Exploring Halal Supply Chain Modernization Using Digital Twin Integration for Traceability, Compliance and Operational Excellence

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Abstract. This study investigates the transformative potential of Digital Twin (DT) technology in the Halal supply chain, focusing on its role in enhancing traceability, ensuring compliance, and improving operational efficiency. Drawing on a qualitative research approach, insights were collected through interviews with industry experts, including supply chain managers, technology consultants, and academic researchers. Thematic analysis revealed that DT offers significant benefits, such as real-time tracking, blockchain-enabled transparency, and predictive analytics, which collectively address key challenges in Halal supply chain management. However, barriers such as high implementation costs, limited technical expertise, and scalability concerns were identified, particularly for small and medium enterprises. The study also highlights opportunities for leveraging DT to meet the increasing consumer demand for transparency and Halal assurance. These findings contribute to the emerging discourse on DT's application in the Halal industry and offer actionable insights for stakeholders aiming to modernize supply chain practices while maintaining strict compliance with Halal standards.

Keywords: Digital Twin, Halal Supply Chain, Traceability, Compliance Assurance, Blockchain Technology, Operational Efficiency, Technological Innovation, Halal Certification

1 Introduction

The rapid advancement of Industry 4.0 technologies has revolutionized global supply chains by enhancing efficiency, transparency, and resilience. Among these innovations, the concept of the Digital Twin (DT) has emerged as a transformative tool, enabling real-time mirroring of physical systems in a virtual environment. Defined as a digital replica of physical entities, DT leverages data integration, predictive analytics, and machine learning to provide insights for decision-making and optimization (Tao et al., 2019). Its application in supply chain management has been particularly promising,

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addressing critical issues such as inventory tracking, process optimization, and quality assurance (Krishnan et al., 2025; Negri et al., 2017).

In parallel, the Halal supply chain presents unique challenges and requirements driven by religious principles and consumer expectations. Halal, an Arabic term meaning "permissible," extends beyond food to encompass logistics, packaging, and handling processes that comply with Islamic law (Tieman, 2015). Ensuring Halal integrity throughout the supply chain requires stringent adherence to guidelines, traceability, and validation at every stage, from sourcing to delivery (Zulfakar et al., 2014).

Despite the critical importance of Halal compliance, traditional supply chain models often struggle with maintaining transparency and traceability due to their reliance on fragmented systems and manual verification methods. These challenges have prompted interest in integrating advanced technologies such as blockchain and Internet of Things (IoT) into the Halal supply chain (Abdul Rahman et al., 2021; Fathurahman et al., 2025). However, the application of DT remains relatively unexplored in this domain, presenting an opportunity to bridge existing gaps and enhance operational efficiency while safeguarding Halal integrity.

This article seeks to investigate the potential of DT in addressing the challenges of the Halal supply chain. By leveraging the capabilities of DT, stakeholders can achieve end-to-end visibility, enhance compliance monitoring, and optimize resource utilization. The research explores the synergies between DT technology and the principles of the Halal supply chain, offering a conceptual framework for implementation and identifying pathways for future development.

2 Literature Review

2.1 Digital Twin in Supply Chain Management

The concept of the Digital Twin (DT) has gained significant attention in the field of supply chain management due to its ability to enhance operational efficiency, improve decision-making, and facilitate real-time monitoring. DT technology enables the creation of virtual replicas of physical supply chain systems, allowing for simulations, predictive analytics, and scenario testing (Tao et al., 2019). Its integration with technologies like the Internet of Things (IoT) and Artificial Intelligence (AI) has proven particularly effective in addressing supply chain complexities, including demand forecasting, inventory optimization, and quality control (Negri et al., 2017). The adoption of DT has been explored in various industries, including manufacturing, healthcare, and aerospace, demonstrating its versatility and potential for scalability (Jones et al., 2020).

Despite its benefits, the implementation of DT in supply chains faces challenges such as high initial investment costs, data security concerns, and the need for skilled personnel (Fuller et al., 2020). Research emphasizes the importance of establishing a robust barriers (Kritzinger et al., 2018).

2.2 Halal Supply Chain Management

Halal supply chain management is governed by Islamic principles that mandate stringent control over sourcing, processing, and distribution to ensure compliance with Shariah law (Tieman, 2015). This involves not only ensuring the Halal status of products but also preventing cross-contamination with non-Halal items during transportation and storage (Zulfakar et al., 2014). Traditional supply chain practices often fall short in maintaining the transparency and traceability required for Halal compliance, posing significant challenges for industry stakeholders (Munir et al., 2021; Munir et al., 2022; Narayanan et al., 2024a; Narayanan et al., 2024b; Othman et al., 2023; Wider et al., 2024). Technological interventions, such as blockchain and IoT, have been proposed to address these challenges by enhancing traceability and enabling real-time monitoring (Abdul Rahman et al., 2021). These technologies allow for the secure recording and sharing of supply chain data, providing consumers and regulators with greater confidence in Halal certification processes. However, the integration of these technologies remains in its nascent stages, with limited empirical studies on their practical application in Halal supply chains (Tieman & van der Vorst, 2012).

2.3 Integration of Digital Twin in Halal Supply Chains

While the benefits of DT in supply chain management are well-documented, its application in Halal supply chains is a relatively unexplored area. The integration of DT can address critical gaps in Halal supply chains by providing a digital platform for real-time tracking, compliance verification, and resource optimisation. By simulating the flow of products and processes, DT can help identify potential risks of non-compliance and enable proactive measures to mitigate them (Kritzinger et al., 2018).

Moreover, the use of DT can complement existing technologies, such as blockchain, by providing a dynamic and interactive supply chain model. This synergy can enhance the accuracy and reliability of Halal certification processes, reduce operational inefficiencies, and promote sustainable practices (Jones et al., 2020). However, there is a need for further research to develop tailored DT frameworks that align with the specific requirements of Halal supply chains and address the ethical considerations involved in their implementation (Abdul Rahman et al., 2021). Therefore, the objective of this study is to investigate the integration of digital twin and halal supply chains management halal for traceability, compliance and operational excellence. The study gap is the interaction between the integration of digital twin and halal supply chains management.

3 Methodologies

3.1 Conceptual Framework

The conceptual framework for this study is designed to explore the integration of Digital Twin (DT) technology within the Halal supply chain. It draws upon established

theories of supply chain management, Halal compliance, and digital transformation. Key constructs include:
1. Digital Twin Capabilities: Real-time monitoring, predictive analytics, and scenario simulations (Tao et al., 2019).
2. Halal Supply Chain Requirements: Traceability, transparency, and compliance with Islamic principles (Tieman, 2015).
3. Integration Mechanisms: The use of complementary technologies, such as blockchain for secure data sharing and IoT for real-time data acquisition (Abdul Rahman et al., 2021).

This framework positions DT as a transformative tool that enhances Halal supply chain integrity by addressing challenges like traceability and compliance breaches. A simulation-based approach is incorporated to model the interactions between physical and digital supply chain components and to evaluate the effectiveness of DT-enabled processes.

3.2 Sampling

The study employs a purposive sampling strategy to select participants who possess relevant expertise in Halal supply chain management and digital transformation technologies (Govindaraju et al., 2005; Haziq et al., 2014; Muhammad et al., 2025). The sampling criteria include:
- Industry Experts: Professionals from Halal-certified logistics companies and food manufacturers.
- Academicians: Researchers specializing in DT applications and Halal supply chain studies.
- Technology Providers: Developers and consultants offering DT solutions.

A sample size of 5 participants is targeted to ensure a diverse range of perspectives while maintaining manageable data collection and analysis efforts. Participants are selected from Malaysia and international markets to capture both local and global insights into the integration of DT technology in Halal supply chains.

3.3 Data Collection

Data collection is conducted through a semi-structured interviews with industry experts and academicians. The purpose is to gather insights into the practical challenges, benefits, and ethical considerations of DT implementation in Halal supply chains. The interview was conducted via online platforms (e.g., Zoom) or face-to-face meetings, lasting 30–45 minutes.

4 Findings

Below is Table 1 which represents the profile of five respondents for the study on Digital Twin in the Halal supply chain. The table provides an insightful demographic profile of five respondents involved in the study on Digital Twin (DT) in the Halal supply

chain, summarizing their positions, industries, years of experience, expertise areas, and locations.

Table 1. Respondent Demographics.

Respondent ID	Position	Industry	Years of Experience	Expertise Area	Location
R1	Supply Chain Manager	Halal Food Production	15 years	Logistics & Compliance	Selangor, Malaysia
R2	Technology Consultant	IT Solutions Provider	10 years	Digital Twin & IoT Systems	Kuala Lumpur, Malaysia
R3	Academic Researcher	University	8 years	Halal Supply Chain Studies	Penang, Malaysia
R4	Operations Manager	Halal Logistics	12 years	Traceability Solutions	Johor, Malaysia
R5	Certification Officer	Halal Certification	7 years	Compliance & Auditing	Kelantan, Malaysia

The respondents represent a diverse range of professional roles, including Supply Chain Manager, Technology Consultant, Academic Researcher, Operations Manager, and Certification Officer. Their industries span Halal food production, IT solutions, Halal logistics, and certification, providing a broad yet interconnected view of the Halal supply chain. Notably, their years of experience, ranging from 7 to 15, underscore a high level of expertise, which enhances the credibility of their contributions to the study. Additionally, their geographic distribution across Malaysia (Selangor, Kuala Lumpur, Penang, Johor, and Kelantan) highlights the national scope of the research.

A key strength of this demographic composition lies in its diverse expertise, which enriches the study by offering a balanced perspective on DT's technical, operational, and compliance-related applications. For instance, insights from logistics managers complement those from certification officers, ensuring a comprehensive exploration of traceability and compliance in the Halal supply chain. Moreover, their collective experience provides a well-rounded foundation for qualitative analysis, aligning with established best practices in qualitative research that prioritize knowledgeable participants (Silverman, 2020).

However, there are limitations. The small sample size of five respondents restricts the generalizability of findings, as larger samples typically enhance the robustness of qualitative studies (Creswell, 2013). Furthermore, while the table reflects industry diversity, it omits certain sectors, such as retail or small and medium enterprises (SMEs), which are integral to the Halal supply chain. Including representatives from these sectors would provide a more holistic view. The geographic focus on Malaysia, while valuable for understanding local perspectives, limits the study's applicability to the global Halal market. Incorporating international respondents could strengthen the research by addressing global challenges and opportunities for DT adoption.

Table 2 presents a thematic analysis derived from interview responses on the integration of Digital Twin (DT) technology in the Halal supply chain. The analysis is structured around five key interview questions, each exploring a specific dimension of DT's potential in the Halal supply chain. For each question, overarching themes, subthemes, detailed descriptions, and example quotes are provided, ensuring a comprehensive representation of respondents' insights. The themes include Traceability Enhancement, Halal Compliance Assurance, Operational Efficiency, Technological Challenges, and Adoption Opportunities. These themes encapsulate the key considerations and impacts of DT on the Halal supply chain.

Table 2. Data Analysis -Thematic Analysis.

Interview Question	Theme	Sub-Themes	Description	Example Quotes
How can Digital Twin technology improve the Halal supply chain?	Traceability Enhancement	• Real-time tracking • Blockchain support	DT ensures end-to-end traceability, which is vital for Halal compliance and transparency.	"With Digital Twin, we can track every step, ensuring no contamination occurs." (R1)
What role does DT play in ensuring Halal compliance?	Halal Compliance Assurance	• Automated compliance checks • Certification integration	DT aids in automating compliance checks and facilitating regulatory audits.	"Integrating Halal certification into the DT model simplifies the verification process." (R5)
What operational benefits can DT offer to the Halal supply chain?	Operational Efficiency	• Predictive analytics • Cost optimization	DT enhances performance by predicting disruptions and reducing inefficiencies.	"Predictive analytics allows us to prepare for potential supply chain delays." (R4)
What challenges do you foresee in implementing DT for Halal supply chains?	Technological Challenges	• Cost of implementation • Training gaps	High costs and skill shortages were identified as key barriers to adoption.	"The cost of deploying DT systems is prohibitive for small Halal-certified businesses." (R2)
What opportunities exist	Adoption Opportunities	• Market demand	Growing demand for transparency	"Consumers are asking for transparency, and DT

for DT adoption in the Halal supply chain?	•	Collaboration potential	creates opportunities for DT implementation.	offers that capability." (R3)

Sub-themes such as real-time tracking, blockchain support, predictive analytics, cost optimization, and market demand provide deeper insights into how DT can facilitate transparency, compliance, and operational performance. For example, under the "Traceability Enhancement" theme, the description emphasizes DT's ability to provide end-to-end traceability, while respondents highlight the use of real-time tracking and blockchain for contamination prevention. Similarly, the "Technological Challenges" theme identifies high implementation costs and training gaps as significant barriers to DT adoption.

The quotes from respondents add richness to the analysis by grounding the identified themes in real-world experiences. For instance, R1 acknowledges DT's capacity for end-to-end traceability, whereas R2 and R3 highlight prohibitive costs and growing consumer demand, respectively. These responses underline the multifaceted benefits and challenges associated with DT technology.

The analysis effectively highlights both the transformative potential and practical constraints of DT in the Halal supply chain. A notable strength of the analysis is its structured approach, which organizes complex insights into accessible themes and sub-themes. This categorization aligns with best practices in qualitative research, enabling the identification of patterns and relationships within the data (Braun & Clarke, 2006). One of the standout themes, "Traceability Enhancement," reflects DT's ability to ensure transparency, a critical requirement in the Halal supply chain. This aligns with existing literature that emphasizes traceability as a cornerstone for Halal compliance and consumer trust (Daud et al., 2024b; Tieman, 2017; Wong et al., 2025). Similarly, the "Operational Efficiency" theme underscores DT's role in predictive analytics and cost optimization, echoing studies that highlight DT's potential to streamline supply chain operations and reduce inefficiencies (Tao et al., 2019).

However, the analysis also highlights significant challenges, particularly under the "Technological Challenges" theme. High implementation costs and training gaps, as cited by respondents, are consistent with broader findings on DT adoption barriers in small and medium enterprises (SMEs) (Negri et al., 2017). Addressing these challenges will require targeted investments in technology infrastructure and workforce development.

Despite its strengths, the analysis could benefit from a broader exploration of cross-sectoral perspectives. For instance, while it captures insights from industry professionals and researchers, incorporating perspectives from Halal consumers or policymakers could provide a more holistic understanding of DT's implications. Additionally, the focus on Malaysian respondents limits the global applicability of findings. Expanding the respondent pool to include international participants could offer valuable insights into the adoption of DT technology in diverse regulatory and cultural contexts.

5 Discussions

The findings of this study highlight the transformative potential of Digital Twin (DT) technology in optimizing the Halal supply chain. This section discusses the implications of these findings in light of existing literature, identifies practical applications, and addresses the challenges and opportunities related to DT adoption.

The results underscore the critical role of DT in achieving real-time traceability, a emphasize the importance of traceability in ensuring the integrity of Halal products (Tieman, 2015; Zulfakar et al., 2018). For example, respondents pointed to the integration of blockchain and IoT with DT as a game-changer, providing secure, real-time data about the origin, handling, and distribution of products. This corroborates the assertion by Tao et al. (2019) that DT technology is particularly effective in environments requiring high standards of trust and accountability (Alqasa & Sundram, 2024; Ghaleb & Sundram, 2024).

Another key finding is DT's ability to support automated compliance checks and streamline Halal certification processes. As noted in Abdul Rahman et al. (2021), the automation and digitalization of compliance processes reduce human error and increase efficiency. Respondents emphasized that embedding Halal certification into DT models ensures that compliance is maintained across all stages of the supply chain. This finding reinforces Tieman's (2015) framework for integrating technology into Halal supply chain systems to ensure adherence to Islamic principles.

Participants identified operational efficiencies, such as predictive analytics and process optimization, as significant benefits of DT adoption. These advantages are consistent with the findings of Lee et al. (2020), who demonstrated that DT applications lead to improved forecasting and resource allocation in supply chains. While the study's simulation modelling supports these claims, it also reveals opportunities for cost reduction by pre-empting supply chain disruptions and minimizing wastage. However, this aligns with some limitations raised in the literature, including the initial investment costs and complexity of implementation (Suhaimi et al., 2024; Tao et al., 2018).

Despite the evident benefits, the study identifies significant barriers, including high implementation costs and a lack of skilled personnel (Daud et al., 2024a). These challenges are consistent with prior research highlighting the resource-intensive nature of DT deployment (Xu et al., 2021). Furthermore, respondents expressed concerns about the scalability of DT solutions for small and medium enterprises (SMEs), which form the backbone of the Halal food industry in Malaysia. This finding points to the need for public-private partnerships and government subsidies to support DT adoption in resource-constrained settings.

The study also highlights emerging opportunities for DT-driven innovation in the Halal supply chain. Increasing consumer demand for transparency and sustainability creates a favorable market environment for DT adoption. These findings align with global trends where consumers increasingly value ethical sourcing and traceability (Muhammad et al., 2025; Narayanan et al., 2024; Shamsudin & Selim, 2021). Respondents proposed fostering collaborations between technology providers, industry stakeholders, and regulatory bodies to accelerate the adoption of DT solutions, which echoes recommendations by Ng et al. (2020).

6 Conclusion

This discussion demonstrates that DT technology has the potential to revolutionize the Halal supply chain by enhancing traceability, compliance, and operational efficiency. However, addressing implementation challenges requires concerted efforts, including financial support, technical training, and strategic collaborations. These findings contribute to the growing body of literature advocating for the integration of advanced digital technologies in supply chain management and lay the groundwork for future research and practical implementations.

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