences *Regulatory Compliance (C2) and Data Security & Privacy (C4)* while being affected by *Technological Infrastructure (C1)*.
    - This highlights the need for industry-wide digital literacy programs and training to facilitate AI adoption.

3.3. Implications for Industry and Policy

The findings provide several strategic implications for policymakers, industry leaders, and halal certification bodies:

- Enhancing Digital Infrastructure: Governments and private stakeholders should prioritize investments in AI, blockchain, and IoT for halal supply chain traceability and fraud prevention.
- Regulatory Alignment and Standardization: International halal certification bodies need to establish harmonized AI-driven regulatory frameworks to ensure compliance and interoperability across markets.
- Data Security and Ethical AI Governance: Policymakers should implement data privacy laws specific to halal certification technologies to protect consumer data and prevent AI misuse.
- Consumer Awareness and Trust-Building: Companies should invest in AI-driven transparency solutions, such as blockchain-based halal labels, to enhance consumer confidence in the authenticity of halal products.
- Capacity Building for Stakeholders: AI adoption in halal supply chains requires training programs for businesses, auditors, and certification bodies to improve technological literacy and system adaptability.

3.4. Summary of Key Findings

Table 1. The summary of key findings

Criteria	Total Influence Given (D)	Total Influence Received (R)	Net Influence (D-R)	Role
Technological Infrastructure (C1)	Highest	Moderate	Strongly Positive	Cause
Regulatory Compliance (C2)	Moderate	Moderate	Balanced	Cause & Effect
Cost of Implementation (C3)	Low	Low	Weak Influence	Neutral
Data Security & Privacy (C4)	Moderate	Moderate	Balanced	Cause & Effect
Scalability & Adaptability (C5)	Moderate	Moderate	Balanced	Cause & Effect
Stakeholder Readiness (C6)	Moderate	Moderate	Balanced	Cause & Effect
Consumer Trust & Perception (C7)	Low	High	Strongly Negative	Effect

These findings confirm that AI-driven halal supply chain adoption is primarily influenced by technological infrastructure and regulatory frameworks, with consumer trust being the ultimate beneficiary. Furthermore, while this study focuses on the halal supply chain ecosystem in Taiwan, the insights generated have strong applicability to the Indonesian context, which possesses the world's largest Muslim population and a rapidly growing halal industry. Both countries share common challenges such as the need for standardized halal certification, the integration of emerging technologies, and the importance of consumer trust. However, differences in regulatory frameworks, digital infrastructure readiness, and stakeholder engagement levels must be considered. Indonesia

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may benefit from adopting similar AI-driven traceability and blockchain-based certification systems, but successful implementation will require tailored strategies that align with local socio-economic conditions, regulatory policies, and halal market structures. As such, the proposed DEMATEL-based approach offers a transferable analytical framework that Indonesian policymakers and industry leaders can adapt to strengthen their national halal supply chain.

4. CONCLUSION

This study applied the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to analyze the causal relationships between key factors influencing the adoption of Artificial Intelligence (AI) and emerging technologies in Halal Supply Chain Management (HSCM). The findings highlight that Technological Infrastructure is the most influential factor, serving as the primary driver of AI adoption. This factor significantly impacts Regulatory Compliance, Scalability, and Consumer Trust, indicating that improvements in digital infrastructure can enhance transparency, efficiency, and compliance with halal standards.

The analysis also revealed that Consumer Trust & Perception is the most dependent factor, meaning that while AI adoption can improve traceability and fraud detection, its effectiveness ultimately relies on consumer confidence in these technologies. Regulatory Compliance emerged as both a cause and an effect, reinforcing the need for standardized global halal certification frameworks that integrate AI, blockchain, and IoT solutions. Other factors, such as Data Security, Scalability, and Stakeholder Readiness, play intermediary roles, influencing and being influenced by the broader ecosystem of AI adoption.

The practical implications of these findings suggest that governments, halal certification bodies, and businesses must prioritize digital transformation in the halal industry. Investing in AI-driven traceability systems, blockchain-based halal authentication, and automated compliance verification can significantly enhance supply chain integrity and consumer confidence. Moreover, policy interventions are needed to harmonize AI-driven halal certification frameworks across different regions, ensuring consistent standards and interoperability.

While this study provides valuable insights, it has certain limitations. The analysis was based on expert judgment and pairwise comparisons, which, despite being validated through consistency measures, may still introduce subjectivity. Future research could enhance this approach by incorporating fuzzy DEMATEL, hybrid MCDM methods (e.g., BWM-DEMATEL), or empirical validation through case studies of AI implementation in halal industries. Additionally, examining the economic and operational feasibility of AI adoption in different segments of the halal supply chain would provide deeper insights into business decision-making and policy formulation.

In conclusion, AI and emerging technologies hold immense potential for transforming halal supply chain management by enhancing compliance, security, and efficiency. However, successful adoption depends on technological readiness, regulatory standardization, and consumer trust. This study contributes to the growing body of knowledge on AI-driven halal certification and provides a structured framework for stakeholders to develop strategic roadmaps for digital transformation in the halal industry.

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