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Holistic Framework for Blockchain-Based Halal Compliance in Supply Chains Enabled by Artificial Intelligence

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Abstract: The global halal market is growing, driven by rising stakeholder populations and increasing consumer interest in ethical and sustainable food choices. This surge in demand necessitates robust halal compliance throughout complex supply chains. However, there are several challenges, including fragmented information, increased understanding of halal requirements among stakeholders, and difficulties in tracing product provenance. This paper proposes a holistic framework for halal certification and compliance, addressing these challenges through the integration of artificial intelligence (AI) and blockchain technologies. AI can automate halal compliance checks, identify potential irregularities in sourcing and composition, and facilitate risk management. The blockchain offers an ideal platform for tracking product provenance throughout the halal supply chain. This ensures trust and confidence among consumers by providing verifiable information on ingredient origin and production processes. This paper further strengthens the potential of this framework by presenting an illustrative example that utilises knowledge graphs, machine learning, and smart contracts. This exemplifies the potential application of the proposed framework in the context of halal pre-certification processes. By fostering transparency and streamlining compliance procedures, the proposed holistic framework, empowered by AI and the blockchain, can significantly enhance trust and confidence among stakeholders within the halal food industry.

Keywords: halal certification; artificial intelligence; blockchain; knowledge graph; machine learning; supply chain

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1. Introduction

Halal, which simply means permissible, is the subject of growing global demand for food products that conform to its guidelines. The growing halal market in the food industry is driven in part by rising stakeholder populations and increasing consumer interest in ethical and sustainable food choices. In addition, halal extends beyond dietary restrictions, as it has been reported that benefits include positive treatment of animals, particularly in the way in which they are slaughtered.

Despite the increasing demand for halal-certified food, organisations face several challenges to meet this demand. Current challenges associated with halal include fragmented information, low awareness and insufficient understanding of halal requirements among stakeholders, difficulties in tracing product provenance, ingredient availability, complexity of certification processes, trust issues, costs, and cultural barriers [1–5]. In addition, the issue of food safety and the effectiveness of associated management systems is fundamental [6].

There are strict requirements for products to be certified as halal. These requirements span the whole of the halal food supply chain. For example, halal products can be considered non-halal if they have direct contact with non-halal products and processes during distribution, transportation, logistics, and warehousing [7,8]. Cross-contamination is a significant issue and can occur in many ways along the supply chain. Hence, it has been reinforced that the strict requirements for halal have to be met throughout the halal supply chain, which essentially draws upon the role of assurance and integrity of the supply chain and its products.

Several halal certification bodies exist across the world, including the Islamic Food and Nutrition Council of America (IFANCA), Halal Certification Europe (HCE), the Department of Islamic Development Malaysia (JAKIM), and Majelis Ulama Indonesia (MUI). These bodies and others like them are recognised for their stringent certification processes and adherence to international halal standards. There is a growing consensus that certified halal products should embrace sustainability and the halal supply chain process should draw upon advances in digital technology.

There are relationships between the halal supply chain and sustainability, in terms of environmental, social, and economic factors that affect the sourcing, production, and distribution of food products. Abdullah et al. [9] identified several relevant considerations, such as ensuring the halal status of the product through supply chain integrity, thereby reducing risks of food wastage. Food wastage is problematic and costly for the environment and can lead to stakeholder distrust and dissatisfaction with the product. There is also the consideration that a significant proportion of halal businesses use conventional logistics, are economically driven, and seemingly have low transportation and logistics costs. It has been argued that moving towards sustainable halal supply chains can lead to better performance across the chain, and scholars have identified a lack of research related to sustainable practices in the halal supply chain [9–11].

Increasingly important is the need for a comprehensive framework for halal certification and compliance across the halal supply chain that leverages advances in digital technologies such as artificial intelligence (AI) and the blockchain. AI capabilities in the modelling and analysis of knowledge and data can automate halal compliance checks, detect potential irregularities in sourcing and composition, and facilitate risk management. Meanwhile, the secure and transparent ledger system offered by the blockchain provides an ideal platform for tracking product provenance throughout the halal supply chain, ensuring consumer trust by offering verifiable information on ingredient origins and production processes. This paper proposes a comprehensive framework for certification and compliance in the halal supply chain, leveraging AI and blockchain technologies. The study reported in the paper addresses the following two research questions:

- RQ1: How can regulatory compliance and certification in halal supply chains be addressed holistically with the support of digital technologies and a suitable architecture?
- RQ2: How can the integration of AI and the blockchain in a halal framework enable regulatory compliance and certification in halal food supply chains?

Through RQ1, this paper presents a holistic framework that covers three main aspects of the halal supply chain, namely ingredients, production processes, and logistics. An architecture of integrated AI and blockchain technologies is developed to substantiate the role of these digital technologies in the holistic framework. The framework is exemplified through an illustrative example that investigates its applicability incorporating knowledge graphs, machine learning, and smart contracts in the halal pre-certification process. By fostering transparency and streamlining compliance procedures, this framework, empowered by AI and the blockchain, can significantly enhance trust and confidence among all stakeholders within the halal food industry.

The remainder of the paper is organised into six sections. A background to halal certification challenges and a review of related research is presented in Section 2. This is followed in Section 3 by the research methodology adopted in the study. Section 4 reports on the framework developed. An illustrative example is presented in Section 5. Discussion of results, limitations and implications for theory and practice are presented in Section 6. Finally, Section 7 concludes and points out directions for future research.

2. Background and Literature Review

This section includes an overview of related literature sources as well as background information that is required for understanding the research that is presented here. We start by discussing the various challenges that companies in the halal supply chain encounter, broadly categorised as perception and operational challenges. While our analysis in this section focuses on Asian nations, the presented challenges are representative across the global halal industry. This is followed by an overview of the common strategies used for halal process certification and compliance. After that, we go into relevant research on the application of the blockchain in halal supply chains and how AI is being incorporated into food supply chains to ensure regulatory compliance.

2.1. Challenges in Halal Certification in Asian Countries

As the number of Muslims in Asia is growing, halal certification has become even more important, with increasing uptake by non-Muslims as well. Although there is a growing market for food that has been certified halal, achieving certification presents a number of obstacles for most organisations. Difficulties regarding awareness, ingredient availability, certification procedures, trust, expenses, and cultural obstacles are some of the challenges that halal certification agencies have to address, and these are discussed below.

Lack of understanding and awareness.

One of the biggest obstacles facing businesses in Asian countries is the lack of knowledge and understanding of the prerequisites for halal certification. Many businesses find it difficult to handle, store, and serve halal food due to its complexity, which makes it difficult for them to become certified [1]. The risk of cross-contamination and the use of non-halal ingredients increases when there is insufficient understanding, which results in inappropriate training and instruction. In order to ensure adherence to halal standards, this calls for a deeper look at the educational requirements within the culinary profession. Abas et al. [12] underscore, for example, the significance of education and training in enhancing understanding of animal welfare and optimising meat slaughtering procedures for the production of halal meat. Cultural and social barriers also impede the widespread adoption of halal certification in companies across various Asian countries. The perception of halal food as foreign creates resistance among some restaurant owners and consumers. Marohom and Fuerzas [13] highlight the significance of knowledge and subjective norms in influencing the intention to purchase halal food, emphasising the necessity for consumer awareness and societal acceptance.

Scarcity of ingredients with halal certification.

The restricted access to halal-certified ingredients in many Asian nations presents a major challenge for businesses looking to become certified. Their inability to completely adhere to halal standards is caused by this scarcity. According to Yusof and Shuttob [2], the certification procedure is impacted by the Muslim community's frequent difficulties in locating halal products and foods. Businesses struggle to find appropriate ingredients that satisfy the exact specifications needed to prepare halal food [14].

Certification process is time-consuming and complex.

The procedure for halal certification is difficult and time-consuming in many Asian nations, necessitating close adherence to strict regulations and exhaustive inspections. This is a significant challenge, especially for smaller businesses. Many East and Southeast Asian nations lack a governmental agency in charge of monitoring and approving halal certifications, in contrast to nations with a majority Muslim population [15]. The lack of centralised supervision makes the certification procedure more challenging to navigate. The investment of time and resources required to obtain and maintain halal certification can be a deterrent for smaller companies. According to Hasnan et al. [3], the financial burdens associated with acquiring new equipment, training, and compliance measures may outweigh the perceived benefits, leading to a limited availability of halal-certified options for Muslim consumers [16].

Inconsistent regulations and standards.

Inconsistent regulations and the lack of standardised halal certification processes create confusion and inconsistency among certification bodies. This presents a challenge for restaurant owners in meeting diverse certification criteria. Shafie and Othman [4] provide a comprehensive analysis of how varying requirements and expectations complicate the certification landscape. Additionally, Abdallah et al. [17] also highlight the differences present in existing halal standards. For example, there exist different definitions and requirements for animal stunning, which makes it more difficult for businesses, particularly restaurants and food processors, to comply.

Traceability and fraud.

Incorporating halal traceability into distribution and retailing poses extra challenges. Technical systems, logistics, shelf segregation, distribution and retail records, and product recall processes are all crucial areas where food establishments encounter difficulties. For example, the absence of technical infrastructure for traceability makes it challenging to track and trace halal products. Furthermore, logistical issues, such as potential contamination during transportation, compound these challenges [5]. On top of this, instances of fraudulent practices and misrepresentation of halal compliance have led to scepticism among Muslim consumers. Studies by Rafiki [18] have emphasised the lack of trust due to fraudulent practices. Fujiwara et al. [19] and Islam et al. [20] stress the need for comprehensive measures to authenticate and validate halal certification claims. Additionally, Priantina et al. [21] found that trust significantly influences the intention to purchase halal products, highlighting the importance of authentic certification.

A common thread across these themes is the lack of knowledge and operational difficulties in implementing halal certification processes. Across the world, the complexities of supply chains including issues around resilience do present challenges. Ensuring that all ingredients and components used in a product are halal and that they remain so throughout the supply chain can be difficult, especially in global supply chains.

2.2. Halal Process Compliance and Certification

The process of obtaining a halal certification is extremely important for businesses aiming to provide products to consumers, especially within the food and beverage industry. It involves a detailed assessment of the product and its manufacturing procedures to ensure compliance with the dietary laws outlined in the Quran. Drawing from the Islamic

Services of America (ISA), the process flow for halal process compliance and certification is illustrated in Figure 1 and is explained below.

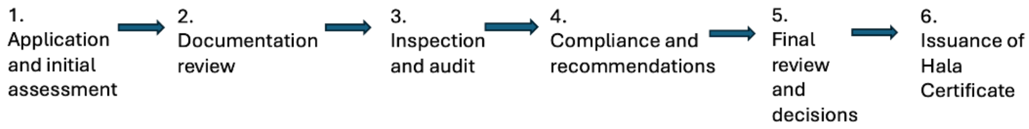

Figure 1. ISA certification process flow.

To get started, enterprises must submit a comprehensive application to a recognised halal certification body, providing detailed information about the product, its ingredients, and the entire supply chain. The certification body then conducts an initial review to confirm that the product meets the basic requirements for halal certification.

Following this, a thorough examination of all ingredients used in the product takes place to ensure they meet halal requirements, such as the absence of pork, alcohol, or any harmful substances. The entire supply chain is closely evaluated to prevent any cross-contamination with non-halal products, and the manufacturing process is scrutinised to ensure that it aligns with halal standards.

Subsequently, an on-site inspection of the manufacturing facility is carried out to ensure compliance with halal standards and to prevent contamination with non-halal products. The documentation provided by the manufacturer is also audited to ensure that ingredient sourcing, process controls, and hygiene standards align with halal requirements.

If any non-compliance areas are identified during the inspection and audit, the certification body provides recommendations for corrective actions, which the manufacturer must implement to meet halal standards. Once the corrective actions have been implemented, the certification body conducts a final review of all documentation and may perform a follow-up inspection to verify compliance with halal standards. If the product and processes meet all halal requirements, the certification body issues a halal certificate, permitting the use of the halal certification logo on the product packaging.

Continuous compliance with halal standards is ensured through periodic audits and inspections conducted by the certification body. Additionally, halal certification typically requires periodic renewal, involving a similar review, inspection, and audit process to ensure continued compliance.

The halal certification process takes into account various critical factors, including the purity of ingredients, processing aids, cleanliness and sanitation, the separation of production lines, and ethical practices, all of which need to align with Islamic principles. Recognised halal certification bodies are well-known for their stringent certification processes and their adherence to international halal standards.

2.3. Blockchain in Halal Supply Chains

Blockchain technology is increasingly widely accepted as an important technology for use in halal supply chains, especially due to its characteristics that include traceability capabilities. A traceability system based on blockchain technology in the halal certification process has the potential to address various challenges and enhance transparency throughout the product journey. Instead of depending solely on the end-product seller to communicate information, every participant in the value chain shares accountability. Blockchain technology utilises a series of interconnected blocks, each containing data and information along with a unique ID (hash) and the previous block's hash. Any attempt to modify the information alters the unique ID, making it challenging to tamper with the data [22]. We now highlight the key characteristics, advantages, and disadvantages of blockchain technology.

Key characteristics of blockchain technology

The data stored in the blockchain are secure and immutable. Once participants agree on the states of these data, they are is challenging to alter. Each created block receives a unique hash ID, which, along with the previous block's hash, secures the chain. If data within a block are tampered with, their hash changes, causing an error in the subsequent block due to the mismatch in the previous hash. The blockchain typically operates on a decentralised peer-to-peer network, ensuring that each participant has a copy of the blockchain. Any data changes or additions are notified to all users. With all network stakeholders holding a copy of the blocks, they can trace and review all historical data within the blockchain.

These highlighted characteristics, included through a secure, immutable, and decentralised ledger, significantly enhance the traceability of the halal certification process. The blockchain allows for transparent information flow, enabling stakeholders, including consumers, to trace data from farm to fork. This transparency can increase consumer trust in the halal labelling of food products.

Advantages of the blockchain in halal traceability.

Albert Tan and Ngah [23] highlight improvements in credibility, accountability, and traceability within the halal production process. Data being stored across different servers prevents manipulation. If any party attempts to alter the data, the entire network is notified. For example, a chicken slaughterer cannot change the status of an animal recorded as ill by a veterinarian to healthy without alerting everyone in the network. This feature bolsters consumer trust in the halal integrity of products. Stakeholders, including consumers, can trace the origin and processes of the food supply chain. The transparency provided by the blockchain system ensures that all parties have access to the same information, including attestations (acknowledgement of authenticity), reducing errors in communication or data transfer.

Disadvantages of the blockchain in halal traceability.

While the blockchain's decentralised nature reduces data tampering, it does not eliminate the possibility of incorrect information being recorded. If incorrect or intentionally misrepresented data are agreed upon by the required participants, they become permanently recorded. However, the blockchain's immutability aids in such cases. If incorrect data are discovered during an audit, they can be annotated with the new information, ensuring that the error and the correction are both permanently recorded. This feature helps to maintain the integrity of the system, even in cases of human error or malfeasance. Moreover, the counterfeiting of halal products can be prevented with the help of blockchain technology, making it more difficult to falsify information. Real-time data that can be provided by the blockchain can help stakeholders in making good decisions.

2.4. AI Integration in Food Supply Chains for Regulatory Compliance

In addition to the blockchain, researchers have also explored the use of AI technologies to tackle the issues outlined in Section 2.1. Below, we summarise recent research articles on integrating AI approaches into food supply chains in the context of improving regulatory compliance.

Chandra et al. [24] identify three major challenges for the halal food supply chain: (a) there are over 300 halal certifiers with inconsistent standards—though full consistency is impossible and undesirable, some alignment and harmonisation is necessary; (b) raw materials for halal products are poorly regulated (e.g., cross-contamination of non-sharia-compliant ingredients); and (c) there is insufficient scrutiny of suppliers to ensure processes are sharia-compliant. To address these challenges, they suggest the use of the blockchain, IoT, and AI. However, their investigation focuses primarily on a blockchain-focused technical analysis, with a minimal overview of data generation and no discussion of intelligent functionality.

Ramachandran et al. [25] emphasised six critical requirements for partially automating compliance management in food supply chains. These include trusted data and identity, privacy, reputation, inspection recommendation, and managing heterogeneous regulations. The authors proposed a framework that leverages blockchain technology, incorporating an Oracle component with machine learning algorithms for risk assessment during the regulatory process. Along similar lines, Sadovoy et al. [26] explore the use of clustering, specifically Kohonen maps, to compare the compositions of food products with technical documentation for recipe composition compliance.

Dora et al. [27] present a conceptual model of critical success factors for the adoption and use of AI in food supply chains. Their study identifies technological, organisational, environmental, and human factors as critical for the successful adoption of AI. The case study conducted in India demonstrates the significance of technological and environmental factors in comparison to organisational or human factors.

Hasnan et al. [28] identify inefficiencies in food manufacturing processes and discuss the potential of big data analytics, AI, and robotics under the Industrial Internet of Things. They emphasise the benefits of big data analytics for process control and quality management while viewing AI as a catalyst for quality monitoring, evaluation, and the prediction of various quantities. Robotics is also highlighted as a solution for addressing food safety standard compliance.

Finally, Chhetri [29] conducts a systematic literature review on the applications of AI in food quality control and safety assessment, focusing on regulatory compliance. This review highlights seven potential AI applications, including establishing food safety management systems, increased traceability and transparency with blockchain and AI, and the analysis of product labelling to ensure regulatory compliance.

The analysis presented in this section points towards a clear research gap that needs addressing: research on the application of AI and the blockchain for halal supply chains is still at an exploration stage, focusing primarily on suggesting their potential benefits but not following through with proposing specific frameworks, implementations, and case studies illustrating these benefits. In addition, there is limited focus on explainable AI, which may hinder the adoption of developed solutions. To the best of our knowledge, there is no attempt at presenting a holistic framework that encompasses the blockchain and explainable AI for halal certification.

3. Research Methodology

This section outlines the research design employed to investigate the interplay between AI, the blockchain, and halal supply chains. The approach adopted is primarily quantitative to provide a good insight into the tackled research problem. The research methodology is illustrated in Figure 2 and it involves three main strands, namely a literature review, framework development, and an illustrative example.

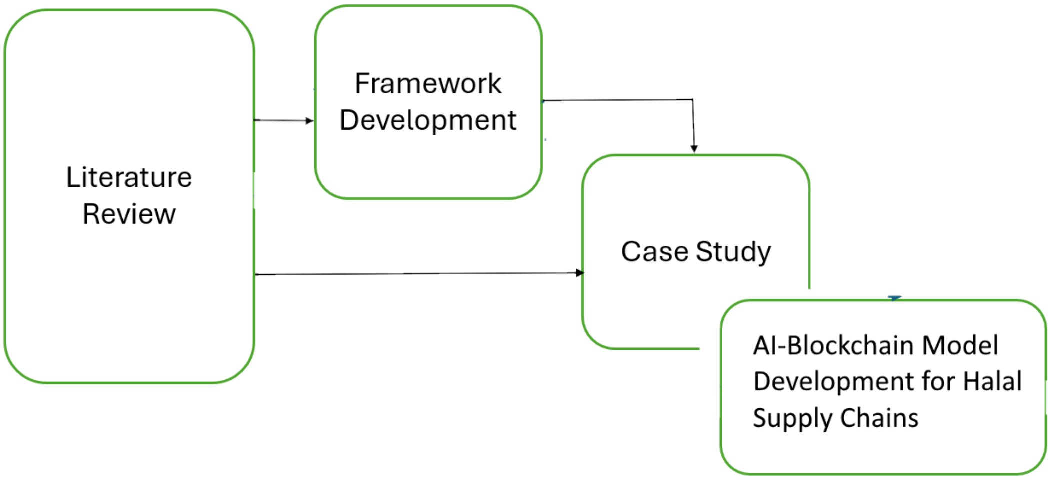

Figure 2. Research methodology.

A literature review was conducted to explore the existing body of knowledge on halal supply chains, blockchain technology, and AI applications. This review provides a broad overview of the research topic, and it involved gathering information from various sources, summarising key findings, and synthesising the information to form a coherent narrative. This review helped to establish a robust foundation for this study. The outcome of the literature review formed a basis for the development of the proposed framework and contributed to the AI-blockchain model developed in this study for the illustrative example presented.

A framework was developed to visualise the key phases of the halal supply chain, providing a foundation for the application of AI and the blockchain in halal supply chains. This framework delineated the key phases of the halal supply chain and the potential applications of AI and blockchain within each phase. This framework was grounded in the existing literature and informed by preliminary data collection, serving as a foundation for the illustrative example presented in this paper.

Finally, in the third phase, an illustrative example was used to present the potential and practical applications of the framework for AI and blockchain in halal supply chains. The illustrative example represented a limited case study that focuses on the issue of product compliance, an aspect of the first key phase of the framework. Over several decades, case study research has grown in reputation as an effective methodology to investigate and understand complex issues in real-world settings. Case study designs have been used across a number of disciplines, including in supply chains, to address a wide range of research questions. The case study methodology offers several advantages for exploring complex approaches such as integrated AI and blockchain implementation in halal supply chains, including a deep exploration of the research context, providing rich insights into the complexities and nuances of the phenomenon and use of real-world data in the exploration.

By combining a literature review, framework development, and a case study in the form of an illustrative example, this research aims to provide a comprehensive and nuanced understanding of the research problem studied.

4. Framework for AI/Blockchain Integration in Halal Supply Chain

A high-level view of the halal certification framework is presented in Figure 3. Central to the framework is an integrated blockchain infrastructure. The infrastructure creates a more comprehensive and efficient halal certification solution. It involves seamlessly connecting diverse digital technologies and integrating them with other systems and applications, particularly Industry 4.0, including AI and enterprise systems. The benefits of the integrated blockchain infrastructure include enhanced efficiency with which halal certification is accomplished, with increased transparency, security, interoperability and scalability.

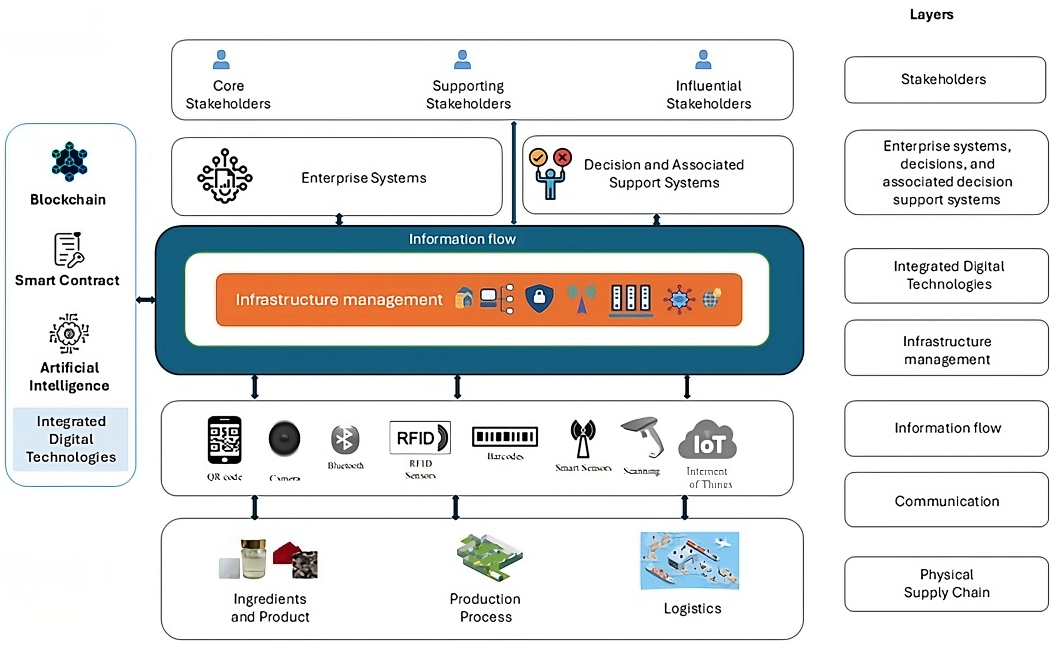

Figure 3. Framework illustrating a halal supply chain architecture that incorporates integrated digital technologies.

Figure 3 depicts a layered architecture that encompasses key components of the halal supply chain. This architecture integrates digital technologies and a robust digital supply chain layer. Additionally, it includes a communication layer leveraging IoT and data capture technologies, an information flow facilitated by communication buses, and a robust infrastructure management system. Enterprise systems such as ERP, CMS, and CRM are essential components, alongside a decision-making layer incorporating policies, protocols, and supporting systems.

The architecture recognizes three key classes of stakeholders:

- Core Stakeholders: Producers, processors, consumers, and halal certification bodies.
- Supporting Stakeholders: Government agencies, logistics providers, consultants, auditors, financial institutions, and research institutions.
- Influential Stakeholders: Religious leaders, media and marketing professionals, food scientists, legal and regulatory experts, and insurance companies.

Together, these stakeholders form a complex ecosystem that drives the evolution of the halal supply chain. This ecosystem is characterised by interdependence and collaboration among several of the actors to ensure the production, distribution, and consumption of halal products. Ultimately, this ecosystem aims to maintain the integrity of the halal supply chain, ensuring that products meet the required standards and are ethically produced. Integrated AI and blockchain technologies plays a key role in the ecosystem.

4.1. Framework Components

The framework is structured around three main components, each focusing on an aspect of the halal certification process, namely product validation, production process validation, and logistics process validation. The components are described further as follows.

4.1.1. Product Validation

This is a critical component of the halal certification process. It involves ensuring that all ingredients used in a product are halal-compliant and do not contain any prohibited substances. Essentially, each ingredient is validated to ensure that it is halal and any ingredient not listed in the halal list of ingredients will be subjected to further investigation. Ingredient validation is a critical component of the halal certification process.

Product validation in halal certification requires the careful consideration of various factors. The source of ingredients must be verified, ensuring they originate from halal-certified suppliers with appropriate documentation. The chemical composition of ingredients should be analysed to avoid prohibited substances like pork, alcohol, or blood, especially for animal-derived ingredients, amongst several others. There should also be important considerations for accurate labelling, the use of halal-compliant packaging materials, and appropriate product communication to ensure product integrity and consumer trust.

4.1.2. Production Process Validation

This requires detailed descriptions of food preparation, food handling, site auditing, and associated processes. These need to follow the halal guidelines from their regulator. For example, the manufacturing area or the kitchen must comply with health and hygiene standards. Several important factors must be carefully considered and they include the following: (a) facilities must be clean and hygienic, with strict segregation measures in place for non-halal products; (b) production methods should adhere to halal principles, and quality control measures must be implemented; (c) personnel involved in the production process need to be trained and competent, with appropriate segregation of duties to prevent conflicts of interest; and (d) equipment and utensils must be thoroughly cleaned, sanitised, well kept, and halal-compliant.

4.1.3. Logistics Process Validation

The last component of halal certification focuses on the transportation, storage, distribution, and third-party logistics providers, if they are present. In each of these, the resources involved must be halal-compliant and free from non-halal substances, with strict segregation measures in place for mixed shipments. Cross-contamination with non-halal products in the logistics process must be avoided. Products requiring specific temperature conditions should be stored and transported accordingly. Warehouses and storage facilities must also adhere to halal standards and maintain segregation. Halal-certified distributors should be involved in the distribution process, with traceability systems and documentation in place. Third-party logistics providers must be halal-certified and regularly audited.

4.2. Integration of the Blockchain

The key advantage of the blockchain in the context of halal certification is the permanent, transparent, and immutable record of transactions. This allows for the ability to properly audit and trace disruptions and attacks in the supply chain as well as track ingredient provenance. To understand this in greater detail, we discuss some specifics of how blockchain technologies are integrated into the proposed framework, in terms of platforms, smart contracts, and the importance of improved data integrity.

4.2.1. Platforms

The blockchain serves as a secure and transparent ledger for storing information about food products, ingredients, sourcing, processing, storage, as well as manufacturers and certificates. Each block contains a cryptographic hash of the previous block, ensuring both data integrity and immutability. However, this study will not go into detail about the consensus mechanism.

Our proposed framework is adaptable to various blockchain technologies, and is thus not designed for any specific platform in particular. As many halal supply chains tend to adopt a consortium-based model, we opt to adopt a blockchain technology that is more suitable for a private, consortium-based use case. This is in contrast to more popular but public blockchains that can use smart contracts such as Ethereum, VeChain, or Solana.

Hyperledger Fabric is a permissioned blockchain platform for enterprise use that was developed by the Linux Foundation [30]. It offers a modular architecture that allows the customization of components such as consensus mechanisms, membership, and transaction validation criteria. Its permissioned nature ensures proper access control, which is necessary for halal food certification, where regulatory compliance is essential. The framework also supports the use of chaincode, Hyperledger's version of smart contracts, enabling a decentralized application logic to run securely. This flexibility has been successfully demonstrated in use cases like the IBM Food Trust [31], where companies like Walmart utilize Hyperledger Fabric for end-to-end supply chain traceability, ensuring product safety and transparency [32]. Moreover, Hyperledger Fabric has seen applications in critical supply chain use cases such as pharmaceuticals [33,34], agriculture [35], and food traceability [36].

Ethereum can be an alternative to consider in place of Hyperledger, as the former is one of the most widely used blockchain technologies. However, a potential drawback would be the transaction costs (gas fees) and scalability issues, which can make Hyperledger Fabric a better fit for a closed and regulated supply chain context. In particular, a *permissioned* blockchain like Hyperledger Fabric aligns with halal certification, as it ensures only authorised entities (e.g., certifiers, producers) can access and validate sensitive data.

4.2.2. Smart Contracts

A smart contract is a self-executing program stored on a blockchain that automatically enforces the terms of an agreement between parties when predefined conditions are met. It eliminates the need for intermediaries by automatically handling tasks like payments, approvals, and data exchanges. The value of smart contracts lies in their ability to automate agreements between parties in a timely manner, reducing the risk of errors and fraud. This is highly relevant to the halal supply chain, where trust and transparency are essential. For instance, a smart contract can automatically release a payment to a supplier upon verification that a shipment of ingredients meets all the requirements. Such automation not only streamlines the certification process but also minimizes the potential for disputes. Going a step further by integrating smart contracts with AI and knowledge graphs, a smart contract could automate the decision-making process for the pre-certification screening of new product recipes based on outputs from machine learning classification and knowledge graph analysis.

Their design includes the following key elements:

1. Automated Compliance Verification. By cross-referencing blockchain-stored halal certification data, smart contracts can automatically flag anomalies such as uncertified suppliers, expired certifications, or discrepancies in product documentation, enabling swift resolution before further processing.
2. Facilitation of Multi-Stakeholder Agreement. By acting as an impartial validator, smart contracts allow stakeholders, including halal certifiers, suppliers, and regulators, to verify and approve transactions transparently before certification is finalised. This ensures that all parties adhere to standardised protocols without requiring a central authority.

3. Practical Workflow Example.
    - Step 1: Input Validation. A supplier uploads batch data to the blockchain, including ingredient provenance, certification documents, and handling records. The smart contract automatically verifies the integrity and validity of these inputs against halal compliance criteria.
    - Step 2: Event Triggers. If the data meets all requirements, the contract generates a token, signalling approval for further processing or payment release. Conversely, any anomalies, such as missing certifications or inconsistencies, trigger an alert for manual review.
    - Step 3: Logs. Each interaction is logged on the blockchain, creating an immutable transparent and accessible record for stakeholders to audit at any time.

By embedding these functionalities into the halal supply chain, smart contracts enhance operational transparency, reduce administrative overhead, and instil trust among stakeholders, ultimately supporting the integrity of halal certification processes.

4.2.3. Data Integrity

A key problem in the certification process is the collection, trustworthiness, and reliability of data. IoT devices can collect real-time, tamper-proof data throughout the supply chain, such as ingredient provenance, processing conditions, and logistics. Verified human checks can further ensure accuracy by cross-referencing sensor data with physical observations. Additionally, digital signatures from all parties involved in the process can provide an auditable trail, ensuring accountability at every step.

This last point on auditability and accountability is key to mitigating risks and maintaining trust. Any system will remain susceptible to malicious activities (e.g., data poisoning attacks, falsified records) and non-malicious faults (e.g., physical disruptions, failed sensors, contaminations in batches). What is critical is the ability to recover from such instances with an audit of records to identify and trace the source of discrepancies for swift intervention. It should also be noted that the use of the blockchain to ensure data integrity also applies to the data that are used within the AI components of the proposed framework.

4.3. Integration of AI

The main benefit of integrating AI within the proposed halal certification framework is the resulting expansion of its reasoning and decision-making capabilities. The blockchain relies on smart contracts for action automation, but these, on their own, have limited capabilities in terms of modelling and reasoning with relevant knowledge, as well as processing and drawing insights from data. In the rest of this section, we discuss three main capabilities that are offered through AI integration in the proposed framework.

4.3.1. AI for Recipe Validation

The process of checking whether ingredients in a product recipe meet halal requirements can be facilitated through a range of different AI technologies. First, knowledge models, such as knowledge graphs, can be leveraged to represent concepts and relationships related to products, ingredients, manufacturers, and certification and assist in identifying potential areas of risk, such as identifying ingredients that are linked to uncertified manufacturers or discover similarities between ingredients. Additionally, machine-learning-based text classification can be used to process textual descriptions of recipes and determine whether the associated products can be certified as halal or not by relying on common lexical patterns (e.g., same or similar ingredients). Finally, the recent successes of large language models (LLMs) can be exploited to improve text classification through high-performance pre-trained models and extend it to allow for generating explanations of classification outputs in natural language. We explore all three of these applications of AI for recipe validation in the illustrative example presented in Section 5.

4.3.2. AI for Process Compliance

In the case of validating the production and logistics processes to ensure they are halal-compliant, there is a large body of AI research on regulatory compliance that can be leveraged [37,38]. This research employs logic-based constructs (e.g., based on Defeasible Deontic Logic [39]) to encode validation rules, capturing what should hold to confirm that a process is compliant, e.g., confirming that the production process of a food product meets halal rules and guidelines. These validation rules are then applied to event logs that document what actually happened during the production of specific products, not only identifying the level of compliance but also providing actionable explanations for cases of non-compliance. This process validation can be hosted on the blockchain infrastructure in the form of smart contracts, provided that the language used to encode these is expressive enough to capture the complexity of validation rules.

4.3.3. AI for Process Optimisation

Validating production and logistics processes may reveal areas where improvements need to be made to ensure or future-proof halal compliance. AI can again prove useful in this context, primarily in the context of predictive analytics [40], which can be utilised to optimise transportation routes, track product movements, and monitor storage conditions, avoiding logistics issues that can compromise halal compliance of products. Additionally, AI-driven predictive maintenance can optimise equipment maintenance, minimising disruptions to the production process. Finally, computer vision approaches can assist across a wide range of applications, from scrutinising ingredient processing facilities to quality control and monitoring packing and transportation [41].

5. Illustrative Example

In this section, we present an illustrative example to show the potential of the proposed framework in the context of the halal certification processes focusing on the particular instance of product revalidation. The scenario involves a food company that is intending to adapt the recipe of some of the products they manufacture which have previously been certified as halal. This is as part of their continuous improvement process, and in order to ensure that their foods are made to satisfy increasing demand without specific ingredients, such as in free-from products. The company needs to be aware of the impact these recipe changes may have on the halal certification status of the affected products. Using the proposed framework, they can conduct pre-certification checks for all products with modified recipes. The focus in this illustrative example is on the product validation component of the framework, with emphasis on the ingredients. Figure 4 illustrates an example of how the proposed framework can be applied for this illustrative example regarding aspects of the product validation component of the framework. The process includes an integrated AI–blockchain pipeline geared towards decision support regarding to either proceed with the certification process or conduct further checks on their modified recipe. Following data preparation of the data obtained from halal datasets, the process includes two main AI strands, one based on knowledge graphs and the other on machine learning classification, both of which are integrated with a blockchain infrastructure that enables decision support through smart contracts. In the remainder of this section, we describe each step in this process in detail.

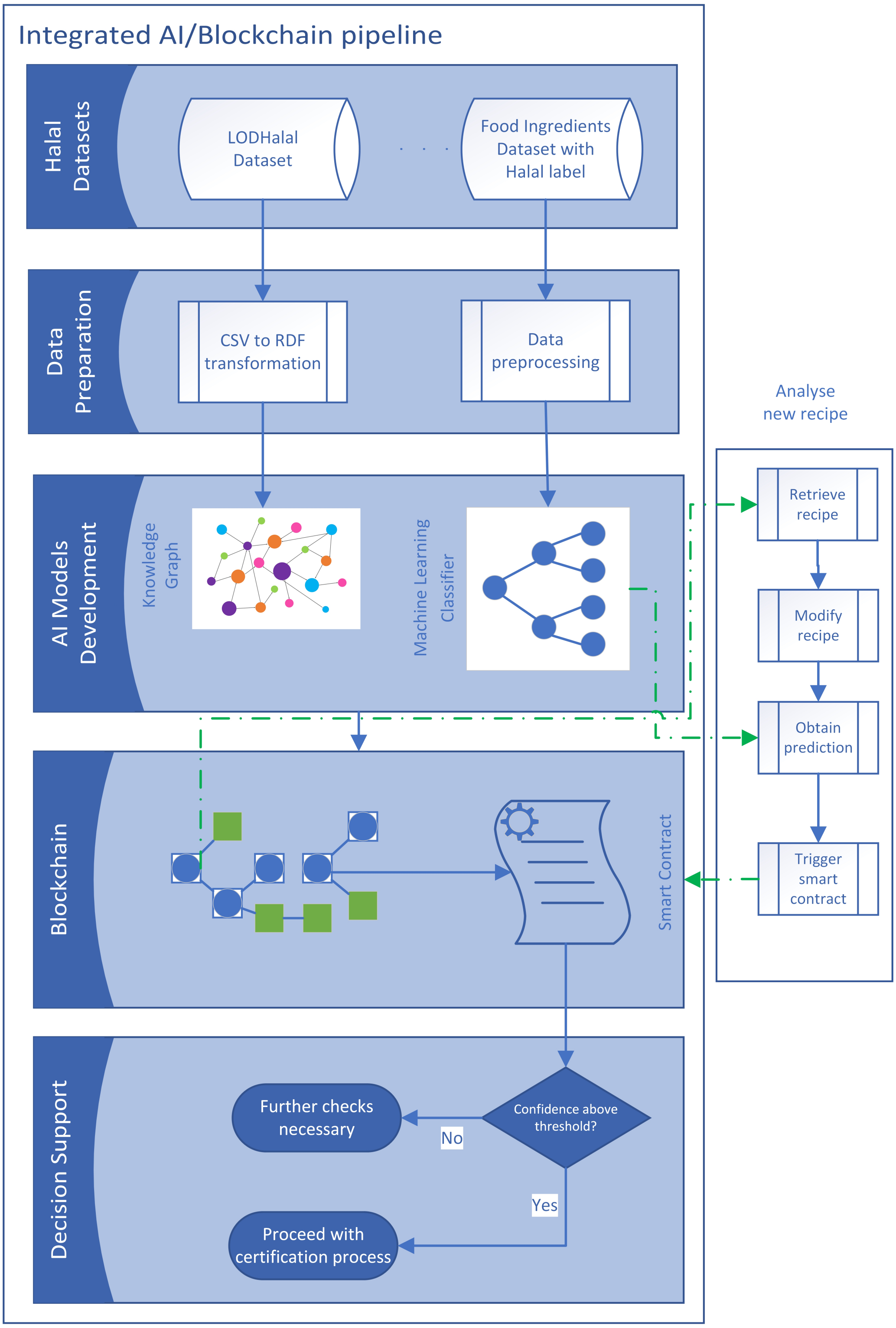

Figure 4. Application of the proposed framework for the example of new halal product pre-certification screening.

5.1. Knowledge Graphs for Representing and Reasoning with Halal Product Information

Knowledge graphs have long been used as the basis for intelligent systems to represent, store, retrieve, and reason with complex information and have had significant impact in various domains [42,43], from search engines (e.g., Google Knowledge Graph[1]) to retail (e.g., Amazon's Product Graph [44]) and manufacturing (e.g., KnowIME [45]) to healthcare (e.g., ADHD-KG [46]). In our context, knowledge graphs can be leveraged as a human-understandable and machine-processable structure for data on products, recipes, manufacturers, and certification that can be used to answer queries and gain insights.

Due to lack of standardisation, food product data can be made available in various unstructured, semi-structured and structured forms. Knowledge graphs typically rely on the Resource Description Framework (RDF) as the representation language, due to its versatility and XML serialisability. The main building block of an RDF document is a subject–predicate–object triple, representing a relationship (predicate) between two entities (subject and object). Unstructured data require the most effort in identifying entities and relationships, which can be facilitated by tags or schemas in semi-structured and structured data.

Our illustrative example focuses on semi-structured data formats, such as JSON and CSV, which are more commonly exportable by food industry software. In particular, we will use the dataset of the LODhalal project[2]. The dataset includes seven CSV files that are organised according to a relational schema, as explained below and shown in Figure 5:

- Food: food products, each including a unique ID and name;
- Ingredient: ingredients, each including a unique ID and name;
- Manufacturer: food manufacturers, each including a unique ID and name;
- Certificate: halal certifications, each including a unique ID, a number and the name of the certification body;
- Food/ingredient pairs, representing the relationship between a food product and the ingredients it contains;
- Food/manufacturer pairs, representing the relationship between a food product and the food manufacturers that produce it;
- Food/certificate pairs, representing the relationship between a food product and any halal certificates it may have received.

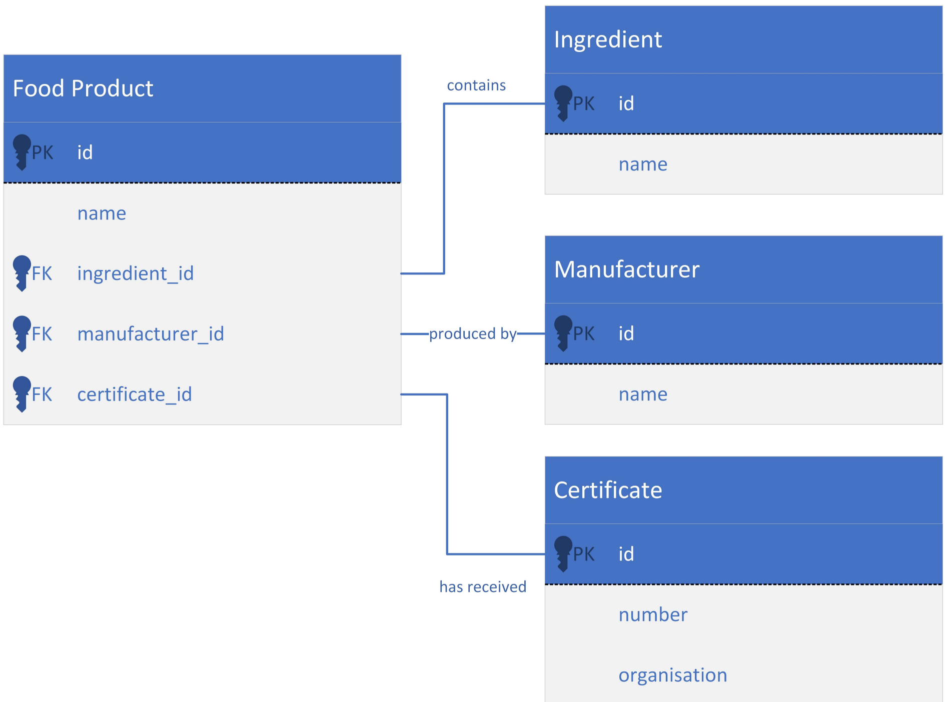

Figure 5. Schema illustration of the LODhalal dataset.

The existence of the aforementioned schema facilitates the conversion to RDF, as subject–predicate–object triples can be drawn from the pairs contained in the latter three CSV files. The CSV-to-RDF conversion process included three steps. First, an RDF schema was produced based on the existing relational schema, which includes the concepts of food, ingredient, manufacturer, and certificate, the relationships of the food concept with the other three, and additional properties such as ID and name. Second, each one of the first four CSV files (containing food products, ingredients, manufacturers and certificates) was processed line by line, creating RDF triples for each line, using the CSV header to map each value to the corresponding concept in the RDF schema. For example, "48119, Yuzu tea" was converted to the following two triples, *F*_48119 rdf:type Food and *F*_48119 rdfs:label 'Yuzu tea', meaning that the product with the ID 48119 belongs to the Food concept and its name is 'Yuzu tea'. Finally, the food/ingredient, food/manufacturer, and food/certificate pairs in the latter three CSV files were also converted into RDF triples. For example, the triple *F*_48119 has_manufacturer *M*_41723 links the aforementioned product to its manufacturer.

The conversion process was implemented using Python and the RDFLib library. The resulting RDF files were loaded on a GraphDB server instance to facilitate visualisation and querying. Figure 6 shows an example sub-graph, from the dataset, of food products by the manufacturer Unilever Indonesia that have received a halal certificate (with id *C*_1566), as well as the ingredients of one of these products (Walls Cornetto Black and White).

The produced RDF documents were loaded on a GraphDB server instance and a sub-graph is indicatively shown in Figure 6. This sub-graph contains three food products that are certified through a particular certification (with ID *C*_900, by the Indonesian Ulema Council-MUI), with products manufactured by Indofood and three indicative ingredients of these products.

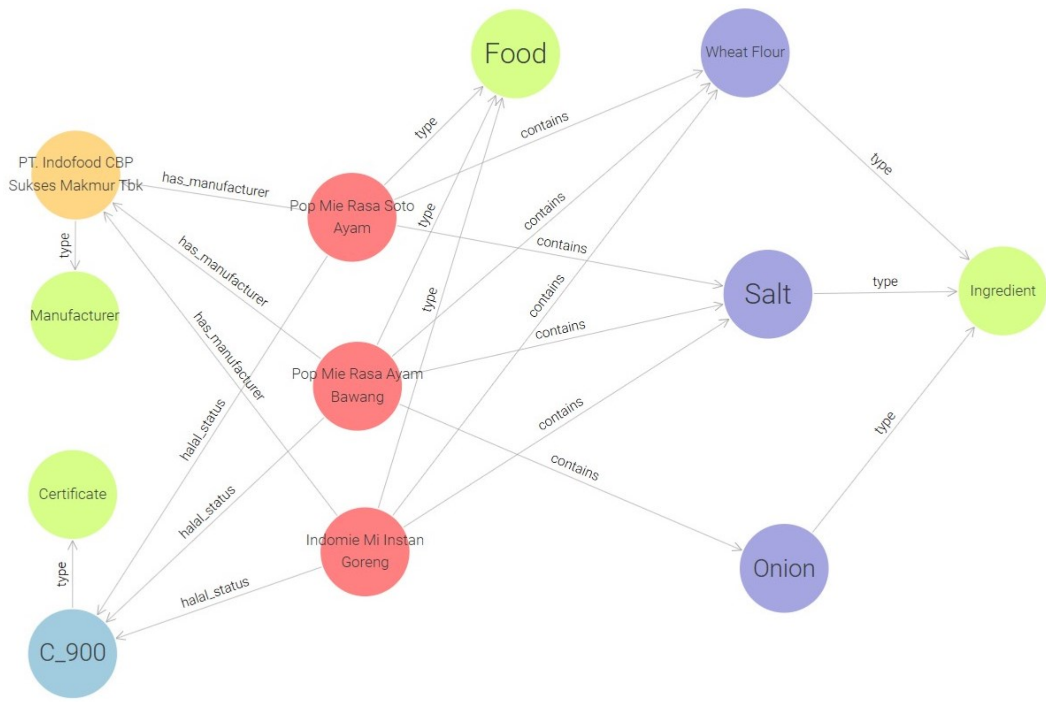

Figure 6. Sub-graph showing a subset of LODhalal dataset.

The full graph can be queried to extract useful insights. The standard query language for RDF is SPARQL, though there also exist several approaches that allow natural language queries with the addition of a translation mechanism from natural language to SPARQL. An indicative SPARQL query in our context is shown in Listing 1. This query retrieves product/certification ID pairs for certified products that contain wheat flour. This allows for identifying products where recipe adaptation is necessary to achieve, e.g., a gluten-free status by replacing wheat flour with almond flour.

Listing 1. Example SPARQL query.

```
PREFIX halal_s: <https://www.halal_project.com/schema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
select ?s ?c where {
    ?s halal_s:contains ?i .
    ?i rdfs:label "Wheat␣Flour" .
    ?s halal_s:halal_status ?c .
}
```

5.2. Machine Learning for Halal Classification of Text-Based Recipes

The previous steps have allowed the creation of a knowledge graph that contains information about certified food products, their ingredients, and manufacturers. However, this graph is unable to determine whether changing an ingredient in a particular product within it may affect its halal certification. In the subsequent steps, we describe an example of how machine learning (ML) classification can be applied in this context.

AI algorithms can analyse large amounts of data quickly, significantly enhancing the efficiency and accuracy of the halal certification process. They can be used to scrutinise ingredient lists, supply chain data, and production processes to identify non-compliant products or ingredients. This capability reduces the time and effort required for manual inspections and can lead to faster certification decisions [47].

For the purposes of our example, we will illustrate the use of ML classification to determine whether a text description of a recipe can be considered halal. Consider a food classification task where an ML model is given a list of ingredients belonging to a food product as its input. The model is expected to output either "halal" or "haram" based on the input text to classify whether or not the food is halal. We employed both classical machine learning methods and LLMs to illustrate their potential in this context.

For classical machine learning, we used Logistic Regression (LR) and Gradient Boosted Machine (GBM) [48]. LR is one of the most simple and widely used linear classifiers, whilst GBM is one the best performing non-deep learning methods for numerical and tabular data [49,50]. As a preprocessing step, we first needed to convert the text into vectors using Term Frequency—Inverse Document Frequency (TF-IDF) vectorisation [51].

The dataset we used[3] consists of 39,787 food ingredient lists, with 21,826 halal and 17,961 haram data points. A sample of the dataset is shown in Figure 7. As a baseline, we implemented a blocklist approach where we flagged an item as haram if it contained any ingredients under a list of banned food items (e.g., pork, alcohol-related). This baseline approach only achieved 73% accuracy, missing out on many haram items. Establishing this baseline is useful in highlighting how inadequate a blocklist approach may be. Then, we performed 10 trials of Monte-Carlo cross-validation with an 80–20 train-test split. The mean test set accuracy, averaged over the 10 trials, is 96.6% for LR and 97.3% for GBM.

```
chicken stock contains less than of yeast extract dehydrated chicken natural flavoring carrot juice concentrate celeriac juice concentrate
chicken fat onion extract
halal

diced tomatoes in tomato juice tomato puree water tomato paste onions olive oil garlic contains less than of salt basil citric acid black p
epper oregano
halal

cultured pasteurized milk salt enzymes rind treated with natamycin a natural mold inhibitor
haram
```

Figure 7. Example food ingredient lists from the dataset with their corresponding labels below each.

These two models performed very well on the dataset with very high accuracy scores. To enhance trust with these models, it is desirable to have a proper understanding of their operation, the decision making process and potential issues. This would require, for example, interpretation of model output based on its input or an end-to-end explanation of a decision based on an output. However, GBM is inherently a non-interpretable algorithm, and although LR should be interpretable, the TF-IDF vectorisation obscures its interpretability component. Considering how sensitive an application this is, it will be difficult to trust these models without proper explanations.

The recent successes of LLMs have led to their use for a variety of tasks, including the generation of explanations for ML classification outputs. We accessed freely available LLM models, namely OpenAI's ChatGPT (specifically the version that relies on GPT 3.5 [52] and Anthropic's Claude 3 Opus [53] for our initial exploration.

Classification of recipes as halal or haram is straightforward using LLMs when there are no ambiguities; e.g., if there is "pork" in the ingredients, then the food item is labeled haram. However, in examples where there is ambiguity, both GPT 3.5 and Claude 3 Sonnet express this as well, as shown in Figure 8.

Verdict:
Based on the provided ingredient list, the product cannot be definitively classified as Halal or non-Halal due to the unknown source of the enzymes. If the enzymes are derived from Halal sources, then the product would be considered Halal. However, if the enzymes are derived from non-Halal sources like pork or alcohol, then the product would be classified as non-Halal.

To make a conclusive determination, further information is required regarding the specific source of the enzymes used in the product.

1. **Cultured pasteurized milk:** Milk itself is generally considered Halal unless contaminated with non-Halal substances.
2. **Salt:** Halal, commonly used in food products.
3. **Enzymes:** The Halal status of enzymes depends on their source. If the enzymes are derived from animals slaughtered according to Islamic principles, they are considered Halal. However, if the enzymes are derived from non-Halal sources, they would render the product non-Halal.
4. **Rind treated with natamycin:** Natamycin is a Halal ingredient and is commonly used as a natural mold inhibitor.

Since the Halal status of the enzymes is unspecified in the ingredient list provided, it's important to verify their source to determine if the product is Halal or not.

Figure 8. LLM outputs from (top) Anthropic's Claude 3 Sonnet and (bottom) OpenAI's ChatGPT 3.5 for the input: cultured pasteurised milk salt enzymes rind treated with natamycin a natural mold inhibitor, which is labeled as `haram` in the dataset.

To test the overall performance, we accessed Anthropic's most advanced model Claude 3 Opus, version `claude-3-opus-20240229` [53], via its API. We set the system prompt so that the model only outputs halal or haram as a classification. On a random sample of 200 data points from our dataset, with an equal number being halal and haram, the Claude 3 Opus achieves 93.5% accuracy. When we investigated its mistakes, it cited the ambiguity of the source of the ingredients, explaining the possibility that the item is halal if certain ingredients were from a halal source.

The resulting classifiers provide a valuable ability that is not available directly through the knowledge graph produced in the previous steps. They can be used to determine whether a previously unseen recipe can be classified as halal or haram, as well as a confidence level that quantifies the probability that this classification is correct. In the final phase of the illustrative example, we describe how the knowledge graph and machine-learning-based models are harnessed within a blockchain infrastructure to support decision making for pre-certification screening of new product recipes.

5.3. Putting It All Together: Smart Contract Based Decision Support

Both knowledge graph and machine learning models face challenges when it comes to determining whether a particular data item and its provenance are trusted and tamper-proof. To that end, a blockchain serves as a unifying infrastructure that can fulfil two purposes: (1) it can host the knowledge graph containing information about food products, ingredients, manufacturers and certificates, ensuring that only trusted parties can make changes to the graph and any change is fully transparent; and (2) it can support smart contracts that are triggered when a recipe is modified to support decision making.

Consider the use case of analysing a new recipe as illustrated on the right side of Figure 4. Using the proposed framework, the first step is to retrieve the recipe information from the blockchain using, for instance, a block explorer. The retrieved data are in the form of graph triples, as those shown in Listing 2.

Listing 2. Sample of retrieved triples.

```
halal:F_35711  halal_s:halal_status  halal:C_900;
               halal_s:has_manufacturer  halal:M_22173;
               halal_s:contains  halal:I_850,  halal:I_809,
               halal:I_1760,  halal:I_1387,  halal:I_3116;
               rdfs:label  "Pop␣Mie␣Rasa␣Ayam␣Bawang"  .

halal:M_22173  rdfs:label  "PT.␣Indofood␣CBP␣Sukses␣Makmur␣Tbk"  .

halal:C_900  halal_s:hasNumber  "90000300799";
             halal_s:hasORG  "MUI"  .

halal:I_850  rdfs:label  "Wheat␣Flour"  .
halal:I_809  rdfs:label  "Salt"  .
halal:I_1760  rdfs:label  "Onion"  .
halal:I_1387  rdfs:label  "Sugar"  .
halal:I_3116  rdfs:label  "Onion␣Powder"  .
```

The subset of these triples that contain the product recipe are then serialised into text, as follows: Pop Mie Rasa Ayam Bawang Wheat Flour Salt Onion Sugar Onion Powder. This text is then provided as an input to the pre-trained classification model, obtaining a predicted class ("halal" or "haram"), as well as a confidence value for that prediction. The next step is to use the prediction output and confidence value of the prediction to trigger a smart contract, such as the indicative one in Listing 3 written in the Solidity language used in a variety of blockchain platforms, including Ethereum.

The smart contract in Listing 3 implements the following behaviour:

- If the predicted class is "halal" and the confidence value is above a predetermined threshold, then the decision is to proceed with the certification process, as pre-certification checks are satisfactory
- If the predicted class is "halal" and the confidence value is below a predetermined threshold, or the predicted class is "haram", then the decision is to conduct further pre-certification checks, as there may be issues with the modified recipe that affect certification.

This smart-contract-based decision support process allows for reducing the risk of going through an expensive and time-consuming halal certification process that will result in the certification not being granted. Note that the smart contract described above encodes a cautious approach, where a prediction of "haram" leads to further checks regardless of the confidence value associated with this prediction. An alternative, less cautious smart contract could potentially allow one to proceed with the certification process if the predicted class is "haram" but with a very low confidence value. Experimental explorations of the smart contract decision support process gave results that indicate good performance of the framework in support of the halal product pre-certification screening decision.

Listing 3. Example smart contract in Solidity.

```
contract PreCert {

    string class;
    int conf_value;

    constructor (string class_, int conf_value_){
        class = class_;
        conf_value = conf_value_;
    }

    function checkRequired(string class, int conf_value)
        public
        returns (boolean checkStatus)
    {
        boolean checkStatus = true;
        if(class == "halal" && conf_value >= 70) {
            checkStatus = false;
        }
        else if((class == "halal" && conf_value < 70) || class == "haram") {
             checkStatus = true;
        }
        return checkStatus;
    }
}
```

6. Discussion, Limitations and Implications

The illustrative example presented in the previous section offers an illustration of how the proposed framework can harness the combined capabilities of AI (in the form of knowledge graphs and ML) and blockchain technologies to address challenges in halal certification and drive improvements in halal supply chains. Through the proposed framework and the associated illustrative example, we have been able to provide some answers to the research questions posed in the introductory section. Specifically, in what concerns RQ1 and the capabilities of digital technologies in the context of regulatory compliance and certification in halal supply chains, we have gathered the following insights:

- Researchers in the literature agree on the potential benefits of digital technologies in terms of providing accountability, establishing traceability and transparency mechanisms, and supporting food safety and quality monitoring, evaluation, and prediction [28,29].
- In contrast, there is limited research on real-world applications showcasing these potential benefits and limited levels of adoption by stakeholders in the halal supply chain [24].
- Our framework aims to address this through a holistic approach to addressing regulatory compliance and certification issues in halal supply chains by matching different digital technologies to different challenges, for example, the blockchain to address issues of traceability and trust, knowledge graphs to provide a transparent and explain-

able view on data related to the halal supply chains, and ML to facilitate and automate the processing of such data to reduce the time and effort required for halal certification.
- AI systems are generally more consistent at following predetermined rules and guidelines for certification, which minimises the risk of human error and bias [54]. Traditional certification processes can be susceptible to inconsistencies due to human judgement, fatigue, or oversight. By automating these processes, AI ensures a more consistent and reliable assessment of compliance. This can lead to greater trust in halal certification among consumers and stakeholders.

In terms of RQ2 and the potential of integrating AI and blockchain to support compliance and certification in halal supply chains, the following can be drawn from our research:

- There are a wide range of technologies under the umbrella of AI which can be brought together to provide a range of combined benefits in the context of halal certification, while addressing drawbacks that arise if they are used in isolation.
- Knowledge graphs provide a machine-processable and human-understandable view into halal supply chain data and can be harnessed to draw insights on products and recipes; however, they do not have predictive capabilities.
- ML classifiers can offer such predictive capabilities, e.g., in determining whether a previously unseen recipe is likely to be certified as halal; however, many ML algorithms are not intrinsically interpretable and understandable by non-experts and their outputs can be explained in a post hoc manner by relying on other AI approaches (including but not limited to knowledge graphs).
- The blockchain can serve as a unifying platform to not only ensure that data are secured, immutable, and transparent, but also bring together different AI technologies under an integrated compliance and certification process.
- Smart contracts can enable and support decision-making within this process, improving speed and efficiency through automation.

There are some limitations to consider in relation to the proposed framework, particularly since it involves the integration of a range of digital technologies, each of which comes with its own limitations. Despite their potential benefits, there are several challenges associated with implementing AI and ML in halal food certification. First and foremost is that the effectiveness of ML systems relies heavily on the quality and availability of data. Incomplete, inaccurate, or outdated data can lead to incorrect assessments and decisions [55]. Therefore, ensuring comprehensive and up-to-date data is crucial for the success of ML-driven certification processes. Second, while AI approaches based on knowledge graphs are less data-dependent and, thus, less affected by issues with data quality and availability, they depend instead on the availability of domain experts that will help validate the underlying knowledge model (e.g., concepts and their interrelationships); such expertise may not be readily available and may require a time commitment on the part of domain experts [43].

A third limitation relates to the fact that halal certification can be deeply rooted in cultural and religious practices. The adoption of AI and ML must be carefully managed to respect these traditions and maintain the trust of the Muslim community [12]. It is essential to involve religious scholars and experts in the development and implementation of AI systems to ensure that they align with Islamic principles. Finally, ensuring the transparency and accountability of AI systems is vital to preventing misuse and maintaining public trust [56]. While the inclusion of a knowledge graph component in the proposed framework increases its explainability and transparency, the ML component may compromise explainability. For instance, in the illustrative example, we employed logistic regression and GBM, with the latter being easily explainable due to its relatively straightforward mathematical underpinning, whereas the former is not, due to the large number of tree-based models included.

6.1. Theoretical Implications

To the best of our knowledge, the proposed framework is the first to integrate the blockchain, knowledge graphs, and ML in the context of supply chains. Previous research has only focused on the integration of the ML subset of AI with the blockchain [57], without including knowledge graphs and the associated benefits in relation to explainability. The presented illustrative example confirms the feasibility of such an integration, as well as its potential in the particular problem instance of evaluating a new recipe as part of a pre-certification process. As discussed in Section 4, there are several other issues that can be addressed using the framework in terms of regulatory compliance and certification in halal supply chains, such as supporting the classification of new or existing ingredients as halal or haram and the suggestion of replacement ingredients to convert a recipe from haram to halal; automating certification processes; and detecting and addressing inconsistencies between different halal regulations and standards.

The proposed framework is also transferable beyond halal supply chains to other supply chains where there are needs in relation to regulatory compliance and certification. Indicatively, this may include the evaluation of product, process, and people integrity in food supply chains [58]; compliance with environmental, social, and government regulations (including net-zero aims) in green supply chains [59]; facilitating compliance with patient record regulations in healthcare supply chains [60]; and the investigation of compliance with workplace safety regulations [61] in any supply chain domain.

6.2. Managerial Implications

The proposed framework raises several implications that supply chain managers need to consider. First, to maximise the usefulness of this framework, it is important to investigate how best to integrate it within current compliance and certification processes. This integration requires identifying the data sources that will be provided as the input to the framework, the activities in current processes that it can replace, and the activities that need to follow the framework and will use its outputs. By considering these necessary integration actions, the risk of the framework unnecessary replicating human effort or its outputs not being fully utilised is minimised.

Second, there is a need for investment in infrastructure and upskilling in relation to AI and blockchain technologies [62]. Infrastructure costs depend on the complexity of the envisioned use cases and typically involves leveraging existing cloud infrastructure for both AI and blockchain, as leading cloud computing providers offer solutions for both. In terms of upskilling, this should include bespoke training for staff that are directly involved with halal compliance and certification processes and focus on their role as both producers of data and knowledge for the framework as well as consumers of its outputs.

Finally, it is important to acknowledge that while there have been significant advances in developing AI and blockchain approaches and that these have reached desirable levels of maturity, there has been relatively low adoption by supply chain stakeholders [63]. This can be attributed to a limited understanding of such technologies and limited trust in their capabilities [64]. The proposed framework has been designed with these issues in mind, purposefully choosing to include AI approaches that are more understandable and explainable, such as knowledge graphs. This should increase the likelihood of its adoption; however, supply chain managers and leaders should also collaborate with AI and blockchain engineers to deliver workshops and events that increase understanding of the potential of these technologies and the ways in which supply chain stakeholders can benefit by adopting them.

7. Conclusions and Future Research

The increasing demand for halal products, driven by ethical and sustainable consumption trends, underscores the critical role of halal supply chains and the need for their improvement through digital technologies. This research has demonstrated the potential of integrating AI and blockchain technology to address the complexities of halal supply chain management. By developing a comprehensive framework for regulatory compliance and certification and an illustrative example of its applicability, this study has contributed to the nascent field of AI and blockchain applications in halal industries. In particular, the presented illustrative example demonstrates a novel integration of neural networks, knowledge graphs, and blockchain technology, facilitating the pre-screening process of halal products, enhancing efficiency, and ensuring compliance.

There are several areas of future work arising from this study. Further research is needed to validate the framework in diverse halal supply chain management scenarios and to address the challenges associated with issues such as data quality and privacy, explainability, and trust. This will require additional case studies focusing on different layers of the proposed framework, including an exploration of potential halal certification formats on the blockchain (e.g., in the form of tokens) and determining the provenance of information that is added to the blockchain. In the same context, it is worth looking into a wider range of smart contracts and associated blockchain mechanisms involving more advanced structures, such as rules involving multiple conditions and events. Furthermore, it will be interesting to explore a deeper integration between knowledge graphs and machine learning in the context of halal supply chains, such as the application of graph neural networks in gaining a deeper understanding of the interconnections and relationships among participants in the chain.

Ultimately, the successful implementation of AI and blockchain-based solutions requires a collaborative effort among industry stakeholders, policymakers, and researchers to create a robust and sustainable halal ecosystem.

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Conflicts of Interest: The authors declare no conflicts of interest.

Notes

[1] https://blog.google/products/search/about-knowledge-graph-and-knowledge-panels/.
[2] https://github.com/utomogirraz/graph-app-kit.
[3] https://www.kaggle.com/datasets/irfanakbarihabibi/food-ingredients-dataset-with-halal-label/.

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