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Blockchain technology design based on food safety and halal risk analysis in the beef supply chain with FMEA-FTA

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ABSTRACT

Beef has an important role in the health of the body. Food safety and halal are the main factors for consumers in purchasing beef. However, in reality, several activities in the beef supply chain result in status changes to be unsafe and not halal for consumption. This occurs due to weak food safety and halal supervision in the beef supply chain system. Therefore, this study proposes the use of blockchain technology to strengthen the food safety and halal supervision system in the beef supply chain. The objectives of this study are (1) to identify food safety and halal risk factors, and (2) to develop a blockchain technology design for mitigating food safety and halal risks in the beef supply chain. This research uses the FMEA method to measure risks and FTA for risk analysis. The results showed that 30 risks were identified in the beef supply chain. The highest risk is the absence of a halal certificate on the product. The 30 risks are grouped into 4 risks that are included in extreme priority risk, 11 risks in high priority risk, 4 risks in moderate risk, and 11 risks as acceptable risk. Based on these results, the role of blockchain technology to minimize risk is in the flow of data, and transactions will be easier to track, more transparent, and safer to use as part of the control and supervision system for food safety and halal standards in the beef supply chain. This research has implications for transparency in the supply chain, the accuracy of product track records, prevention of food poisoning, improving halal compliance, risk management and thus increasing consumer confidence.

Introduction

The beef industry plays an important role in the global food supply chain. This is because beef, as a ruminant commodity, is a source of protein that influences the development of human health. As the world's population increases, a 76% increase in global meat consumption is expected between 2015 and 2025 [30]. In its development, consumer demand for beef is not only related to the amount needed but also to the fulfillment of food safety and halal standards. Food safety and halal are important aspects to ensure that the beef consumed is safe, and follows Islamic law. Fulfillment of these two things is a major consideration for consumers in choosing food for health reasons and compliance with values in Islam (Hana Catur [32]). Food safety standards regulated through national and international policies are an important component of preparing food that is safe for consumption, avoiding potential chemical, biological, and physical risks that can endanger the health of the consumer's body [20]. Halal is an obligtion for adherents of Islam for all products consumed, under the provisions in the Quran and Hadith [10,18].

However, some phenomena indicate that there are activities that result in food safety and halal contamination in the beef industry supply chain. This happens because the beef industry supply chain is more complex than other food industries. Food safety and halal contamination in the beef industry supply chain results in unsafe and un-halal food for consumption. Food safety contamination can come from the use of raw materials that contain harmful enzymes and ethanol [9], working mechanism in the production room and product storage [4], suppliers, distributors, and retailers (H.C. [31]). Halal contamination can come from cross-contamination with halal and non-halal products in warehouses, logistics, equipment used, or production areas that are not separate for halal and non-halal products, the use of raw materials, or additives that have not been certified.

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Assurance of the fulfillment of food safety and halal standards is carried out by avoiding the occurrence of such contamination through the implementation of risk management. In various studies, it has been proven that risk management can identify and manage risks and develop risk mitigation actions to formulate areas of improvement in reducing hazards in the supply chain to improve company performance [24]. Specifically in the case of food supply chains, previous research suggests that risk management has a positive impact on environmental health through cooperation between suppliers and customers in terms of design, purchasing, production, packaging, and the use of green energy [7].

However, in reality, there are problems in the meat supply chain as one of the ruminant commodities related to the implementation of food safety and halal standards and have an impact on the risk of changing the status of food to be unsafe and not halal. Lack of information in the beef supply chain, especially related to the health of livestock (cattle), processing and slaughtering, transport, and storage systems are potential sources of contamination so that products become unsafe and not halal for consumption. This situation is exercerbated by the absence of adequate facilities in the Halal meat supply chain, particularly in terms of slaughterhouses. In Indonesia, as of 2022, fewer than 15% of slaughterhouses possess Halal certification, despite their crucial role in ensuring the production of Halal meat [14].

Therefore, implementing risk management in the beef supply chain to comply with food safety and halal standards requires cooperation between actors in a holistic and integrated manner by utilizing technology. Blockchain technology is the best option that can be used in risk management in the beef supply chain to meet food safety and halal standards because it can guarantee resilience, transparency, and accountability in the risk management decision-making process to respond to uncertain and complex events to support the improvement of supply chain performance [6,13,29].

This research offers a novelty in the form of a blockchain technology model following food safety and halal standards in the beef supply chain. This research is important to overcome the weak control and supervision system of food safety and halal standards in the beef supply chain. With the results of this research, the flow of data and transaction information will be more effective and efficient to be traced, transparent, and secured as a source of control and supervision system for food safety and halal standards in the beef supply chain. With this technology, it is expected that the availability of beef that meets food safety and halal standards can be guaranteed, thereby reducing the value of imports as has been the case. Based on this description, the research objectives are: (1) identify risk factors for food safety and halal, (2) Develop a blockchain technology design for mitigating food safety and halal risks in beef.

BLOCKCHAIN TECHNOLOGY

Blockchain technology represents a method of digitalizing contracts, transactions, and records, exerting an impact on global economic, social, political, and legal systems (Tripathi et al., 2023). Theoretical inquiries into the implications of incorporating blockchain technology into the food supply chain have been ongoing since 2018. These investigations encompass various aspects such as technological assessment, sustainability of the food supply chain, and sales model selection (Akram et al., 2024; Köhler & Pizzol, 2020; Y. Liu et al., 2021; Saurabh & Dey, 2021). Previous research on risks within the food supply chain hasprimarily focused on the areas of tracking, tracing, and authentication (Sugandh et al., 2023). Significantly, there exists a void in the existing literature concerning the utilization of blockchain technology in addressing food safety concerns, specifically in conducting Halal risk analysis within the beef supply chain. Hence, the primary objective of this research is to bridge this gap by investigating and discussing these particular aspects.

Food safety

Food safety means keeping food from becoming contaminated, spoil, or other health threats during production, processing, distribution, storage, and consumption. Food safety is becoming a topic of increasing interest, and in recent years, research on the subject has grown rapidly [19]. Chemical and microbial contamination, adulteration, mislabelling, and expired food are some of the food safety hazards that occur in food markets [11]. One important measure to stop food-borne illness is food safety inspections, which have been criticized for being inconsistent and not adequately solving the problem [2]. Deliberate food crime, which covers a wide range of types and levels of financial gain, requires robust risk assessment and countermeasure tools [23]. In this context, the utilization of blockchain technology enables the direct monitoring of food safety from its point of origin throughout every stage of the supply chain until it reaches the end consumer. This monitoring capability enhances credibility, efficiency, and overall safety (Patel et al., 2023) of Halal food products.

Halal

"Halal" is an Arabic term that means "permissible" or "sharia-compliant". In food and beverages, the term is used to refer to items or ingredients that are permitted or halal for consumption by Muslims. The rejection of alcohol and pork, as well as certain slaughtering techniques, are some examples of the differences between halal and non-halal food [15]. In Islam, the consumption of pork, carrion, blood, all blood derivatives, alcohol, and all ingredients that are considered haram or impermissible is prohibited. Conversely, foods that do not contain these ingredients are called halal [16]. To compete in the global Halal market, investment in Halal food production in developing countries and non-Muslim countries requires the adoption of complex and advanced food technologies [21].

The adoption of the Halal supply chain provenance is essential to ensure and certify the Halal status and integrity of products, thus preventing contamination (Kurniawati & Cakravastia, 2023). The application of the Halal supply chain has extended to various sectors, including the food industry in Malaysia (Ab Rashid & Bojei, 2019; Mohamed et al., 2020), subsectors such as frozen food (Kristanto & Kurniawati, 2023), and considerations related to Halal integrity (Ali & Suleiman, 2018).

Aligning with this study, previous research has explored the themes of halal integrity and contamination risks within the Halal supply chain. However, there is a need for a more detailed examination of the sources of these risks and the introduction of mitigation strategies, leveraging technologies such as blockchain. This research brings a novel contribution by focusing on risk mitigation through the utilization of blockchain technology, grounded in the identification of risk sources associated with each participant in the supply chain.

Risk analysis

Risk analysis is a systematic process for identifying, assessing, and managing potential risks or uncertainties that may affect the achievement of project objectives, business decisions, or other activities. Risk analysis is used in the field of occupational health and safety to identify and control risks in laboratory research. This includes training, creating emergency plans, and ensuring the proper use and storage of chemicals [17].

Beef supply chain

The beef supply chain involves the flow of products, financial transactions, and information among the various actors involved. Highly technical, professional, and competitive livestock production, mainly based on quality and technology, will lead to global progress in the supply chain [22]. Supply chain governance encompasses the rules, regulations, and organizations that govern the supply chain to achieve various objectives, including environmental objectives, to maintain the sustainability of the industry [5].

FMEA

A systematic method known as FMEA (Failure Mode and Effect Analysis) is used to identify, evaluate, and manage possible failures in a process or product. FMEA uses expert data to determine the risk of failure modes [8]. In industries such as manufacturing, healthcare, and aerospace, FMEA is commonly used to improve product quality, reliability, and safety. The FMEA process includes identifying potential failure modes, determining their causes and effects, and assigning a risk priority number (RPN) to each failure mode based on severity, occurrence, and detectability [33]. The RPN is calculated by multiplying the severity, occurrence, and detectability scores for each failure mode. A higher RPN score indicates that the failure mode poses a greater risk. FMEA can be used independently or in combination with root cause analysis (RCA) and fault stem analysis (FTA) to improve the reliability and safety of a system or product [25].

Fault tree analysis (FTA)

A graphical and analytical tool called Fault Tree Analysis (FTA) is used to evaluate potential causes of system failure. This tool is commonly used in many fields, such as engineering, safety, and risk management. FTA starts with a critical event, such as a system failure, and then identifies all the factors that could have contributed to the event. A tree-like structure shows these causes, with the main event at the top of the tree and potential causes branching out below it. To improve the efficiency of recursive failure analysis, FTA is often used in conjunction with other methods such as FMEA (Failure Mode and Effects Analysis) [27]. FTA also uses fuzzy logic and ontology-based approaches to perform comprehensive analyses that are based on rich domain knowledge and in a fuzzy environment [1]. FTA can help find and prioritize risks and create safety protocols to prevent or mitigate failures [26].

Methods

This research was conducted on the beef supply chain in East Java, Indonesia. The structures involved in the beef supply chain are farmers as cattle suppliers, beef processing companies, transporters, and distributors/retailers. The stages of research implementation were carried out in the following stages:

By conducting semi-structured interviews with purposively selected experts representing various stages of the beef supply chain, including cattle farmers, processing companies, and distributors, the researchers identified several risks related to both food safety and adherence to Halal standards. The validation and risk assessment processes, as well as their subsequent formulation, were significantly shaped by insights from these seven experts, encompassing academia, practitioners, and government officials.

This activity is carried out by experts by filling out a questionnaire based on aspects, namely: O (Occurance), S (Severity), and D (Detection). Occurrence indicates the frequency of errors or failures. Severity indicates the severity of the impact of an error/failure. Detection describes the effectiveness of the detection system to detect errors or failures that will occur. This assessment refers to the mechanism in the FMEA (Failure Mode Effect Analysis) method [28]. The RPN value is obtained based on the following equation:

$$RPN = S x O x D$$

The RPN value is then classified into priority levels as in the following [12]. The higher the RPN value, the higher the risk level for that factor so it becomes a priority that must be mitigated. Risk prioritization is done by arranging the RPN values from highest to lowest as the first to last priority. S, O, and D risk assessments were conducted by experts through FGDs. In the FGD, all experts discussed and agreed to provide an assessment as shown in Table 2 below:

Each RPN (Table 1) value is classified into critical risk, high risk, moderate risk, and minor risk. Extreme priority risk is the most critical risk that affects the safe and halal status of beef. Therefore, the four risk factors must be further analyzed to obtain information about the root of the problem so that a solution can be formulated. In this study, risk analysis was carried out using FTA (Fault Three Analysis). The FTA design in this study was prepared for extreme priority risk and high priority risk levels. Moderate risk and acceptable risk levels can be controlled through corrective actions carried out periodically by utilizing existing resources.

Fig. 2 shows the root causes of beef supply chain risk. These root causes need to be addressed. Therefore, to increase effectiveness and efficiency in minimizing risks in the beef supply chain, technology needs to be used. One form of technology that is currently being developed to minimize risk is blockchain technology. Furthermore, based on these results, a blockchain technology model is designed to maintain beef conformity based on food safety and halal standards as follows:

Fig. 3 outlines the application of hybrid blockchain technology in managing the livestock supply chain. The process initiates with livestock registration at the farm, followed by continuous tracking during transportation to the feedlot, processing at the facility, to the eventual distribution of meat cuts to food services. At each stage, secure data recording on the blockchain ensures a traceable and unalterable trail. In this network, supply chain actors function as proposers and validators,

Table 1
Risk factors on food safety and halal in the beef supply chain.

Supply Chain Actors	Risk Factor	Risk Code
Supplier	No animal health data yet	R1
	Transmission of disease from cattle to humans	R2
	Physical damage	R3
	Foreign body contamination such as glass, plastic, or metal	R4
	Residual drug or chemical content	R5
	Chemical or heavy metal contamination	R6
	Unhygienic storage	R7
	Unhygienic transport	R8
	No traceability of animal origin	R9
	Misinformation	R10
	Does not have a halal certificate	R11
	The process of slaughtering cattle does not follow Islamic law	R12
	Cross-contamination with non-halal meat in storage or transport	R13
Production System	Cross-contamination of equipment used with non-halal products	R14
	Contamination using unhygienic equipment	R15
	Use of food additives that are not halal-certified	R16
	Use of food additives or preservatives that are not suitable for human health	R17
	Production room temperature is not up to standard	R18
	Products not yet halal-certified	R19
	Physical contamination of product packaging	R20
Distribution System	The storage warehouse is not halal-certified	R21
	Cross-contamination with non-halal products	R22
	Use of unhygienic modes of transport	R23
	No temperature control during the transport process	R24
	Storage room temperature is not suitable	R25
	Cross-contamination with other products in the storage room	R26
	Subscription of unhygienic products	R27
	Subscription of halal-contaminated products	R28
	No record of product expiry yet	R29
	There is no inspection of the halal status of the product	R30

Table 2
Supply Chain Risk Assessment.

Actors	Risk	S	O	D	RPN	Risk Priority Level
Supplier	R13	3	2	5	30	Acceptable risk
	R10	3	5	3	45	Acceptable risk
	R3	3	4	7	84	Acceptable risk
	R4	7	2	7	98	Acceptable risk
	R5	7	2	8	112	Acceptable risk
	R6	7	3	6	126	Acceptable risk
	R12	7	4	5	140	Acceptable risk
	R9	5	6	3	150	Moderate priority risk
	R2	7	4	6	168	Moderate priority risk
	R7	6	6	7	252	High priority risk
	R1	6	7	7	294	High priority risk
	R8	7	7	8	392	High priority risk
	R11	8	7	8	448	Extreme priority risk
Production system	R20	3	3	6	54	Acceptable risk
	R14	7	3	7	147	Acceptable risk
	R18	8	3	8	192	Moderate priority risk
	R15	7	5	8	280	High priority risk
	R17	5	8	8	320	High priority risk
	R16	6	8	8	384	High priority risk
	R19	8	8	8	512	Extreme priority risk
Distribution system	R25	3	3	5	45	Acceptable risk
	R23	3	5	7	105	Acceptable risk
	R26	5	5	7	175	Moderate priority risk
	R24	6	6	7	252	High priority risk
	R27	6	6	7	252	High priority risk
	R28	8	4	8	256	High priority risk
	R22	7	6	8	336	High priority risk
	R29	8	6	8	384	High priority risk
	R30	7	8	9	504	Extreme priority risk
	R21	8	8	8	512	Extreme priority risk

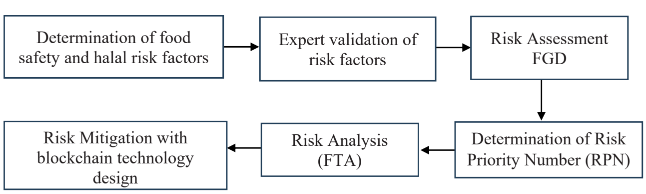

Fig. 1. Research Stages.

engaging in mutual validation, often employing multi-signature (multisig) systems to enhance security and transparency. This reflects the collaborative efforts among various entities within the supply chain. A hybrid blockchain, combining features of both public and private blockchains, enables organizations to establish a permission-based private system alongside a permissionless public system. This setup allows organizations to regulate access to specific data stored on the blockchain and determine which data is accessible to the public.

Blockchain technology in mitigating food safety and halal risks in the beef supply chain (Fig. 3), especially to minimize risks at the extreme priority and high priority risk levels can be done in the form of:

Development of a data traceability system

Data traceability systems with blockchain technology in the supply chain make it possible to develop and implement decentralized, immutable, transparent, and reliable systems, where process automation facilitates real-time data monitoring and decision-making activities. Moreover, the development of data traceability systems with blockchain technology enables visibility and fulfills consumers' needs for transparency and quality assurance.

Smart contracts

Smart contracts based on blockchain technology make it possible to establish cooperation with trading partners by automating contract execution and reducing the role of intermediaries. Through this smart contract, the relationship between actors in the meat industry supply chain can be carried out effectively, efficiently, and securely. The positive impact of using smart contracts is cost and time savings, ensuring data security, openness, trust, and increasing speed. This has been proven by the use of smart contracts in various fields, such as health, real estate, insurance, energy management, and transportation in the development of smart cities.

Improving data management

Blockchain offers excellent data security and integrity, though methods like encryption help combat data breaches. Blockchain technology helps organizations by providing better protection against data

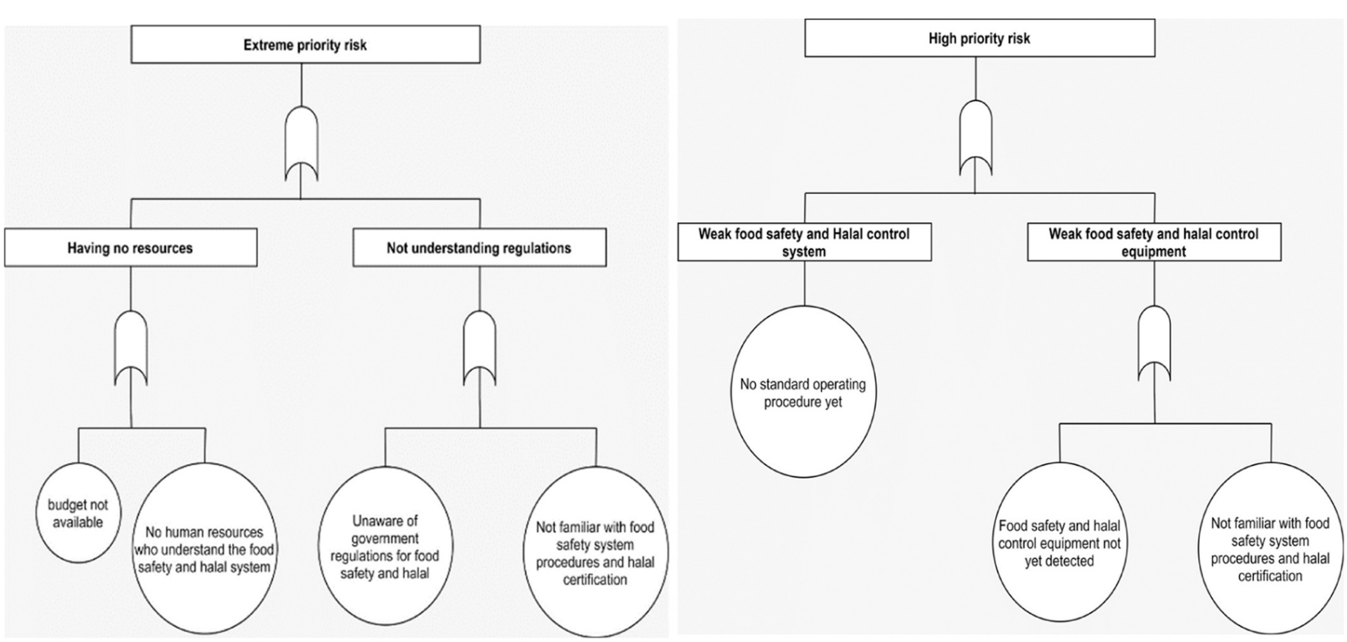

Fig. 2. Meat Industry Risk Analysis with FTA.

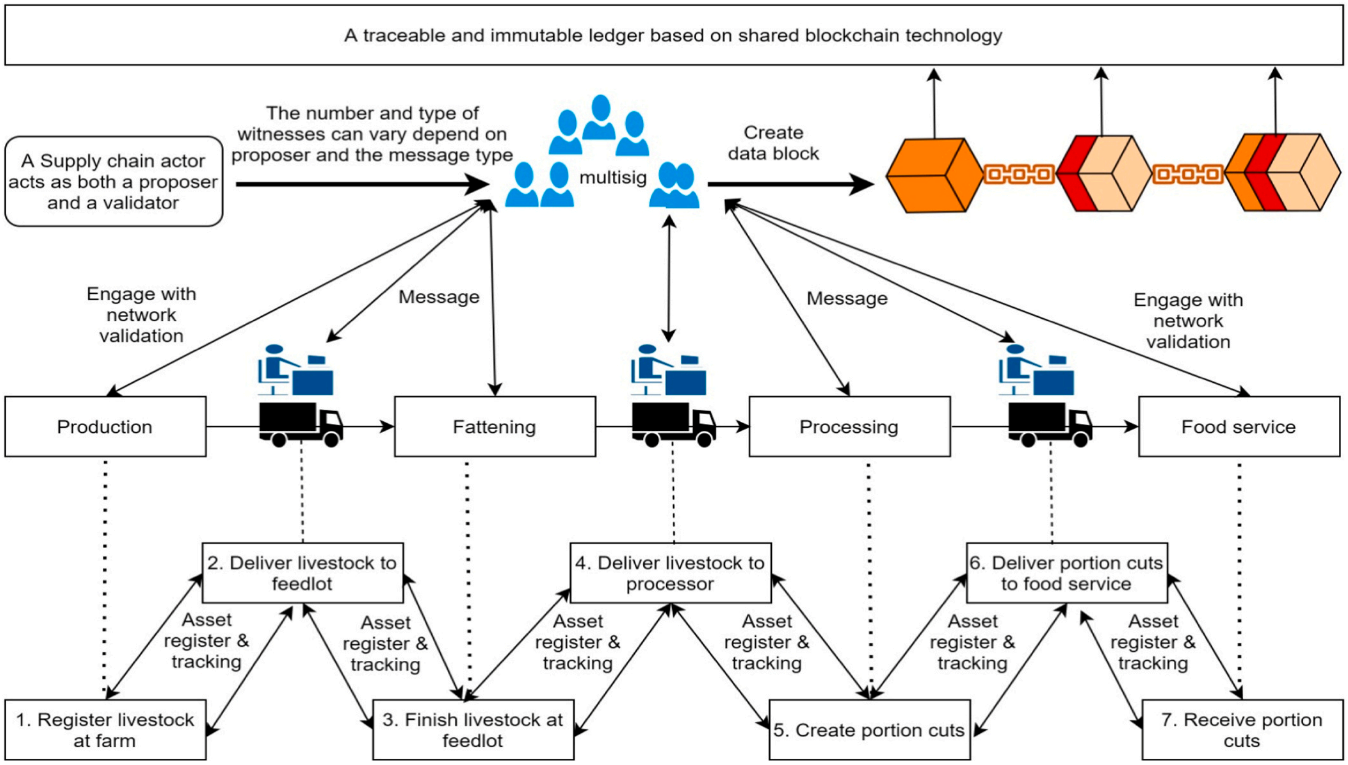

Fig. 3. Design Blockchain Technology for Beef Supply Chain.

breaches, using hashing techniques to store data securely, which helps the company secure data and also helps in data sharing. The primary characteristic of blockchain is decentralization, which allows easy and secure data exchange between organizations.

Improving system management supply chain

Blockchain technology makes it easier for stakeholders to track and trace products, which can improve supply chain traceability. This can lessen waste, stop fraud, and boost productivity [3]. Blockchain technology offers a decentralized, safe platform for data sharing and storing, which can enhance data management in the supply chain. This can increase efficiency and transparency while preventing data breaches and loss [13].

CONCLUSION

The implementation of blockchain technology in the beef industry supply chain can increase transparency and accountability, reduce the possibility of fraud, and enable better tracking of the origin and halal status of beef products. Blockchain technology can also help ensure that beef products meet food safety and halal standards set by regulatory authorities and religious norms. Contamination or diseases that may endanger consumer health can be tracked quickly and accurately through blockchain technology. Blockchain technology can help with halal and food safety risk management in the beef industry. It will make it easier to find and eliminate potential problems. With this research, data, and transaction flows will be easier to track, more transparent, and more secure to be used as part of the control and supervision system for food safety and halal standards in the beef supply chain. The implication of this research is transparency in the supply chain, the accuracy of product records, prevention of food poisoning, improving halal compliance, risk management and thus increasing consumer confidence.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hana Catur Wahyuni reports financial support was provided by Ministry of Education Culture Research and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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