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Can blockchain revolutionize meat production? Addressing transparency, trust, and compliance in conventional and cultured meat

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ABSTRACT

Background: The demand for safe and sustainable meat production is increasing, necessitating innovative solutions for food safety, transparency, and regulatory compliance. Blockchain technology has emerged as a potential tool to address these challenges, particularly in the conventional meat sector. However, its application in the cultured meat industry remains underexplored, raising questions about its effectiveness in enhancing trust, traceability, and regulatory adherence in this emerging sector.
Scope and approach: This study conducts a scoping review following the PRISMA protocol to examine the role of blockchain in both conventional and cultured meat industries. The review was based on searches conducted in June 2024 using two major databases— Scopus and Web of Science —and focused on peer-reviewed literature related to blockchain applications in meat production. The search covered publications up to mid-2024 and targeted titles, abstracts, and keywords using terms such as "blockchain", "meat supply chain," and "cultured meat". After applying inclusion and exclusion criteria, 14 relevant empirical studies were selected for full-text analysis.
Key findings and conclusions: Findings indicate that blockchain significantly improves traceability and trust, particularly in ensuring product authenticity and safety. It facilitates regulatory compliance by enabling stakeholder collaboration and maintaining auditable data trails. Internet of Things integration further enhances monitoring capabilities. However, challenges such as data interoperability, high implementation costs, and the absence of standardized protocols hinder broader adoption. Overcoming these barriers is crucial to unlocking blockchain's full potential. Future research should focus on blockchain integration strategies, consumer perceptions, and regulatory frameworks to support its adoption in cultured meat production.

1. Introduction

In recent decades, global meat consumption has increased dramatically due to population growth, urbanization, and rising incomes, leading to a significant increase in livestock farming (Hansen, 2018; Ritchie et al., 2023). This production contributes significantly to environmental issues, including greenhouse gas emissions (12 %) (FAO, 2023) and water pollution from untreated animal waste (Bashir et al., 2020). The intensified livestock farming often leads to poor living conditions for animals, including overcrowding, lack of space and insufficient access to natural behaviours, which not only raise ethical concerns but also affect the overall welfare of the animals (Aquilani et al., 2022).

In response, various initiatives have emerged, including more sustainable practices such as extensive livestock farming (Pulido-Herrera et al., 2024), agroecology and carbon-neutral livestock systems (Pulina et al., 2022), as well as cutting-edge innovations like cultured meat production (Mancini & Antonioli, 2022). These approaches may offer notable advantages, such as reducing greenhouse gas emissions, improving animal welfare, and addressing food security concerns (Chriki et al., 2022). However, several challenges remain, including the scalability of meat alternatives, high production costs, regulatory barriers, and traceability (Caputo et al., 2024).

Hocquette et al. (2025) highlighted that cultured meat has an uncertain future compared to other sustainable strategies like shifting to

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alternative proteins (e.g., plant-based and algae, and insects). The uncertainties surrounding cultured meat span a wide range of concerns, from general consumer aversion to unfamiliar foods (Pakseresht, Ahmadi Kaliji, & Canavari, 2022) to uncertainties surrounding its long-term impact and safety (McClements, 2023). Moreover, the legal framework for cultured meat varies greatly from region to region, making regulatory compliance more complicated for producers and leading to uncertainty among consumers about labelling and safety standards (Miyake et al., 2023).

To address these challenges, solutions like enhanced labelling and more effective traceability systems could be implemented. Effective labelling could help educate consumers about the benefits and limitations of both conventional and cultured meat, including its environmental impact and contribution to animal welfare, while traceability systems could ensure the safety and quality of these products. One of the most promising tools for improving traceability and transparency in the food supply chain is blockchain technology (Patel et al., 2023). Unlike conventional systems such as centralised databases, cloud-based systems and Enterprise Resource Planning (ERP) tools, blockchain offers a decentralized ledger of immutable records of transactions that cannot be altered without consensus (Pongnumkul et al., 2025). Its immutability as well as ability to embed smart contracts provide automated verification and conditional execution— making it uniquely suited to address long-standing trust issues in meat supply chains (Ahmadi Kaliji & Pakseresht, 2022).

Blockchain has been extensively examined for agricultural products such as coffee (Alamsyah et al., 2023), cocoa (Bai et al., 2022), and dairy (Tan & Ngan, 2020), where it has been used to enhance traceability, ensure fair trade practices, and improve supply chain transparency. However, implementing blockchain in these contexts is not without challenges. High costs of adoption, technological complexity, and the need for extensive stakeholder collaboration may hinder its integration (Tangsakul & Sureeyatanapas, 2024).

Recent examples in blockchain for meat production have revealed its ability to improve traceability, reduce fraud, and enhance food safety by tracking the entire process from farm to table (Akram et al., 2024). However, its potential for improving sustainability in both conventional extensive livestock farming and cultured meat production remains largely unexplored. This paper aims to explore the potential of blockchain technology in addressing the issues related to sustainable meat production practices and cultured meat production. To address this gap, we review existing research on blockchain applications in conventional meat production and investigate its potential benefits for farmed meat, an area that has yet to be explored in the literature.

To further contextualize blockchain's transformative potential in meat production, it is helpful to draw on evidence from other industries. For example, in the construction sector, blockchain has been successfully applied to enhance transparency and support circular economy objectives in the supply chain of construction materials (Singh & Kumar, 2024c). Similarly, facility management in infrastructure development has seen the strategic deployment of blockchain in combination with Building Information Modelling (BIM) to overcome adoption barriers and improve data integrity (Singh & Kumar, 2024a). Another study examined how blockchain contributes to achieving sustainable development goals and environmental, social and governance objectives in infrastructure projects by improving accountability and cross-stakeholder coordination (Singh & Kumar, 2024b). These cross-sectoral insights offer valuable lessons for blockchain implementation in the meat industry, particularly regarding traceability, stakeholder integration, and regulatory alignment.

While previous reviews have examined blockchain in agri-food supply chains more broadly, they often focus on general food categories (Vern et al., 2024; Yogarajan et al., 2023), crop-based systems such as cocoa, coffee, or grain (e.g., Alamsyah et al., 2023; Bai et al., 2022), or seafood supply chains (e.g., Bharathi et al., 2024). Very few have addressed the meat sector specifically, and to our knowledge, none has comparatively assessed blockchain's role in both conventional and cultured meat systems. This study fills that gap by offering a focused scoping review of blockchain applications in conventional meat industry and extending to the emerging cultured meat sector. Specifically, this paper contributes to the literature in some important ways:

This article provides a structured review of blockchain applications in the meat industry, beginning with conventional meat supply chains and extending to the emerging cultured meat sector.

First, it is among the first studies to systematically explore the potential of blockchain technology for enhancing transparency, traceability, and regulatory compliance in both conventional and cultured meat production.

Second, unlike existing research that primarily focuses on blockchain in general agri-food contexts or conventional meat supply chains, this study specifically addresses its role in the emerging and underexplored domain of cultured meat.

Third, by synthesizing empirical findings through a scoping review methodology, the paper identifies critical gaps, outlines potential applications, and provides actionable insights for stakeholders aiming to improve consumer trust and sustainability in meat production. Consequently, the study will address some key research questions. The research questions are developed based on a gap-oriented approach informed by the initial scoping of existing literature. While blockchain has been widely applied to conventional food systems, especially in agri-food traceability and fraud prevention, its role in the cultured meat sector remains insufficiently explored. In particular, few studies have examined how blockchain could enhance transparency, traceability, and regulatory compliance in this emerging domain—factors that are essential for building consumer trust in novel food technologies. Moreover, comparative analyses that assess how blockchain's impact might differ between conventional and cultured meat systems are still lacking. These observations guided the formulation of the following research questions.

Q1: What specific advantages could blockchain offer in terms of improving transparency, traceability, and trust among consumers for both conventional and cultured meat?

Q2: Can blockchain help ensure regulatory compliance and safety standards in the production of both conventional and cultured meat, and if so, how might these advantages differ between the two types of meat?

Q3: How can blockchain technology address trust-related barriers to consumer acceptance of conventional and cultured meat, particularly in relation to safety, quality, and ethical production?

The results of this study will contribute to more informed decision-making about cultured meat, supporting policy dialogues and providing valuable insights into how technological innovations can facilitate the shift towards more sustainable production.

1.1. Technical background and context

1.1.1. Overview cultured meat production

Cultured meat, also called lab-grown or cell-based meat, is produced by growing animal cells in a controlled environment using nutrient-rich bioreactors (Castellani et al., 2025). While it offers potential benefits such as lower environmental impact and improved animal welfare, widespread consumer acceptance remains limited due to concerns around safety, unfamiliarity, and regulatory uncertainty (Chriki et al., 2025).

Consumers are often sceptical about both conventional and cultured meat (J. Liu et al., 2023), especially regarding safety, quality, and ethical implications. For cultured meat, unfamiliarity with its composition can evoke feelings of unnaturalness or aversion, sometimes described as the "disgust factor" (Pakseresht, Ahmadi Kaliji, & Xhakollari, 2022). To gain acceptance, the product must closely match the taste, texture, and appearance of conventional meat. Transparent disclosure of ingredients is essential to demystify cultured meat, but companies must strike a balance between providing enough information and not overwhelming consumers (Kulus et al., 2023). Listing components like growth media and hormones in understandable terms is key to building trust, especially as unfamiliar terms like "fetal bovine serum" or genetically modified organisms (GMOs) may cause concern (Santos et al., 2023).

Quality assurance is another critical issue. Cultured meat production requires strict control to prevent contamination and ensure consistent quality in taste, texture, and nutritional value (Bryant & Barnett, 2018). Without established regulations or certifications, consumers lack reliable information to assess the safety and quality of cultured meat (Cook et al., 2023). This uncertainty underscores the need for transparency through clear labelling and third-party audits to build consumer confidence. The conventional meat industry faces similar challenges with ensuring authenticity and preventing fraud, despite existing labels and certifications (Williams et al., 2023). Addressing these issues is essential for integrating cultured meat into mainstream markets.

Production practices also raise concerns, particularly regarding transparency and compliance with religious dietary laws. Cultured meat production involves complex biotechnological processes that differ significantly from traditional meat supply chains (Treich, 2021). For religious consumers following kosher or halal practices, transparency about the cell source, growth medium, and possible contamination is vital. Without clear assurances that cultured meat meets religious standards, it may face resistance in these markets (Weinrich et al., 2020).

Proponents argue that cultured meat offers sustainability and ethical advantages over conventional farming, such as reducing land and water use and lowering greenhouse gas emissions (Chriki et al., 2022). It addresses animal welfare concerns by eliminating the need for animal slaughter, appealing to consumers who prioritize humane treatment (Reis et al., 2021). However, critics highlight issues like high energy consumption during production, which could undermine environmental benefits unless renewable energy is used (Cai et al., 2024). Scaling up production to meet global demand may require resource-intensive facilities, complicating sustainability efforts (L. Chen et al., 2022). Additionally, by-products like unused cell cultures and waste from growth media must be managed responsibly to avoid environmental harm (Hubalek et al., 2022).

Transparent technologies that provide detailed, immutable records of production practices are essential for building consumer trust. Ensuring both conventional and cultured meat are produced sustainably and ethically is critical for achieving wider acceptance. As awareness of cultured meat grows, so does the demand for clear and trustworthy communication about its production and impact. Addressing these concerns is necessary to foster consumer confidence and facilitate the transition to more sustainable food systems.

1.1.2. *Blockchain technology: overview and definitions*

A blockchain is a specialized form of distributed ledger system in which blocks of data representing individual transactions are securely linked using cryptographic hash algorithms to ensure their reliability and integrity (Javaid et al., 2022). The architecture of this system consists of a chain of blocks, each containing two main components: the header and the main data (Liang, 2020). As shown in Fig. 1, each block contains a header with essential components including the Merkle root, current and previous block hashes, and timestamp. These elements ensure the integrity and chronological ordering of blocks. In meat supply chains, annotations such as batch IDs, certification events, and quality parameters (e.g., temperature logs or halal status) can be recorded within the transaction data layer, ensuring traceability and regulatory compliance.

The main data part of a block contains the detailed transaction records. However, the header is more complex and includes several important elements. It contains the Merkle root, a summarizing hash of all transactions within the block, which ensures data integrity (Tripathi et al., 2023). In addition, the header contains a hash of the current block and the previous block, a timestamp indicating when the block was created, a nonce used in the mining process, and other relevant metadata.

A cryptographic hash is a mathematical function that converts input data into a fixed-size encrypted output called a 'hash value' (D. Liu et al., 2009). The hash value of each block links it to its predecessor and forms a secure and immutable chain. These hash values are unique and irreversible and ensure the integrity and immutability of the data within the blockchain (Tripathi et al., 2023). A key component of blockchain technology is the Merkle tree, which is based on cryptographic hash functions (Kuznetsov et al., 2024). Within each block, the transactions are organized in a binary data structure called a Merkle tree (Baidya et al., 2021). In this structure, the hashes of child nodes are iteratively

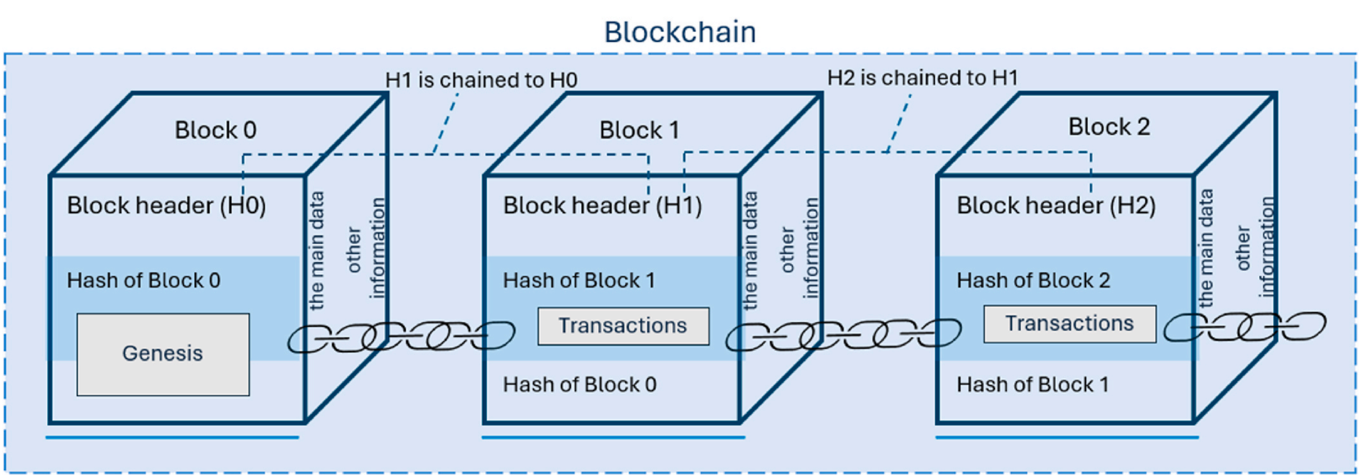

Fig. 1. The architecture of the blockchain.

combined to form the head of the parent node until a single root node, the Merkle root, is formed. This root node acts as a concise identifier for the entire tree and encapsulates all transaction information within the block (Chen et al., 2019).

To ensure trust across distributed participants, blockchains use consensus mechanisms — protocols that allow the network to agree on a single version of the truth. Common consensus mechanisms include Proof of Work (PoW), Proof of Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT). While PoW is secure but energy-intensive (e.g., used in Bitcoin), PoS and PBFT offer more scalable and environmentally friendly alternatives, often preferred in private or consortium blockchains (Jain et al., 2024a).

Blockchains can be divided into three main types based on access control: public (permissionless, such as Ethereum), private (permissioned, such as Hyperledger) and hybrid (public, permissioned) blockchains (Helliar et al., 2020). The type of participation in blockchain networks can also vary and is referred to as either open or alliance, which depends on whether the network involves Internet of Things (IoT) devices or is integrated with other blockchain systems (Alam, 2023).

In the context of food systems and meat supply chains, the key advantages of blockchain include decentralization (eliminating reliance on a central authority), transparency (ensuring visibility across all stakeholders), and immutability (making records tamper-proof). These features are critical in ensuring food traceability, verifying certifications, reducing fraud, and building trust in novel products such as cultured meat. Additionally, the integration of smart contracts—automated code that executes rules—allows for real-time compliance checks and faster dispute resolution (Bassan & Rabitti, 2024a).

The remainder of this paper is organized as follows. Section 2 outlines the research methodology and details the scoping review process. Section 3 presents the results, structured around four key themes: enhanced traceability, regulatory compliance, dispute resolution, and digitalization. Section 4 provides a discussion of the findings, with a focus on blockchain's role in cultured meat production. Finally, Section 5 concludes the study by summarizing the main contributions, implications, and directions for future research.

2. Research method

We conducted a scoping review to explore the applications of blockchain technology in the meat sector as the part of the food industry that is involved in the production, processing, distribution, and sale of meat products. Following the methodological framework for scoping reviews, we documented sources, search terms, and inclusion and exclusion criteria according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Pakseresht et al., 2024) reporting approach as well as the results of the synthesis (Table 1).

Unlike systematic reviews, scoping reviews are particularly useful for examining the breadth of research on an emerging topic and for synthesizing diverse sources of evidence without the restrictive inclusion criteria of systematic reviews. A scoping review comprehensively covers the literature and provides a comprehensive perspective on a topic (Jahan et al., 2016). This method is particularly valuable when it comes to providing insights and interpretations that are frequently used in recent studies (Rajput & Datta, 2020). We selected this approach because our objective was not to conduct a detailed technical analysis of blockchain frameworks but rather to explore how blockchain technology fosters trust in meat production—particularly in cultured meat, given its status as an emerging technology with evolving regulatory and consumer landscapes.

On Jun 28, 2024, we performed a search in the well-known electronic databases Scopus and Web of Science. Supplementary sources such as Google Scholar, AgEconSearch or various databases of grey literature, online resources, journals and non-peer-reviewed articles that could have provided a more comprehensive overview of this emerging topic were not considered. By focusing on these reputable databases, we ensured that we had access to high-quality, peer-reviewed publications, which allowed us to prioritize the content without compromising the scientific credibility of the research.

The initial search results for blockchain and cultured meat reveal a substantial number of publications on each topic independently. For instance, a general search yielded 67,310 documents related to blockchain and 2333 documents on cultured meat in the Scopus database. However, this research will focus on the intersection of blockchain technology and the meat industry, as no studies were identified specifically exploring its application in the cultured meat sector. Hence, the search strategy focused on two primary terms—'blockchain technology' and 'meat sector' (including beef, chicken, pork, etc.)—by targeting titles, abstracts, and keywords within the selected databases. We excluded commentaries, reviews and grey literature (e.g. conference proceedings, book chapters, unpublished dissertations, reports and white papers). Our focus was exclusively on original empirical research on the application of blockchain solutions in the meat sector. Articles focusing on other aspects, such as Industry 4.0 and the Internet of Things, were also excluded.

The steps of our scoping literature search, as illustrated in Fig. 2, encompass four stages; identifying sources and search terms, selecting studies based on inclusion and exclusion criteria, choosing the sample, and synthesizing the results. Ultimately, 12 articles were deemed suitable for full-text review (Table A in Appendix).

Table 1
The inclusion and exclusion criteria.

Inclusion criteria:
• Articles showcasing the original findings from empirical blockchain models and frameworks.
• Emphasis on the implementation of blockchain technology in the meat industry.
• Case studies demonstrating effects on enhancing eco-efficiency, reducing asymmetric information, ensuring traceability, and valorization.
• Complete papers published in peer-reviewed journals.
• Full-text articles written in English.
Exclusion criteria:
• Sources that do not explore the use of blockchain in the meat industry.
• Non-empirical papers (e.g., conceptual articles, editorials, and reviews), grey literature.
• Conference papers, book chapters, unpublished theses, reports, and white papers.
• Studies focusing on other facets of precision agriculture[a], such as Industry 4.0 and the Internet of Things.
• Research on the use of blockchain for climate change adaptation and biodiversity conservation.
• Conceptual advancements in blockchain technology.

[a] Precision agriculture is a farm management approach that refers to the gathering, processing and analyzing temporal, spatial and individual data acquired from information technology devices to ensure resource use efficiency and optimum production (Monteiro et al., 2021).

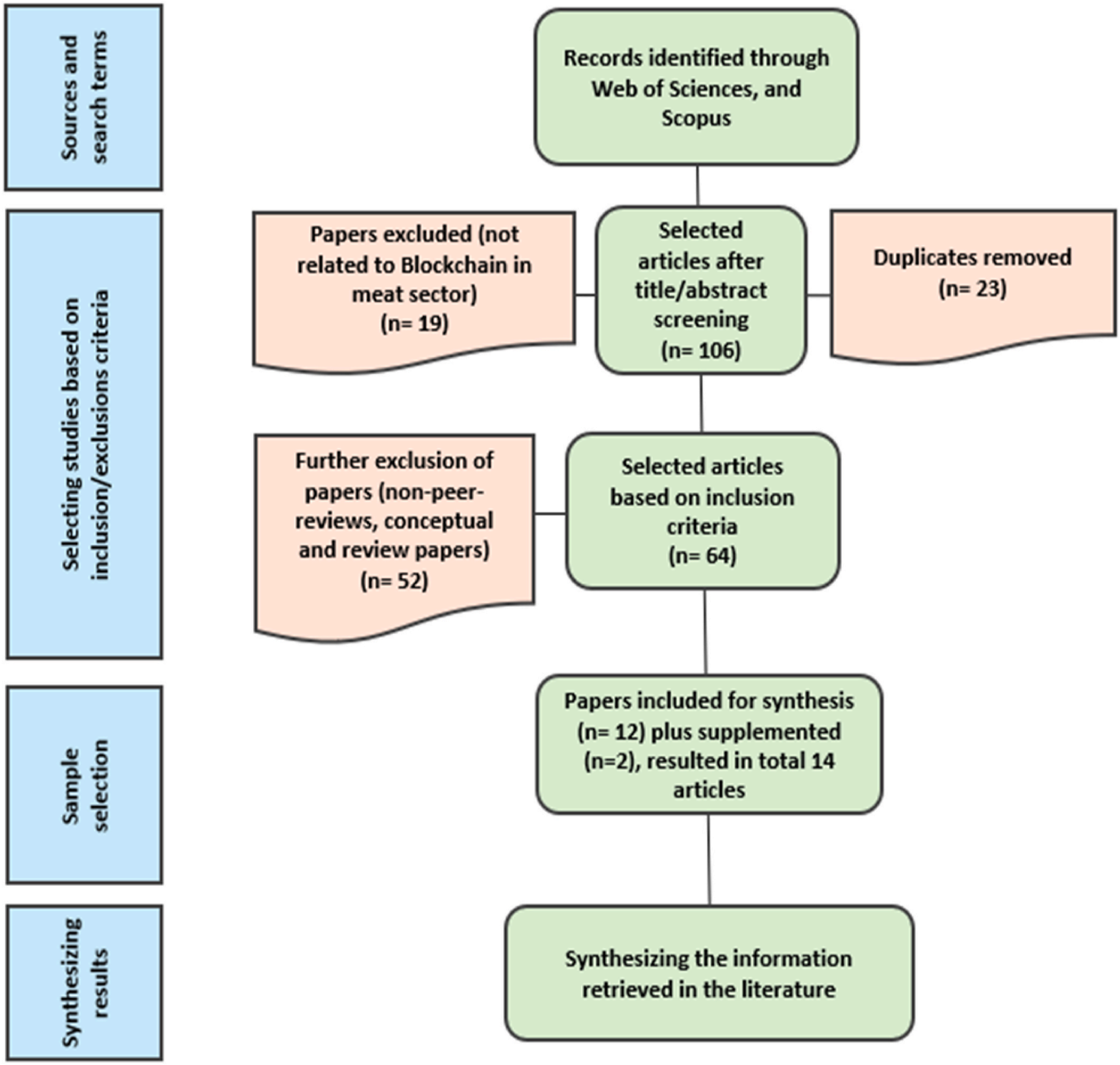

Fig. 2. The overall flow of literature search and selection.

3. Results

In this section, the results of the article review, and analysis are presented across four key subsections, enhanced traceability for food safety, regulatory compliance, dispute resolution, and digitalization in supply chain. These subsections address the potential characteristics of blockchain technology within the meat industry. The summary of these results is shown in Table 1, providing an overview of the key findings across the identified areas.

3.1. *Enhanced traceability for food safety*

Food safety refers to preventing contamination, spoilage, and health risks during food production, processing, distribution, and consumption. It has gained increasing attention, with recent research highlighting issues like chemical and microbial contamination, adulteration, and expired food as major risks. Conventional food safety traceability, although crucial, has been criticised for inconsistency and limited effectiveness in preventing foodborne illnesses (Barnes et al., 2022).

As showed in Table 2, some case studies demonstrate the practical integration of blockchain and IoT technologies for traceability and real-time monitoring in meat production. These applications underscore how blockchain enhances data security, provenance, and stakeholder accountability throughout the supply chain.

Blockchain cryptography ensures immutability by preventing unauthorised alterations to data and guarantees that transactions remain accessible only to their intended participants, maintaining both security and privacy (Tripathi et al., 2023). Blockchains use Merkle trees that provide cryptographic assurance by hashing transaction data into a single root, which is then stored on-chain. In meat supply chains, each stage—from farm to retail—can insert their data, and the resulting Merkle root enables any party to verify the integrity of the entire batch

Table 2
Challenges and concerns in the meat industry and blockchain solutions to address them.

Key Themes	Challenges in the Meat Industry	Examples of Concerns	Blockchain Case Studies
Traceability and Food Safety	Food Safety and Quality	-Risk of contamination (e.g., E. coli, Salmonella) during processing and transportation (Iftekhar & Cui, 2021). - Antibiotic residues and overuse lead to resistance (Bharathi S et al., 2024). - Detecting the origin of products during recalls (Powell et al., 2022).	- Blockchain-IoT beef supply chain enhanced data integrity, trust, and economic incentives through event monitoring (Powell et al., 2022). - Blockchain integration with NFTs enabled a time-stamped data ownership and exchange in the poultry supply chain (Pingos et al., 2024). - IoT sensors monitor environmental conditions in frozen meat chains, triggering warnings for contamination risks (Iftekhar & Cui, 2021). - Quicker detection of potential issues and more efficient recalls during the COVID-19 pandemic (Akram et al., 2024).
	Transparency and Trust in the Production Process	- Limited transparency in the origin and handling of meat products (Pingos et al., 2024). - Rising demand for transparency regarding production methods, organic, or ethically sourced meat products (Powell et al., 2022).	- Improved data accuracy and faster origin verification (Pingos et al., 2024). - Hybrid blockchain enables meat supply chain stakeholders to control data access, sharing specific information while restricting others (Wahyuni et al., 2024).
Regulatory Compliance	Regulatory Compliance Issues	- Complex regulatory requirements across different regions (Alshehri, 2023). - Challenges in adhering to health and quality standards across supply chain stages (Cao et al., 2021). - Issues in complying with varying international regulations and standards (Chandan et al., 2023).	- Improved labour data management, interoperability and regulatory compliance (Arvana et al., 2023).
	Fraud and Mislabelling	- Instances of food fraud, such as substituting premium meat with lower-quality alternatives (Kshetri, 2019). - Mislabelling of meat types, origins, or organic certifications. - Challenges in meeting labelling and certification requirements (Duan et al., 2024).	- Blockchain-based traceability system prevented meat fraud (Kshetri, 2019). - Integration with IoT facilitates the verification of food products' authenticity and the detection of counterfeit trades (Cao et al., 2021). - Integrating QR codes and smart contracts to ensure halal compliance in chicken meat supply chains (Susanty et al., 2024). - Traceability for halal meat in Indonesia, enabled consumers to verify product authenticity and distribution details (Alamsyah et al., 2022). - Blockchain minimises the risk of fraud and improves the tracking of product origin and Halal certification (Wahyuni et al., 2024).
	Ethical (animal welfare and religious dietary) and Sustainability Concerns	- Animal welfare issues during farming, transportation, and slaughter (Aquilani et al., 2022; Arvana et al., 2023). - Environmental concerns, including high carbon emissions, water usage, and deforestation for grazing (Bashir et al., 2020; Pulina et al., 2022).	- Blockchain ensures halal compliance via sequential traceability (Susanty et al., 2024). - Blockchain-based system enhances consumer trust through halal meat traceability in Indonesia (Alamsyah et al., 2022). - IoT-Blockchain enhanced livestock management, ensuring transparency, animal welfare, and environmental sustainability in farming (Alshehri, 2023). - blockchain allows verification of seafood standards including ethical labour, and eco-friendly production methods (Bharathi S et al., 2024). - Blockchain maintained sustainable practices, preventing overgrazing, and reducing ecosystem damage (Alshehri, 2023).
Dispute Resolution	Supply Chain Disruptions	- Vulnerability to pandemics (e.g., COVID-19) or disease outbreaks (e.g., avian flu, swine fever) (Arvana et al., 2023). -Transportation and logistics delays affecting the freshness and availability of meat (Marchese & Tomarchio, 2022).	- IoT-enabled systems in frozen meat distribution hold potential for the prevention of the spread of COVID-19 through imported food products (Iftekhar & Cui, 2021). - Blockchain holds the potential to enhance traceability in crisis events (Akram et al., 2024).
	Intermediaries and Miscommunications	-Transportation and logistics delays affecting the freshness and availability of meat (Qian et al., 2022).	- Blockchain significantly enhanced the efficiency of the meat supply chain by reducing intermediaries, eliminating paperwork, simplifying processes and accelerating transactions (Akram et al., 2024).
Digitalization in Supply Chain	Waste and supply chain inefficiencies	- High levels of waste at production, processing, and retail levels (Yontar, 2023). - High levels of waste due to overproduction, spoilage, or rejected products (Tang et al., 2024).	- Blockchain minimises spoilage risks and waste by optimizing resource allocation, helping to reduce waste at the production, processing, and retail levels (Yontar, 2023). - Blockchain minimises spoilage risks and waste by controlling temperature throughout the cold chain (Qian et al., 2022).
	Technology and integration gaps	- Limited adoption of digital solutions for transparency, traceability, and efficiency (Lincopinis & Llantos, 2024). - Resistance to innovation due to cost or lack of expertise (Irani et al., 2023).	- IoT integration enhances data management and ensures secure, transparent exchanges between meat supply chain actors (Alshehri, 2023). - The high initial costs and technical complexities associated with adopting blockchain technology in industries, especially for smaller businesses lead to limited adoption and resistance to innovation (Kumar Singh et al., 2023).
	Cargo integrity and security	- Logistics challenges, including maintaining cold chain integrity (Treiblmaier & Garaus, 2023).	- A quality assurance management system for frozen cold fish integrates IoT with blockchain technology to optimize

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Table 2 (*continued*)

Key Themes	Challenges in the Meat Industry	Examples of Concerns	Blockchain Case Studies
		- Demand-supply mismatches, leading to shortages or surpluses (Zarbà et al., 2024).	temperature control across the entire cold chain, ensuring the integrity of the cold chain and minimizing the risk of spoilage during transport and storage (Qian et al., 2022). - An IoT-based blockchain system enhances livestock monitoring and farming efficiency by optimizing resource use, which can indirectly address logistics challenges such as temperature management and timely delivery of fresh products (Alshehri, 2023).

history without needing to access full datasets (Yao & Zhang, 2022). Once data has been stored in the blockchain, it can no longer be changed or deleted, as any manipulation would interrupt the cryptographic hash of the chain, which would signal a manipulation (Patel et al., 2023). Consensus algorithms ensure decentralized validation of this data, preventing unilateral changes by a single entity and ensuring the accuracy of traceability information (Jain et al., 2024b). This inherent immutability and transparency of blockchain technology is particularly valuable in the context of food quality assurance. For instance, Powell et al. (2022) provided insights from a blockchain and IoT-enabled beef supply chain project focused on event monitoring and provenance assurance. Their system enhanced data integrity and built greater trust among stakeholders by securely recording past supply chain events—such as goods movement, quality checks, and certifications. As another integration approach, Pingos et al. (2024) developed a blockchain-based algorithmic framework for poultry meat production that utilizes data layouts to dynamically generate data networks (interconnected data points or nodes representing relationships and information flows within the production system) and data products, such as traceability reports or analytics. A central feature of this framework is the integration of Non-Fungible Tokens (NFTs) to securely manage data ownership and enabling a time-stamped for the traceability of NFTs, which serve as unique digital identifiers recorded on the blockchain, certify both ownership and authenticity of data at each stage of operations hence reducing accountability and governance challenges in meat traceability. Arvana et al., 2023 examined the role of blockchain smart contracts (within a multi-chain architecture) for ham production traceability. The authors confirmed that smart contracts enable automate certification and stakeholder verification in each production stage.

Besides data management, blockchain-integrated IoT sensors can continuously monitor critical parameters such as temperature, humidity and contamination levels in food production environments (Soori et al., 2023). This data is securely recorded in the blockchain so that deviations from optimal conditions can be detected and corrected immediately. This proactive monitoring system helps to maintain consistent quality and safety, reduce contamination risks and ensure that food products meet high standards for texture, flavour and nutritional content (Treiblmaier & Garaus, 2023). Iftekhar and Cui (2021) studied frozen meat supply chains and found that IoT sensors trigger warnings related to environmental conditions and potential contamination risks in the frozen meat supply chain. When such warnings are activated, immediate corrective actions are taken and documented on the blockchain. Traceable records of the data on the entire production process then can be verified by independent parties. This helps maintain the quality of the meat by ensuring optimal storage conditions are continuously met, preserving its freshness, texture, and nutritional value.

Blockchain technology enhances data transparency; however, the extent of information sharing remains a persistent concern among many supply chain stakeholders (Helliar et al., 2020). Wahyuni et al. (2024) conducted a risk analysis and the potential of Blockchain technology for improving the food safety of the (halal) beef supply chain. The authors concluded that a hybrid blockchain allows stakeholders in the meat supply chain to manage access to specific data stored on the network and controlling the information need to be shared publicly. However, challenges such as integrating blockchain into legacy systems and ensuring data accuracy still is a challenge (Bouzembrak et al., 2019). Legacy systems present significant challenges when incorporated into modern innovations like blockchain (Irani et al., 2023). This is important because outdated legacy systems can hinder the full potential of blockchain. In addition, the reliability of the system still depends heavily on the quality of data captured by IoT devices which poses risk of sensor tampering and inaccuracies in environmental monitoring remain critical challenges (Iftekhar & Cui, 2021). Addressing these integration issues is crucial for achieving traceable and trustworthy data flow across supply chains.

3.2. Regulatory compliance

Compliance with regulations and standards is a significant challenge in the food supply chain due to the broad scope of risks, variability of laws and standards, geographical expansion of supply chains, and issues with interoperability between systems. Decentralized, immutable, time-stamped blockchain data is ideal for auditing and legal compliance. All stakeholders including regulatory authorities and external auditors can access data to verify compliance with standards across all supply chain stages (Patel et al., 2023). Smart contracts—self-executing agreements coded on the blockchain—play a key role in automating compliance by enforcing regulatory conditions in real-time (Bassan & Rabitti, 2024b). For example, they can automatically trigger alerts or actions, such as halting transactions, if specific standards are not met. This reduces reliance on manual oversight and enhances adherence to regulations.

Table 2 highlights real-world implementations of blockchain systems addressing regulatory compliance, including halal certification and sustainable sourcing. These examples reinforce blockchain's role in automating audit trails and supporting ethical claims through verifiable, time-stamped records.

Blockchain's characteristics are increasingly acknowledged in the food industry as effective tools for combating food fraud, including practices such as mislabelling, ingredient substitution, and product quality false claims (Duan et al., 2024; Ellahi et al., 2023). Unique digital tags assigned to food items enable seamless tracking through the integration of smart contracts and Internet of Things (IoT) sensors (Duan et al., 2024). Research conducted by Chiaraluce et al. (2024) demonstrated that IoT-integrated Blockchain could save an estimated $31 billion in food fraud prevention over five years. In the meat sector, JD.com, a prominent Chinese e-commerce platform, addressed meat fraud by deploying a blockchain-based traceability system to enhance trust and transparency in the supply chain. This system provided consumers with verified information about the origin, safety, and processing of Australian-sourced meat (Kshetri, 2019). Cao et al. (2021) developed a framework promoting shared, traceable responsibilities among stakeholders in the beef supply chain. Meat products must be transported and stored under appropriate conditions (e.g., chilled or frozen) to prevent spoilage. This necessitates monitoring both the movement of products across supply chain actors (including production information such as quantity and feeding methods) and the condition of the meat (such as temperature and humidity) during transit (Cao et al., 2021). Blockchain enhances security compliance in this context by integrating multi-signature protocols, requiring validation from multiple participants before data or transactions are added to the ledger (Duan et al., 2024). This shared accountability ensures that no single actor can manipulate or compromise the integrity of the system.

Information about the animal breed and feed types (e.g., grass-fed or grain-fed) is validated through a multi-signature protocol (requiring two or more signatures to confirm transactions) ensuring shared accountability among network participants. Smart contracts further enhance accountability by automating the verification of critical data inputs, such as temperature thresholds or transit durations, to prevent non-compliance (Alqarni et al., 2023). Real-time data updates using wireless RFID (Radio-Frequency IDentification) sensors and IoT devices help prevent data tampering by tracking key variables such as temperature, humidity, storage time and traded quantity (Cao et al., 2021). By integrating these tools, the food industry, particularly the meat sector, can minimize risks related to data tampering and counterfeit trades (Habib et al., 2022).

In addition, Blockchain technology is particularly valuable for addressing certifications and ethical concerns, such as ensuring adherence to animal welfare standards, organic production, and religious dietary requirements (Alamsyah et al., 2022). In a case study (Bharathi S et al., 2024), proposed a blockchain-based model to enhance efficiency in the seafood supply chain. The system demonstrated how blockchain maintains transparent transaction records and facilitates verifying compliance with environmental and social standards (including sustainable sourcing practices, ethical labour, and eco-friendly production). Alshehri (2023) has developed an IoT blockchain framework for smart livestock farming and found it enhances transparency on animal welfare practices by monitoring parameters such as health, feeding schedules, and housing conditions through IoT devices. This data, collected from farmers and verified by regulators, was securely stored on the blockchain, ensuring accountability across the supply chain. Susanty et al. (2024) designed a blockchain-based traceability system to examine its potential to monitor and ensure halal compliance throughout the entire chicken meat production chain. The system comprised four key components: a distributed ledger with QR codes, a smart contract for transaction confirmation, user permissions with private passwords, and accessible traceability data for customers. Their findings revealed that this blockchain-modelled system facilitated the sequential input of halal assurance information within the supply chain. In another study, Alamsyah et al. (2022) designed a blockchain-based traceability system to uphold halal compliance in Indonesia's meat industry. The system offered substantial consumer benefits, such as enabling the identification of all distribution chain participants and verifying halal certification by recognised authorities. Furthermore, blockchain technology has significant potential to advance food systems by promoting more sustainable and efficient practices (Duan et al., 2024). While evidence specific to the meat supply chain remains limited, examples from other sectors demonstrate how Blockchain can ensure fair trade, uphold labour standards, and reduce waste and carbon emissions within food supply chains (Kshetri, 2018).

3.3. Dispute resolution

Dispute resolution in the meat supply chain using blockchain refers to leveraging the technology to resolve conflicts related to transactions, safety, and compliance in the supply chain (Kakarlapudi & Mahmoud, 2021). Blockchain decentralized and immutable architecture with the help of smart contracts fit for dispute resolution (Allen et al., 2019). A smart contract is an automated mechanism that self-executes specific functions (protocols) once predefined conditions are met without requiring third parties to validate, intervene, or enforce it (Liang, 2020). Hence, the Blockchain enables network participants to anonymously access the documents provided by the disputing parties and enforce necessary decisions without the intervention of third parties.

In the wake of this digital transformation, the emergence of advanced technologies, such as IoT-enabled Blockchain systems, has proven effective in managing crises, as exemplified during the COVID-19 pandemic (Zarbà et al., 2024). Recent developments highlight an immense potential in aiding supply chain actors with complex decision-making and substantial capabilities yet to be explored (Zarbà et al., 2024). Blockchain enables more prompt responses to food safety incidents by providing a complete, transparent record of each stage of production, processing, and distribution, enabling stakeholders to trace issues efficiently and mitigate risks (Marchese & Tomarchio, 2022).

As outlined in Table 2, blockchain applications during crisis periods, such as the COVID-19 pandemic, provided transparent documentation and timely data retrieval, which helped resolve disputes and restored supply chain reliability.

A study by Akram et al. (2024) examined the potential of blockchain technology to enhance traceability in China's meat supply chain, particularly during the COVID-19 pandemic. They highlighted how IoT-enabled blockchain transforms traditional supply chains by improving producer's accountability and eventually consumer trust in product integrity. Specifically, the study confirmed blockchain's power in addressing challenges such as labour data management, interoperability, data accuracy and regulatory compliance. During crises like COVID-19, where concerns about contamination and safe sourcing were heightened, the origin of meat emerged as a pivotal factor in reinforcing consumer trust. The real-time monitoring capabilities offered by the Blockchain contribute to quicker detection of potential issues and more efficient recalls, making the supply chain more responsive and resilient. For example, the systems proposed by Arvana et al., 2023 have shown how blockchain-based traceability significantly reduces the time needed to verify the origin and process of meat products.

Furthermore, some studies highlight blockchain's potential to enhance operational efficiency in food supply chains by reducing intermediaries. Rejeb et al. (2020) emphasised that one of blockchain's most prominent features is its capacity for disintermediation. By enabling automation of business transactions among food supply chain partners, blockchain reduces lead times and costs. Additionally, it facilitates the creation of an ecosystem where seamless value transfers occur with greater efficiency. In the meat industry, Akram et al. (2024) conducted a survey that included input from a respondent representing a prominent online retailer and an early adopter of blockchain for food and meat products. The respondent reported that blockchain technology significantly enhanced supply chain efficiency by eliminating paperwork and streamlining processes. Survey participants agreed that blockchain's ability to reduce intermediaries not only expedited transactions but also ensured secure and transparent operations. By enabling automated and secure data sharing among stakeholders, blockchain reduces delays, lowers costs, and builds trust within the supply chain.

Although Blockchain implementation has reduced the reliance on intermediaries (Kamble et al., 2020), the demand for them in the food supply chains is unlikely to disappear entirely in the future (Tseng & Shang, 2021). Instead of becoming obsolete, the role of intermediaries is shifting to that of facilitators, focusing on enabling interoperability between blockchain networks and user communities (Tseng & Shang, 2021).

3.4. Digitalization in supply chain

Table 2 summarises blockchain-based digitalization efforts, showing how integrated systems improve resource optimization and monitoring through AI and IoT, particularly in livestock and meat production settings. Incorporating technological innovations like Blockchain into the agri-food sector has the potential to drive a significant digital transformation (Zarbà et al., 2024). This shift can help businesses achieve a competitive edge while also promoting greater sustainability. Real-time monitoring, facilitated by integrating blockchain technology with IoT devices, is argued to significantly enhance both data accuracy and management efficiency (Tang et al., 2024). Examples include waste reduction, optimized resource allocation, enhanced supply chain resilience, and energy efficiencies across the supply chain (Yontar, 2023). Alshehri (2023) proposed an IoT-based Blockchain system to improve monitoring livestock and farming efficiency. By collecting and analysing real-time data, the system optimizes resource use, such as feed and water, while minimizing unnecessary energy consumption. This also contributed to efficient farm management by supporting the maintenance of organic and sustainable practices, preventing overgrazing, and reducing ecosystem damage.

Despite these advantages, the environmental drawbacks of blockchain, particularly its high energy consumption and carbon footprint, remain subjects of ongoing debate (Alzoubi & Mishra, 2023). For blockchain networks that rely on energy-intensive consensus mechanisms, these environmental concerns may conflict with the meat industry's sustainability goals, potentially offsetting the intended benefits of its implementation. Additionally, Qian et al. (2022) developed an enhanced quality assurance management system for frozen cold fish by integrating IoT into the Blockchain. The authors reported that this integrated system enabled reliable monitoring by documenting critical control points across the entire cold chain. This ensured optimized temperature control throughout transport and storage hence reducing the risk of spoilage products.

Moreover, the integration of Distributed AI (the convergence of Artificial Intelligence and Blockchain) could represent another transformative topic in this domain. Distributed AI offers potential applications for safe, privacy-preserving, and secure meat data processing (Wang & Li, 2024). This integration could enable advanced functionalities, such as disease monitoring and prediction, optimizing farm management practices, and enhancing the efficiency of meat processing workflows. Alshehri (2023) demonstrated that sensors and AI technologies can monitor animal behaviour, detect illnesses up to 5–6 days earlier than conventional methods using skin temperature and Total Internal Reflection (TIR) of the eye, and prevent disease spread. Additionally, machine learning-based facial recognition can identify welfare concerns, aiding in enhanced farm management and breeding program efficiency.

However, despite these potential benefits, the challenges associated with blockchain implementation could hinder its effectiveness in achieving these goals. High initial costs and technical complexities present significant barriers (Kumar Singh et al., 2023), particularly for smaller industry, limiting their ability to adopt blockchain for regulatory compliance. Moreover, scalability issues in blockchain networks—especially in public systems—may become increasingly problematic as the meat industry expands (Lincopinis & Llantos, 2024). If transaction volumes surpass the network's capacity, inefficiencies such as slower processing speeds and rising operational costs could undermine blockchain's ability to provide reliable, real-time compliance verification.

3.5. *Framework for blockchain integration in conventional meat supply chains*

To respond to growing demands for transparency, safety, and compliance in meat production, we propose a framework to guide the integration of blockchain into conventional meat supply chains. This framework synthesizes empirical insights from 14 reviewed studies and consists of three interrelated components: (i) a Data Flow Diagram (DFD), (ii) a stakeholder activity matrix, and (iii) a comparison of traditional versus blockchain-based workflows.

(i) a Data Flow Diagram (DFD):

Fig. 3 illustrates the data flow in a blockchain-enabled meat supply chain, highlighting how blockchain can address the limitations of traditional data management systems. In conventional meat supply chains, data is typically fragmented across stakeholders—such as farmers, processors, distributors, regulators, and retailers—with limited interoperability and frequent reliance on paper-based records or siloed digital platforms. This structure increases the risk of data manipulation, delays in traceability, and inconsistent reporting standards.

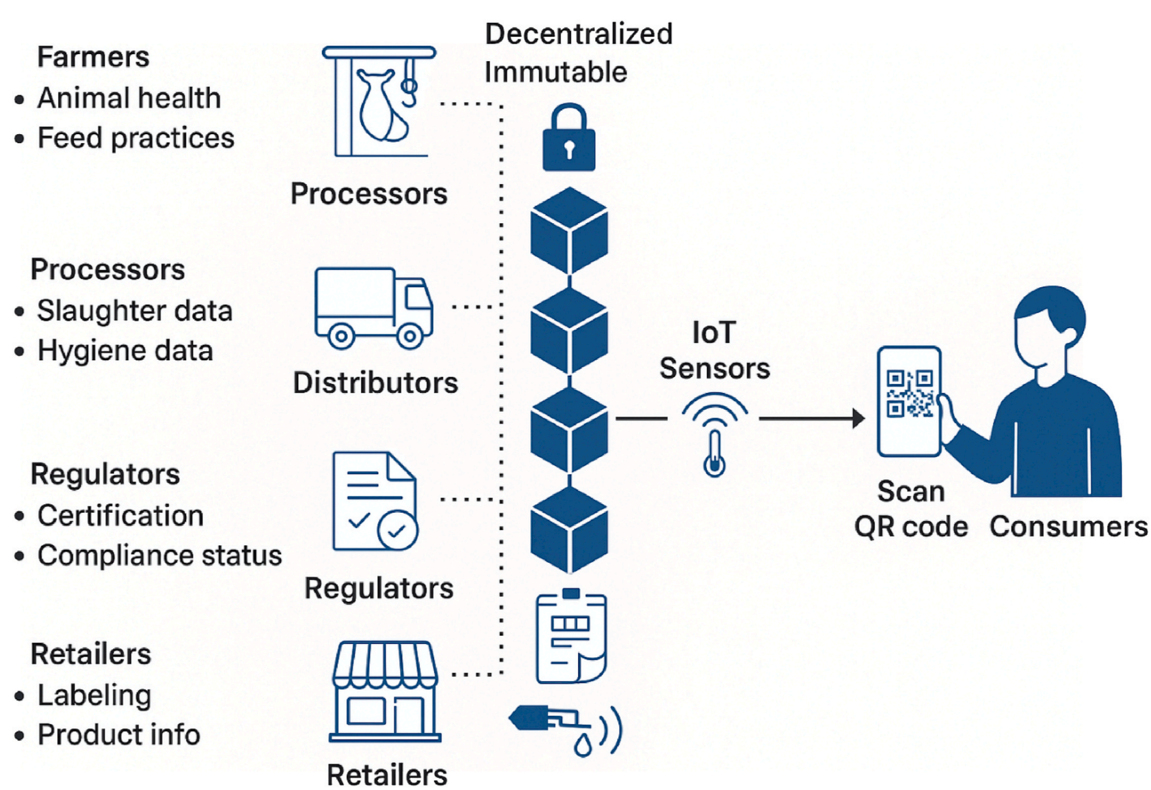

Fig. 3. Data flow in Blockchain enabled meat supply chain.

By contrast, blockchain technology establishes a decentralized, immutable ledger that records each transaction or data point in real time. As depicted in the figure, different actors in the supply chain input verified data at various stages: farmers contribute information on animal health and feed practices; processors record slaughter and hygiene data; distributors upload environmental metrics such as temperature logs; regulators provide certification and compliance status; and retailers add labelling and product information. All of this data is cryptographically secured and stored on the blockchain, creating a continuous, tamper-proof audit trail.

Importantly, consumers can access this verified data by scanning a QR code linked to the product, allowing them to trace its journey from farm to fork. This visibility fosters greater transparency and trust while also enabling rapid responses to food safety issues. The integration of IoT devices (e.g., sensors for temperature or humidity) further enhances the system's reliability by automating real-time monitoring and minimizing the risk of human error. Overall, the blockchain-based model enables seamless, accountable, and secure data exchange, improving traceability and operational integrity across the entire meat supply chain (Iftekhar & Cui, 2021; Pingos et al., 2024; Powell et al., 2022).

(ii) a stakeholder activity matrix:

Table 3 shows how each actor contributes to and benefits from verifiable blockchain-based records. In a blockchain-based meat supply chain, each stakeholder plays a clear role in recording and verifying information. Farmers provide basic details like the type of animal, what it was fed, and health records. This data is checked by veterinarians or authorities and stored on the blockchain to ensure it cannot be changed later (Cao et al., 2022; Alshehri, 2023). Processors record when and how the animal was slaughtered, along with hygiene checks and meat quality grades. These are confirmed by inspectors and securely added to the system (Kshetri, 2019; Powell et al., 2022). Distributors use sensors to track temperature and transport conditions. These readings are automatically sent to the blockchain to prove that the cold chain was maintained (Iftekhar & Cui, 2021; Qian et al., 2022). Regulators can then review this data to confirm safety and compliance, with some checks handled automatically by smart contracts (Susanty et al., 2024; Wahyuni et al., 2024). Retailers use this verified information to label products accurately and offer proof of origin and quality (Arvana et al., 2023; Alamsyah et al., 2022). Finally, consumers can scan QR codes to see the full history of the product, helping them make more informed and confident choices (Akram et al., 2024; Pingos et al., 2024).

Table 3
Stakeholder activities in conventional blockchain-enabled meat supply chains.

Stakeholder	Data Recorded	Verification Role	Key Reference(s)
Farmers	Breed info, feeding logs, vet reports	Confirmed by regulators or vet authorities	Cao et al. (2022); Alshehri (2023)
Processors	Slaughter data, meat grade, hygiene audits	Co-signed by inspectors	Powell et al. (2022); Kshetri (2019)
Distributors	Cold chain data, logistics timestamps	IoT-based auto-verification	Iftekhar and Cui (2021); Qian et al. (2022)
Regulators	Certification info, lab test results	Smart contract–enabled validation	Wahyuni et al. (2024); Susanty et al. (2024)
Retailers	Label integrity, product origin	Cross-checked via hash and smart contract	Arvana et al. (2023); Alamsyah et al. (2022)
Consumers	N/A	Access verified records via QR or apps	Pingos et al. (2024); Akram et al. (2024)

Table 4
Traditional vs. Blockchain-Based Traceability Systems.

Feature	Traditional System	Blockchain-Based System	Empirical Support
Data Storage	Centralized, editable	Decentralized, immutable	Iftekhar and Cui (2021); Cao et al. (2022)
Access to Information	Limited, manual request-based	Real-time, permissioned or public access	Wahyuni et al. (2024); Alshehri (2023)
Certification	Manual inspection and paperwork	Smart contracts enforce rule-based compliance	Susanty et al. (2024); Duan et al. (2024)
Cold Chain Monitoring	Fragmented, prone to error	IoT-verified, continuously logged on-chain	Qian et al. (2022); Treiblmaier and Garaus (2023)
Consumer Transparency	Based on opaque labeling	Direct access to verified data via QR	Pingos et al. (2024); Arvana et al. (2023)
Fraud Prevention	Reactive auditing	Proactive prevention via immutable records	Kshetri (2019); Akram et al. (2024)
Dispute Resolution	Manual, time-consuming	Transparent, traceable resolution trail	Akram et al. (2024); Allen et al. (2019)
Intermediary Dependence	High	Reduced via automation and consensus validation	Tseng and Shang (2021); Rejeb et al. (2020)

(iii) a comparison of traditional versus blockchain-based workflows:

To illustrate the improvements brought by blockchain, Table 4 contrasts traditional and blockchain-based traceability systems across key performance dimensions. Traditional systems often rely on paper records or centralized digital databases, which are vulnerable to tampering, human error, and delayed access. Traceability is frequently reactive—used only after problems occur—and relies heavily on intermediaries to coordinate information flows (Cao et al., 2022; Irani et al., 2023).

Blockchain systems, by contrast, offer tamper-proof, time-stamped, and decentralized records accessible to all authorized parties in real time. These systems minimize the need for intermediaries, reduce fraud, and allow regulators and consumers to verify information instantly (Akram et al., 2024; Powell et al., 2022). Smart contracts automate compliance checks by executing rules encoded into the system—such as halting shipments if temperature thresholds are breached (Qian et al., 2022; Susanty et al., 2024). Moreover, blockchain enhances accountability by attributing data input to specific actors via digital signatures.

4. Discussion

Drawing on the review of studies in the conventional meat industry, the discussion of blockchain in cultured meat production is divided into some sections. First, we explore how blockchain can enhance trust in traceability, boosting transparency and consumer trust. Next, we discuss ensuring safety in production, focusing on how blockchain helps monitor and secure processes to meet safety standards. The third subsection covers stakeholder collaboration and regulatory compliance, highlighting blockchain's role in facilitating coordination and ensuring regulatory adherence. Finally, the challenges and future research section outlines key obstacles and suggests future research directions to overcome barriers and blockchain's full potential in cultured meat production.

4.1. Trust in cultured meat traceability

In conventional meat production, despite some weaknesses, blockchain provides a reliable solution for traceability, enabling stakeholders to track the origin and movements of meat products throughout the supply chain (Pingos et al., 2024). This level of transparency helps in reducing fraud, ensuring product authenticity, and swiftly identifying potential safety issues, such as contamination or mislabelling (Akram et al., 2024; Arvana et al., 2023). Therefore, blockchain's transparent, immutable records can also potentially reduce consumer scepticism regarding the authenticity and safety of cultured meat. Recent studies on consumer acceptance of blockchain-based traceability highlight its potential to enhance trust in novel food technologies by offering a clear view of the product's process and ingredients (Castellini et al., 2022). For instance, Pingos et al. (2024) study has demonstrated that consumers value traceability labels, particularly when blockchain technology is used to ensure the accuracy of information regarding the poultry meat production process (Pingos et al., 2024). Hence, by offering traceability from cell cultivation to the final product, blockchain can also ensure that cultured meat adheres to safety, ethical, and regulatory standards, thus strengthening consumer trust.

Specifically, the integration of IoT sensors enables real-time data monitoring, which can be accessed via QR codes or other digital means, allowing consumers to verify claims about safety, ethical, and regulatory standards (Soori et al., 2023). The use of such traceability systems in conventional meat supply chains has already demonstrated how transparency can build trust, help identify, and eliminate or control misinformation (Pingos et al., 2024; Powell et al., 2022). For cultured meat production, IoT sensors can continuously monitor cell proliferation in bioreactors, ensuring adherence to the required growth curves and other parameters which provide essential information for regulatory bodies. In addition, the culture medium, which supplies nutrients to the growing cells, must maintain a precise balance of glucose, amino acids, and other components (Benny et al., 2022). IoT devices can monitor nutrient consumption in real-time and signal when replenishment or adjustment is needed.

While IoT sensors provide real-time monitoring and actionable insights, their data is tampering if stored in conventional systems. By recording this information on a blockchain ledger, producers can ensure that the data remains immutable and verifiable, building consumer trust and facilitating compliance with regulatory and ethical standards. Furthermore, blockchain creates an efficient way to share this verified information with stakeholders across the supply chain, from regulators to end consumers, enhancing accountability and trust in cultured meat production processes.

4.2. Ensuring safety in cultured meat production

Real-time monitoring of environmental conditions, such as temperature, humidity, and contamination risks, is important in bioreactors commonly used in cultured meat production, where precision is critical. IoT sensors can track these variables, and any deviations from the optimal range can trigger early identification and warning alerts or adjustments (Iftekhar & Cui, 2021). Blockchain ensures that these environmental controls are transparently documented for regulatory and quality assurance purposes. Blockchain allows this data to be recorded securely and immutably, providing an auditable trail that can be reviewed by stakeholders and regulatory authorities (Iftekhar & Cui, 2021).

For example, blockchain-enabled systems in the frozen meat industry have been shown to mitigate contamination risks by documenting deviations and triggering corrective actions (Treiblmaier & Garaus, 2023). Such systems can integrate IoT sensors and AI technologies to detect early warnings, such as temperature fluctuations or abnormal microbial activity, which are then immediately recorded on a tamper-proof blockchain ledger. The blockchain not only timestamps the deviation but also logs details of the event, such as the specific location and nature of the risk. This allows for automated alerts to be sent to relevant personnel, ensuring that corrective measures (such as adjusting storage conditions, isolating affected batches, or initiating cleaning protocols) are implemented without delay. By preserving a transparent record of these actions, blockchain enhances accountability and aids in compliance with safety standards (Qian et al., 2022).

In cultured meat production, such systems are essential to prevent safety violations during sensitive stages of cell cultivation, ensuring that any deviations from optimal conditions are promptly addressed. By offering these real-time capabilities, blockchain can enhance the safety and consistency of cultured meat products, addressing one of the main concerns related to consumer acceptance of novel foods.

4.3. Stakeholder collaboration and regulatory compliance

Cultured meat production potentially may involve a diverse range of stakeholders, including producers, regulators, distributors, and others across the supply chain. As for conventional meat production for which a higher number of actors do exist (numerous farmers, many slaughterhouses, distributors, restaurants, diverse shops), blockchain can facilitate efficient collaboration between these parties by allowing selective data sharing without compromising sensitive information (Arvana et al., 2023). For instance, hybrid blockchain systems, such as those used in halal meat certification (Susanty et al., 2024), have shown how blockchain can provide transparent yet controlled access to information. This can be crucial for ensuring compliance with regulations governing cultured meat, particularly regarding the origin of cells and growth media. Blockchain's immutability provides a reliable record that supports audits and verification, which is important for regulatory transparency (Wahyuni et al., 2024). Furthermore, multi-signature protocols, commonly used in meat supply chains (Cao et al., 2021), could be adapted for cultured meat production to ensure shared accountability among stakeholders. This level of collaboration and regulatory compliance will be essential as cultured meat moves toward broader market acceptance.

4.4. Challenges and future research

Blockchain holds significant potential in both conventional and cultured meat industries but faces considerable integration challenges. In conventional meat, outdated legacy systems hinder seamless adoption, while cultured meat, as a nascent industry, lacks standardized protocols and infrastructure. A major barrier to adoption across both sectors is interoperability, including data semantics and differing technologies, alongside issues with data sharing and accessibility within fragmented supply chains (Sri Vigna Hema & Manickavasagan, 2024). Governance complexities, such as defining accountability and creating a fair data economy, further complicate blockchain implementation. Regulatory frameworks for cultured meat are still evolving, requiring collaboration with stakeholders and regulators to ensure blockchain can verify compliance effectively.

To address evolving regulatory needs, blockchain must be applied in ways tailored to the operational realities of cultured meat. Regulatory uncertainty remains a central issue, as approval pathways for cell-based products differ widely across countries and continue to evolve. Blockchain can serve as a flexible tool for storing and sharing time-stamped compliance records, helping producers meet shifting legal standards and facilitating more efficient oversight and certification. In addition, verifying the origin and handling of critical inputs—such as cell lines and growth media—is essential for product authentication and consumer trust. Blockchain provides a secure, tamper-proof system for recording these biotechnological processes, enabling regulators and consumers to trace product development with confidence. This is particularly relevant for religious consumers, who may require transparency regarding whether animal-derived substances like fetal bovine serum are used.

Cultured meat also presents logistical challenges, especially related to cold chain integrity due to the product's sensitivity to temperature fluctuations. When integrated with IoT devices, blockchain can log real-time temperature data, trigger alerts for deviations, and generate a transparent, auditable record of handling conditions. These targeted applications demonstrate that blockchain's potential in cultured meat extends beyond theoretical advantages—it offers practical solutions to traceability, regulatory, and ethical challenges that are unique to this emerging sector.

While some trust-related challenges in cultured meat align with those in conventional meat (e.g., transparency and authenticity), others are unique to the biotechnological nature of the product. Unlike traditional meat, cultured meat raises concerns about artificiality, health risks, and unfamiliar production inputs like cell lines and growth media. Therefore, blockchain applications must be tailored accordingly. For example, verifying the ethical sourcing and biosecurity of cell cultures or documenting serum-free media use can directly address transparency gaps specific to lab-grown meat. Moreover, blockchain can certify adherence to emerging ethical, environmental, or religious norms (e.g., halal or kosher compliance in cellular processes) via smart contracts and regulatory validation. By emphasizing these cultured-meat-specific blockchain functions, the technology can move beyond generic traceability and actively build consumer trust in this novel protein source.

In addition to technical integration barriers, the lack of standardized protocols across blockchain networks poses a critical limitation to scalability. Interoperability challenges—such as inconsistent data semantics, fragmented system architectures, and vendor lock-in—limit the seamless flow of data across different platforms and stakeholders. To overcome these issues, organizations such as the ISO Technical Committee on Blockchain and Distributed Ledger Technologies (ISO/TC 307) and the Blockchain in Transport Alliance (BiTA) are developing global standards and frameworks for data exchange and interoperability based on the FAIR standards (Wilkinson et al., 2016). In the agri-food sector, initiatives like GS1 are promoting standardized identifiers and traceability formats that can be integrated with blockchain. Adoption of these evolving standards will be essential for scaling blockchain applications across national and global meat supply chains. Without coordinated efforts toward harmonization, blockchain implementation risks remaining siloed and inefficient.

Additionally, capturing reliable environmental data remains a challenge, particularly in conventional meat production, where complex supply chains and diverse practices hinder consistent tracking. While cultured meat offers more centralized control, its early-stage development poses adoption barriers such as high implementation costs and the need for organizational change. To address these challenges, future research should prioritize the development of standardized protocols, integration with IoT technologies, and investigation of consumer perceptions. Cross-industry collaborations and pilot programs can further support the identification of best practices for scalable and sustainable blockchain implementation.

5. Conclusion

This paper explores how blockchain can improve transparency, regulatory compliance, and consumer trust in both conventional and cultured meat sectors. Blockchain enhances transparency and traceability, ensuring product authenticity and safety, and its integration with IoT sensors enables real-time monitoring across the supply chain. In conventional meat production, blockchain addresses issues like fraud prevention, and these benefits extend to cultured meat, fostering trust and ensuring compliance with ethical standards. While blockchain offers significant potential, challenges such as data interoperability, cost, and the need for standardized protocols remain. Addressing these challenges will help blockchain realize its full potential in promoting sustainability, trust, and compliance in meat production.

To translate these insights into practice, industry stakeholders are encouraged to conduct pilot programs using blockchain in meat traceability, focusing on high-risk areas such as cold chain logistics and animal-origin verification. Policymakers should prioritize the development of interoperable legal frameworks and digital standards that facilitate blockchain adoption while ensuring data security and auditability. Cultured meat startups can adopt blockchain to document ethically sensitive inputs—such as serum-free growth media—and automate regulatory compliance through smart contracts.

This study is subject to two key limitations. First, it focuses exclusively on peer-reviewed academic literature indexed in major databases to ensure methodological rigor. While this approach supports transparency and replicability, it excludes grey literature such as industry reports and pilot project documentation, which may offer valuable insights into real-world blockchain applications—particularly in the emerging cultured meat sector. Second, due to the early stage of industry development, there is a lack of empirical research specifically addressing blockchain use in cultured meat. As a result, the analysis remains largely theoretical. Future studies should expand the scope to include grey literature and investigate pilot initiatives from lab-grown meat startups to generate more practice-based evidence.

Nevertheless, the findings of this paper have important implications for both the conventional and cultured meat industries. The adoption of blockchain can enhance consumer trust and ensure compliance with safety and ethical standards, both of which are critical for the acceptance of new food technologies. In conventional meat supply chains, blockchain helps build trust by recording production information—such as origin, feed, health, slaughter, and processing—to enable end-to-end traceability via immutable records. In contrast, for cultured meat—where no animal is reared—blockchain plays a different role. Here, it can ensure transparency around the production process itself, such as the conditions inside bioreactors, growth medium provenance, and compliance monitoring (Rodríguez Escobar et al., 2021). Instead of tracking the origin of the animal, the focus shifts to validating the safety and consistency of the process that creates the meat. Yet, the challenges identified in blockchain implementation—such as data interoperability, cost barriers, and regulatory uncertainties—must be addressed through cross-industry collaborations, standardization efforts, and consumer education. Further research should explore how blockchain can be integrated into existing supply chain systems more efficiently, and how its use can be expanded to foster sustainability and transparency. Additionally, studies on consumer perceptions will be key to understanding the role of blockchain in shaping the future of food production.

Building on this foundation, future research should (i) empirically test blockchain systems in lab-grown meat supply chains through real-world case studies; (ii) compare blockchain's effectiveness against conventional traceability systems in terms of compliance and consumer trust; (iii) examine how blockchain-based transparency influences consumer acceptance of cultured meat; and (iv) explore standardization and interoperability frameworks to scale blockchain adoption across diverse stakeholders. These focused research avenues will help bridge theoretical potential with applied outcomes in both conventional and novel meat production systems.

Appendix

Table A
List of the reviewed literature included 14 articles—12 found through databases and 2 added manually.

Row	Authors, Year	Title	Use Case, Country	Purpose	Key Findings
1	Akram et al. (2024)	Blockchain technology in a crisis: Advantages, challenges, and lessons learned for enhancing food supply chains during the COVID-19 pandemic	The meat industry, China	Investigating the application of blockchain technology within China's food supply chain amid the COVID-19 pandemic, highlighting its advantages and challenges.	This study points to the benefits of improved efficiency, transparency, reliability and traceability in the blockchain-based food supply chain. However, it also points to challenges, such as the limited focus on labour-related elements, issues with integrating blockchain with legacy systems and concerns about the accuracy and reliability of data.
2	Bharathi S et al. (2024)	From ocean to table: examining the potential of Blockchain for responsible sourcing and sustainable seafood supply chains	Seafood, Denmark, India, USA	Presenting a structure utilizing Blockchain technology that enables the evolution of the seafood supply chain ecosystem from its present condition to a more efficient and organized state in the future.	The findings underscore the significance of accurate data management, active participation from stakeholders, regulatory compliance, cybersecurity measures, cost efficiency, transparency, and sustainability for the effective incorporation of Blockchain technology in seafood supply chain systems.
3	Pingos et al. (2024)	Security and ownership in user-defined data meshes	Poultry meat, Cyprus	Development of a blockchain-based algorithmic framework that uses data blueprints to dynamically create data networks and data products based on user requests.	The decentralized system provides a secure, efficient and user-oriented framework for managing data in a poultry meat production plant.
4	Susanty et al. (2024)	Design of blockchain-based halal traceability system applications for halal chicken meat-based food supply chain	Chicken, Indonesia	Designing a blockchain-based traceability system that tracks and ensures halal compliance throughout every stage of the chicken meat production chain, from farming and slaughtering to distribution and food processing.	The halal traceability system, modelled after blockchain, enabled sequential input of halal assurance information in the chicken meat supply chain. It included four key components: a distributed ledger with QR code, a smart contract for transaction confirmation, user permissions with private passwords, and a consensus process for validating halal certificates, culminating in accessible halal traceability data for customers.
5	Wahyuni et al. (2024) #	Blockchain Technology Design Based on Food Safety and Halal Risk Analysis in the Beef Supply Chain with FMEA-FTA	Beef, Indonesia	Enhancing food safety and halal supervision in the beef supply chain by identifying key risk factors and proposing a blockchain-based framework.	The blockchain technology reduces safety risks by optimizing data flow, improving transaction transparency, and enhancing the control and supervision of food safety and halal standards in the beef supply chain.
6	Alshehri (2023)	Blockchain-assisted internet of things framework in smart livestock farming	Livestock farm, N/A	Addressing the application of blockchain technology in livestock-based goods by analyzing its current uses in the food market and farming supply chain.	The integration of the Internet of Things (IoT) and blockchain technologies in smart livestock management systems enables transparent and secure exchanges between farmers. Additionally, a blockchain-based sensing system helps trace the transmission of agricultural goods from farmers to consumers.
7	Arvana et al. (2023)	Agri-food value chain traceability using blockchain technology: Portuguese hams' production scenario	Hams, Portugal	Proposing a blockchain-based traceability system for the agri-food sector, in particular for the meat industry (ham), using a multi-chain architecture.	Using blockchain in the traceability system ensured data immutability, reliability, and transparency throughout the value chain. Additionally, it reduced traceability process time by allowing users to access traced information with a unique product identifier.
8	Alamsyah et al. (2022)	Blockchain-Based traceability System to Support the Indonesian halal supply chain ecosystem	Halal meat, Indonesia	Enhancing assurance practices in Indonesia's halal meat supply chain and developing a blockchain-based traceability system model to ensure halal compliance.	The proposed system increases transparency by enabling the traceability of goods movements in the supply chain and consumers benefit from being able to identify all parties involved in the distribution and verify the halal status of the goods as certified by the official halal authority.
9	Cao et al. (2022)	A blockchain-based multisignature approach for supply chain governance: a use case from the Australian beef industry	Beef, Australia	Designing a blockchain-based multisignature system to enhance governance in geographically dispersed, multi-tier beef supply chains.	The study demonstrates that deploying a blockchain-based multisignature system enhances beef supply chain governance by ensuring full-chain transparency and reliable information sharing, helping supply chain professionals understand how to leverage blockchain for transformative improvements.
10	Qian et al. (2022)	Food cold chain management improvement: A conjoint analysis on COVID-19 and food cold chain systems	Frozen meat and fish, China	Performing food cold chain systems and developing an enhanced management system incorporating Internet of Things (IoT) and blockchain technology.	The proposed system enhances cold chain management by improving temperature ranges. It also ensures credible traceability by documenting critical control points throughout the entire cold chain.

(continued on next page)

Table A (*continued*)

Row	Authors, Year	Title	Use Case, Country	Purpose	Key Findings
11	Powell et al. (2022)	Garbage in garbage out: The precarious link between IoT and blockchain in food supply chains	Meat, Australia and China	Presentation of observations and findings from an ongoing beef supply chain project that integrates blockchain and IoT for event tracking and provenance assurance of beef and proposes two solutions to improve data integrity and trust in the blockchain and IoT-enabled food supply chain.	The IoT and blockchain technology improve meat supply chains not only by providing a reliable record of past events, but more importantly by enabling the definition of future data states and creating economic incentives to achieve these states.
12	Cao et al. (2021)	Strengthening consumer trust in beef supply chain traceability with a blockchain-based human-machine reconcile mechanism	Beef, Australia and China	Enhancing consumer trust in the cross-border beef supply chain by implementing blockchain technology.	The proposed mechanism, which utilizes innovative features of a human-machine matching mechanism and facilitates shared responsibility between agriculture and supply chain participants, provides verified traceability data to consumers within the Australian-Chinese beef supply chain.
13	Iftekhar and Cui (2021)	Blockchain-based traceability system that ensures food safety measures to protect consumer safety and COVID-19 free supply chains	Frozen meat, China	Presenting a blockchain-enabled frozen meat supply chain architecture that guarantees the availability of a tamper-proof audit trail.	In addition to enabling real-time, tamper-proof data sharing, blockchain technology ensures that all necessary safety measures are followed through a secure audit trail. This reduces the risk of COVID-19 and other pathogens in the frozen meat supply chain.
14	Kshetri (2019),[#]	Blockchain and the Economics of Food Safety	Beef, Australia	Developing a blockchain-based framework that ensures shared, transparent, and traceable responsibilities among stakeholders in the beef supply chain.	Blockchain technology has significant benefits, contributing to positive economic impacts and improved public health at the national level through safer, higher-quality food products, while enabling food supply chain firms to tackle inefficiencies, opacity, and fraud.

[#] Note: two articles incorporated in Table A are added manually.

Data availability

Data will be made available on request.

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