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Review

Adoption of Blockchain Technology for Enhanced Traceability of Livestock-Based Products

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Abstract: Blockchain has become a modern technology that can enhance the traceability of products and services, which is particularly relevant to agri-food supply chains. This paper reviews studies on blockchain technology applications to the agri-food supply chain system and food industry, and discusses potential adaptation of blockchain technology for livestock-based products with a focus on the ASEAN Region and Thailand. A comprehensive method for reviewing the literature was adopted, and this paper encompasses stakeholders along the supply chain of livestock-based products to understand the prospect of applying blockchain technology to the sector. It was found that while blockchain technology is potentially sustainable and worthy of applications, there remain various limitations and complications toward adoption, such as the low awareness among stakeholders, the weak sector-wide coordination, and the lack of capacity in primary suppliers. Potential benefits and implications of blockchain technology for the food industry have yet to be widely understood, especially in the ASEAN. These findings would call for coordinated support from both the governments and the private sector, especially to raise awareness of the technology, reinforce sector-wide coordination, and develop skills required for adoption.

Keywords: blockchain; capacity building; food safety; food supply chain; traceability; ASEAN; Thailand

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1. Introduction

Food safety has become a major global public health concern, causing considerably decreased consumer confidence due to various outbreaks of food-borne illnesses, including epidemics [1]. Furthermore, globalization of trade and industrialization of food processing have exposed consumers to a greater number of hazards. The elimination of trade barriers and the complexity of the food processing chain has caused problems, due to both the range and quantity of food products available and to the speed of dissemination of infection or contamination linked to food consumption [2]. With the lack of transparency and traceability in food supply chain systems, consumers' concerns regarding food provenance and quality are growing in many countries, resulting in the increased demand for food products whose origin is certified [3]. Consumers increasingly insist on a comprehensive and integrated food safety policy, such as the farm-to-table policy, which has consequences for both producers and control authorities. For producers, this implies the following: (a) full responsibility is assumed by farmers, animal feed manufacturers, the food industry, and retailers for the quality of the products marketed, in relation to the safety of the final products; and (b) food products, animal feed, and all ingredients are fully traceable. For the control authorities, the tasks are as follows: (a) undertake proper risk analysis to describe and quantify risks along the food chain, including animal feed quality and animal health, in order to either eliminate or mitigate these risks by the application of proper safeguards; and (b) provide sound scientific advice to consumers regarding the risks of particular food products or food types [2].

Enforcement of an adequate and integrated traceability system, covering both plant and animal products, is essential for performing effective risk assessment along the production chain. In particular, an effective food safety policy must recognize the inter-linked nature of food production, and thus, the need for an accurate system to assess and monitor the risks associated with raw materials, farming practices, and food processing [4]. A sound food safety policy requires regulatory action to manage risks and the implementation of an effective control system to monitor and enforce regulations. Each element is part of a chain; thus, changes in farming practices, feed and food production, and processing often require amendments to existing regulations, while feedback from the control systems helps to identify and manage both existing and emerging risks [5]. Each part of the cycle is critical to ensure that the highest safety standards are enforced. The identification of high-risk components in food production (e.g., feed production, animal rearing, transportation, preslaughter processing, slaughter, further processing, retailing, and consumption practice) requires knowledge of the flow of trade from raw materials to semi-manufactured, final product lots, and final products sold to consumers. In the absence of an effective traceability system, this knowledge can only be achieved through exhaustive monitoring of the entire production system [2].

Supply chain management is increasingly leveraging online processes in their business operations. For instance, the online-to-offline (O2O) supply chain strategy uses an online trigger to prompt potential customers to visit the outlet in person to complete the purchase, which is gaining popularity in certain industries, such as print-on-demand. [6,7]. Recent research suggests the advantage of strong coordination between manufacturers and retailers in decentralized supply chain management to address the risk of demand fluctuation in short life-cycle products [8]. Moreover, the concept and practice of green supply chains are gaining momentum in the agri-food sector. The green supply chain network (GSCN) is an emerging topic, reflecting challenges in product life cycle assessment, inventory management, return–refund policy, and coordination facts [9]. In response to the COVID-19 pandemic, hybrid practices have been adopted in businesses in accordance with the demand across different generations. Businesses are currently expected to provide services in both online and offline modes to cater to the different segments of customers. Nonetheless, in consideration of the rapidly changing global environment and economy, all industries have to be ready to incorporate adaptive measures such as the O2O strategy, decarbonization policy, and sustainable supply chain management [7,9,10].

According to the report from Research Drive [11], the meat product market in Southeast Asia is estimated to exceed USD 117 billion by 2026. Thailand's meat product market is projected to exhibit the largest growth among the ASEAN countries over the forecast period. The livestock-based sector in the ASEAN faces some issues and challenges, such as the following: (1) increasing demand for livestock products and effects of trade policy—the demand for livestock products is compulsive from the increasing complexity of the food chain, including restrictions on quality and standards, while trade policies affect both importing and exporting countries; (2) climate change and natural resource degradation—increasing livestock production drives water pollution, land degradation, and greenhouse gas emissions; and (3) food safety and public health, such as the risk of zoonotic diseases originating from livestock and transmitting to humans. Moreover, livestock products are not a priority commodity in the ASEAN Economic Community (AEC) Blueprint 2025, as it focuses on trade and relevant issues, such as standards and food safety [12]. Previous papers investigated various topics related to blockchain technology and its varied applications in industries across the globe. This paper aims to critically review the adoption of blockchain technology for enhancing the traceability system in the agri-food supply chains, including for livestock-based commodities, with a focus on the ASEAN region. Through a literature survey, the paper describes (1) the product traceability in the agri-food industry and current practices; (2) the adoption and integration of blockchain technology into the traceability system; and (3) key challenges toward blockchain technology adoption in the agri-food industry. The review is based on the key words, namely, traceability in the agri-food industry, adaptation of supply chain management practices and policies in the ASEAN, blockchain technology, and adoption of blockchain for agri-food traceability in the ASEAN. Lastly, challenges and opportunities are discussed.

2. Traceability in the Agri-Food Industry

Traceability is widely recognized as the basis for any modern food safety control system integrating both animal health and food hygiene components. Traceability is the ability to recognize the origin of foods or agricultural products, especially when products are found to be defective [13]. A traceability system leads the organization through all the stages of the value chain, from the origin until the end. Traceability and transparency are necessary for building trust in the agri-food supply chain [14]. According to the Food Standard Agency, traceability in the agri-food supply chain can be obtained in three categories: first, identification of units of all ingredients and products; second, information on where and when they are moved and transformed; last, a system linking these data [15]. In the agri-food supply chain, traceability refers to the ability to identify the sources, such as the farm where the products were produced and the sources of input materials, which extends until the end of the supply chain, including the identification of the location and tracking of the post-harvest history of products [16].

According to Opara [17], traceability in the agricultural supply chain can be divided into six major elements: (1) product traceability, which describes the location of a commodity at any stage of the supply chain to simplify the logistics, inventory management, and other required information for customers and stakeholders; (2) process traceability, which describes the types and order of activities that occur with the product during the operations, including the interaction between the product and other elements that affect value addition to the product; (3) genetic traceability, which describes the genetic information of the product, including the type of materials or ingredients for creating a raw material; (4) inputs traceability, which describes the types of inputs such as fertilizer, irrigation water, feed, and other relevant activities or inputs used during the production and processing stages; (5) disease and pest traceability, which describes any contamination that occurs resulting from agricultural raw materials; and (6) measurement traceability, which describes the single measurement results that follow the national and international standards. In addition, according to Shankar et al. [18], the traceability system for the agricultural supply chain can be classified into three stages: (1) tracing the source of contamination from downstream to upstream; (2) tracking the physical movement of the agri-product from upstream to downstream; and (3) maintaining the product history information associated with the movement of products along the supply chain.

The importance of a traceability system for food-borne risk assessment and management is emphasized [19], and the most recent approaches toward a comprehensive and integrated animal health and food safety policy are reported [2]. Traceback systems have been implemented for the purposes of animal health, as part of surveillance, to provide information required for implementing control measures against diseases [20]. Similar systems have been implemented for the food production industry to provide information needed to recall and remove any contaminated product from the market [21]. Traceability systems have a broader scope and aim to document the history of a product along the entire production chain, from primary raw materials to the final consumable product. The scope of these systems is not limited to the ability to detect and trace batches of high-risk animals or products, but aims to support quality assurance processes for animals and products [2].

An integrated food chain control system should be able to identify and document the following with accuracy: (a) all materials and ingredients used; (b) production processes; (c) personnel involved; and (d) final products. This identification and documentation has the following goals: (a) to increase confidence in product safety; (b) to control public health risks derived from product use/consumption; (c) to facilitate disease control procedures, including sampling; (d) to identify the source of possible contamination; and (e) to facilitate the product recall procedure. The globalization of trade complicates the identification of the origins of materials used for either feed or food preparation [22]. Furthermore, the lack of harmonization of labelling requirements, particularly at the international level, often precludes traceback of an ingredient or raw material to the source.

The COVID-19 pandemic and other food safety-related incidents have magnified the importance of traceability to verify food safety. Building a rational and reliable food traceability system would ensure food quality and safety, contributing to the process of building trust between consumers and suppliers [23]. The majority of traditional traceability systems lack transparency and reliability, and therefore, various technologies have been introduced to improve transparency. Several studies have identified blockchain as the technology for this era [24].

3. Adaptation of Technology and Policy in the ASEAN Agri-Food Industry

According to the ASEAN Ministers of Agriculture and Forestry (AMAF) Work Plan toward the ASEAN Economic Community 2025, modern technologies will be practiced to advance the productivity of crop, livestock, and fishery production in the region and improve the quality of products to support the agri-food stakeholders [25]. Digital agriculture, including use of drones to spray fertilizers and pesticides, robotics, and wireless sensors, provides innumerable opportunities for realizing the AMAF Work Plan. Additional technologies, such as data sensors, can provide farmers with information on the optimal quantity of production inputs (e.g., seeds, nutrients) and the environment (e.g., temperature, humidity) to boost yields [25]. Investment is needed to secure key resources of modern technology.

The traceability system uses a traditional procedure to track and trace the supply chain of each product. Use of modern technology has already been practiced for this traceability system. Especially within the agri-food supply chains, various modern technologies have been adopted among stakeholders to maintain the quality of their products, prevent logistic failures, and improve the supply chain efficiency in order to gain competitive advantages [3].

The ASEAN defines the Food Safety Policy into 10 principles: (1) Integrated Food Chain Approach, (2) Systematic Risk Analysis Framework, (3) Science-based Independent Risk Assessment Process, (4) Primary Responsibility of Food Business Operators, (5) Consistency with ATIGA and WTO's SPS and TBT Agreements, (6) Equivalence and Mutual Recognition, (7) Harmonization with International Standards, (8) Reliable Traceability System, (9) Strengthening and Harmonization of Regional and National Food Control Systems, and (10) Transparency [12]. In particular, Principle 8 states that the traceability system of high-risk food should be shared among the ASEAN member states and recognized at any stage of the food chain. The food supply chains must be traceable and transparent in order to enable and expedite recall of unsafe food products. Specifically, the following subsections describe modern technologies that have been practiced within the agri-food supply chain in different countries.

To date, various technologies have been developed and introduced for traceability systems, especially in the agri-food supply chain, for better product quality control and supply chain management [26]. The technologies which have been adopted in the agri-food systems for traceability improvement are radio-frequency identification (RFID), near field communication (NFC), wireless sensor networks (WSN), cloud computing technology (CCT), DNA barcoding, and blockchain technology (BCT).

3.1. Radio Frequency Identification (RFID)

RFID (radio frequency identification) is a type of communication technology for non-contact automatic identification, which automatically identifies multiple high-speed moving objects simultaneously, even in resource-poor environments and without manual intervention. Moreover, it can tag, save, and manage information through a radio-frequency signal. Compared to the bar code, the RFID tag technology has considerable advantages, such as convenience, antipollution, mass-capacity information, and recyclability. With regard to logistics, RFID has been widely used in production-processing, warehouse management, logistics tracing, and product anti-fake. With the extensive applications of RFID, the level of supply chain management has been highly enhanced [27].

In 1998, the agri-food supply chain adopted RFID technology to track cattle. It was first implemented in Britain and later became widespread among European countries, as the European Union passed legislation to track livestock farms by using electronic identification in 2008 [28]. The rancher used the RFID electronic ear tag for tracking livestock such as cattle, pigs, sheep, and horses. Later on, the RFID technology was not only used for livestock, but also for monitoring food products. For example, at the Beijing Olympic Games in 2008, food services used the RFID system for athletes and staff members to receive information about the food they ate. The RFID technology helps to improve the traceability system in the agri-food supply chain by supporting end-to-end traceability [29].

3.2. Near Field Communication (NFC)

NFC (near field communication) is another step from RFID. The NFC technology enables simple and safe two-way interactions between electronic devices. Customers can use the NFC technology on their smart phone to read passive information and important parameters, and thus purchase safe food [30]. NFC works with a low-frequency radio wave in the 13.56 MHz spectrum when close to another NFC device in contact field, and connects with other devices using magnetic coupling technology such as Wi-Fi or Bluetooth [31]. The working distance for NFC is around 10 cm, where the device generates its own RF field, which is called an active device, or retrieves one from another device, which is called a passive device [32].

The following are examples of applications of NFC currently used in field [32]: first, contactless tokens including the RFID label, contactless Smart Cards, and tokens without electric connections. The contactless token has no communication link with the main device and cannot run any complex protocols. Contactless tokens are used for storing some data which can be read by the NFC device. For example, the RFID label contains the URL stored in a tag of the consumer product, automatically linked to the product website so that consumers can read more information and contact the company as necessary. Second, ticketing/micro payment can be stored in a secure device in order to transfer some valuable information. The device can be a contactless Smart Card or even a mobile phone. When users would like to make a payment or use the stored ticket, they simply show the device to a reader, and the reader receives the information and processes the payment or accepts the ticket. This application is sometimes called 'Secure NFC' as it uses NFC hardware with a smart card chip for high security. Last, device pairing is when two devices in the same group communicate with one another. For example, two devices can use Bluetooth to communicate and transfer the information between them when both devices are equipped with the Bluetooth function. However, the NFC technology remains unable to transfer large amounts of data, as its bandwidth is limited [33].

3.3. Wireless Sensor Networks (WSN)

Wireless sensor networks (WSN) aim to increase efficiency and reliability by developing new algorithms, protocols, and techniques. This technology is a joint invention by researchers and developers across the world [34]. As the surroundings in which the sensors are installed vary depending on the situation, WSN networks are always specific to the application, as they are a type of technology which relies on sensor nodes processed in sensing, processing, and communication. The advantages of WSN include its capacity to dispense multiple network topologies, secured communication among nodes, and the ability for long reading ranges. Nonetheless, some disadvantages remain, such as the inapplicability for needs and identification purposes and the high energy consumption in continuous sensing [26].

3.4. Cloud Computing Technology (CCT)

Cloud computing technology (CCT) is the most recent technological concept in many industries, such as banking, retail, education, and logistics. The main benefits of CCT are a reduction in hardware and software cost, better visibility of information, and faster development with well managed computing resources by the provided software [35]. There are three main types of cloud models: public, private, and hybrid. A public cloud is provided by a third-party service provider, such as Google, via the Internet platform, which is convenient and cost-effective. Google Apps are the most common and widely used among organizations of any size. In contrast, a private cloud offers all the same benefits as a public cloud, but can better control the infrastructure, which is suitable for larger organizations. A hybrid cloud is a combination of public and private clouds, where non-critical information is outsourced to the public cloud and critical information is kept under the control by the private cloud [36].

Moreover, CCT can be used as part of a tracking system along the agri-food supply chain. For example, previous researchers conducted research on a cloud-based beef supply chain in order to assess carbon footprint [36]. The literature discusses different stakeholders of the beef supply chain and corresponding sources of carbon emissions [36]. The cloud-based conceptual model for the beef supply chain begins with ranchers, who are responsible for the largest amount of carbon emissions occurring in the beef supply chain. The ranchers need to store potential information that may contribute to carbon footprint in the cloud in order to use the system to calculate and receive feedback for reducing carbon footprint, which helps them to take appropriate action. In the end, ranchers have to store their data on carbon emissions in the cloud, so it becomes visible to all stakeholders. For other stakeholders, the process is the same as for the ranchers. The aim of the cloud-based technology is to share information among the stakeholders and make appropriate decisions for reducing carbon footprint at each stage.

3.5. DNA Barcoding

In order to address the disadvantages of the previous technologies, DNA barcoding was invented to improve quality assurance. DNA barcoding technology functions to analyze proteins in food products and ensure their traceability [26]. In the seafood industry, research shows that standard and inexpensive DNA-based analytical methods presented an excellent opportunity to improve self-regulatory programs within internal traceability systems, achieve customer satisfaction, and protect company interests [37]. Table 1 summarizes the advantages and disadvantages of the five technologies discussed in Sections 3.1–3.4, while Table 2 shows the key characteristics of these technologies.

Table 1. Current advantages and disadvantages of RFID, NFC, WSN, CCT, and DNA barcoding.

Technologies	Advantages	Disadvantages
RFID	• Wide scanning range • Suitable for any businesses	• Vulnerability to hacking • High power consumption • Complexity and high cost for installation
NFC	• Heightened security • No specialized software is needed	• High cost for some business • Works within specific distance of 10–20 cm • High power consumption
WSN	• High convenience • Does not require wires or cords • Suitability for any businesses	• Vulnerability to hacking • Unsuitability for high-speed communication • Unaffordability • The failure of the central node causes the entire network to shut down

Table 1. *Cont.*

Technologies	Advantages	Disadvantages
CCT	• High security • Reliability • Cost reduction	• Server downtime
DNA barcoding	• Increased reproducibility and taxonomic resolution • Reliability • Applicability for all life stages	• Dependence on a single region of mitochondrial DNA

Table 2. Key characteristics of RFID, NFC, WSN, CCT, and DNA barcoding.

Characteristics	RFID	NFC	WSN	CCT	DNA Barcoding
1. Security	-	•	-	•	•
2. Traceability	•	•	•	•	•
3. Transparency	-	-	-	•	-
4. Decentralization	-	-	-	-	-
5. Information Sharing	•	•	•	•	•

Note: • means the characteristic is met by the technology; - means otherwise.

4. Blockchain Technology

Blockchain is a technology made up of the key concepts of decentralization, security, immutability, and smart contracts [38], where smart contacts are a digital contract stored in the blockchain which automatically runs when the conditions are met [39]. Immutability objects refer to objects which are unchangeable after creation [40]. While blockchain technology enables real-time tracking of business activities and synchronization of critical updated documentation, several issues remain, such as block size, efficiency (trans-action throughput and latency), scalability, security, and privacy, which require technical solutions [41,42]. In businesses, several consulting reports suggest that blockchains can be used to reduce business frictions and expenses, solve the inefficiency and vulnerability of transactions, and transform the overall ecosystem into a credible one [43]. Blockchain has potential for application in various sectors, such as medical record management, supply chain management, banking and financial services, accountability and liability management in insurance, Internet of things (IoT), sharing economy, and distributed access control [44–47].

Blockchain provides a distributed data structure, which is replicated and shared among members of a network [48]. It was introduced with Bitcoin to solve the double-spending problem. As a result of how the nodes on the Bitcoin network append validated mutually agreed-upon transactions to it, the Bitcoin blockchain houses the authoritative ledger of transactions, which establishes who owns what. Each block in the chain carries a list of transactions and a hash to the previous block [47]. The exception to this is the first block of the chain, called the genesis, which is common to all clients in a blockchain network and has no parent.

Blockchain technology has been applied in anticipation that it will assume a significant role in ensuring the traceability of the agri-food value chains [49]. Although it is a relatively new technology, blockchain is advancing and developing rapidly [49]. Zhao et al. emphasize a huge opportunity for blockchain applications in global trade [49]. The blockchain market was estimated to grow from USD 210.2 million to USD 2312.5 million during the period from 2016 to 2021, according to the Global Opportunity Report [50]. Due to its potential increase in the global market, blockchain technology is expected to play a critical role in facilitating future industry development and revolution.

Zhang et al. [38]. mentioned that there was a lack of understanding of blockchain technology, which led to failure to harness the true potential of the technology in the agri-food supply chain [38]. Blockchain technology has yet to be well implemented among farmers in Thailand [51], where only a few organizations have recently stepped in to integrate the new technology, as the Trade Policy and Strategy Office (TPSO) stipulates a plan to incorporate blockchain into the rice export industry [52].

4.1. Blockchain and Traceability System

Traceability is defined as the ability to trace and follow a food, feed, food-producing animal, or substance intended or expected to be incorporated into a food or feed through all stages of production, processing, and distribution [53]. Transparency and traceability are necessary in supply chains in order to create trustworthiness among the stakeholders. Blockchain technology can be used to enhance transparency and traceability due to its decentralized, transparent, and independent protocol [54]. Although traceability can be achieved via various technologies in various aspects, blockchain technology can improve the traceability system at each stage by acknowledging and tracking the information from each stakeholder through the supply chain [55].

According to Caro et al. and Kamilaris et al. [55,56], in the agri-food supply chain, blockchain technology can work in the following ways: (1) raw material purchasing—as part of providers in supply chain stakeholders, both providers and producers insert the detail of sales and purchases of raw materials; (2) planting process—producers insert information on the planting process, such as the amount or type of seeds sown; (3) growing process—producers use a sensor as a means to send information to the blockchain system about the growing interval and environments; (4) farming process—farmers input information at each stage of farming, including irrigation or fertilizer; (5) harvesting process—farmers input harvesting information into the blockchain system, such as weight and quality or type of products (e.g., organic); (6) process of delivery to processor—the last process for farmers is to input information on the products that are ready for distribution to processors; (7) processing process—at this stage, processors are the main actor, and are required to enter processing data including the procured amounts, packaging information, and any loss during the delivery from producers or during the processing; (8) process of delivery to retailer—at this stage, processors distribute the processed products to retailers, and this information is always stored in the blockchain; (9) retailing process—retailers are the main actor at this stage and store all information, such as the number of stored products and other relevant details; and (10) consumption process—the last stage of the supply chain is consumption, where consumers can trace back all of the information on the product from the first stage before buying the product, which helps to build trust in consumers.

The agri-food innovation company AgriDigital accomplished the world's first reimbursement of a grain transaction via blockchain [57]. In consequence, the success of AgriDigital led the grain industry to bring more than 1300 applications, and over 1.6 million tons of gain were transacted over this system, earning over USD 360 million in financial transactions. AgDigital inspired other users in the agri-food supply chain to implement blockchain technology, in line with the main goal of AgriDigital, which is to increase the credibility and efficiency among the stakeholders in the agri-food supply chain by using blockchain technology [58]. Another successful example is Louis Dreyfus Co. (LDC), a corporation held between Dutch and French financial institutes and one of the leading global food traders. LDC implemented the first agri-food product trade based on blockchain [59], which succeeded in automatically matching real time data, avoiding duplication and manual checks in document processing, thereby saving one fifth of the time.

Blockchain technology in the agri-food product traceability system shows multiple potential benefits, such as the following: (1) increased reliability of information security; (2) enhanced trust in the traceability chain; (3) decreased economic loss and food waste in the system; and (4) enhanced sustainability and transparency in the agri-food supply chain (Fang et al., 2020). For livestock-based products, traceability systems are adapted for quality assurance. The key principle of traceability systems for livestock-based products is the concept of Traceable Resource Units (TRU) [60], which is defined as the units of recorded information in the traceability system [61]. The TRU is used along the livestock products supply chains to record all information. Livestock identification has several methods, ranging from traditional methods to modern technologies. The traditional methods for livestock identification include body marks, ear shears, and ear tags. On the other hand, modern technologies, such as RFID, DNA fingerprint, and retina scan, are more functional in the livestock identification procedure. Both traditional and modern methods tend to be applied to quadrupeds such as swine, cows, goats, sheep, horses, and cattle [62]. In poultry, there are other systematic traceability systems, such as CCT [3]. The TRU differs by the type of livestock, depending on the sectoral structure of each country and national regulations [63].

4.2. Adoption of Blockchain for Agri-Food Traceability in the ASEAN

In the ASEAN region, blockchain technology is in the early stage of the technology adoption life cycle [64]. Nonetheless, an increasing number of the ASEAN member states lean toward the integration of blockchain technology into their livestock chains to enhance the value and quality of the products. ICT (Information and Communications Technology) companies in Vietnam have been utilizing blockchain platforms since 2018. Some initiatives for tracking agri-foods, such as Wowtrace, Fruitchain, and Agridential have adopted blockchain in practice [65]. In Bihn Dinh, the province with the largest swine herd in Central Vietnam, has adopted Te-Food's blockchain technology in order to manage swine production and control disease outbreaks [66]. In Malaysia, the halal food business OneAgrix adopted blockchain technology into the traceability system for its B2B e-commerce marketplace in order to scale up the supply chain and strengthen their brand equity.

5. Challenges and Opportunities

At present, there are several challenges in the adoption of blockchain technology along the agri-food supply chains, as follows:

- Accessibility: this is a significant challenge because blockchain technology underlies multiple digital technologies, such as IoT, RFID, sensors and actuators, robots, biometric data, and big data [55].
- Matching the physical to the digital: although blockchain can be used to create credibility and highly effective digital assets, participants need to be convinced that it represents what is happening in the physical world. Building robust digital infrastructure of IoT devices, sensors, and on-site integrations is critical for providing physical verification [66].
- Incentives and cooperation: supply chains are networks of diverse participants with widely varying interests. The right incentives need to be provided by way of efficiency gain, improved liquidity, and data security in order to ensure that decision makers will buy in across the entire network [66].
- Gold standards: blockchain technology can be subject to fraud. There needs to be confidence in data inputs and certifying standards in order to ensure that blockchains are not only immutable, but also accurate [66].
- On the other hand, a few opportunity areas have been identified as follows:
- Competitive advantages: blockchain technology has potential to elevate the agri-food industry to the next level by strengthening cyber security and credibility through real-time management [67–69], as well as reducing transaction costs for digital payments [70].
- Benefit and cost: while small-scale farmers produce over 80% of commodities in developing countries, they tend to lack access to financial schemes, including insurance [67]. The transparency allowed by blockchain technology can help to minimize corruption, raise social capital [68], and foster effective supply chains based on enhanced repu-

tation. Overall, Perboli et al. [69] suggest that implementation costs for blockchain technology are sustainable and worthy vis-à-vis its benefits.

In order to overcome the challenges and limitations, as well as to capitalize on the opportunities, the dissemination of blockchain technology in the agri-food sector would require coordinated stakeholder engagement. Sector-wide policies and initiatives should be formulated and executed in order to prevent exclusion and exploitation of any stakeholder in this process [71]. Therefore, it is recommended that the sectoral associations and the government offices in charge collaboratively strive to scale out the technology and assist all actors along the supply chain, particularly farmers, in adopting block chain-based practices.

6. Implications of Blockchain Integration into the Livestock-Based Products Supply Chains in Thailand

Similarly to the case of plant-based products, blockchain technology would potentially bring benefits to the livestock industry in Thailand through decentralized and automated transactions, system integration, organized records of supply chain transactions from farm to table, and superior traceability and transparency within the livestock sector [72]. The relevant features of blockchain are immutability, decentralization, enhanced security, distributed ledgers, and consensus. In view of the competitive advantages of blockchain technology, possible implementation on the livestock-based products in Thailand is related to the traceability at each stage of the livestock supply chain, as follows:

- Ranchers record information on animal well-being during the husbandry stage, according to standards such as nutrition, pasture environments, special treatment, and other relevant practices.
- Processors record all standard processes required for quality assurance.
- Retailers provide information on livestock products and product shelf life to consumers.
- Consumers are the end of the chain, and can retrieve information from all previous stages in order to help make the purchase decision.

Furthermore, the blockchain traceability system not only assists in consumers' purchase decisions, but also helps stakeholders at each stage to clarify and increase their competitive advantage in global markets, as illustrated in Figure 1.

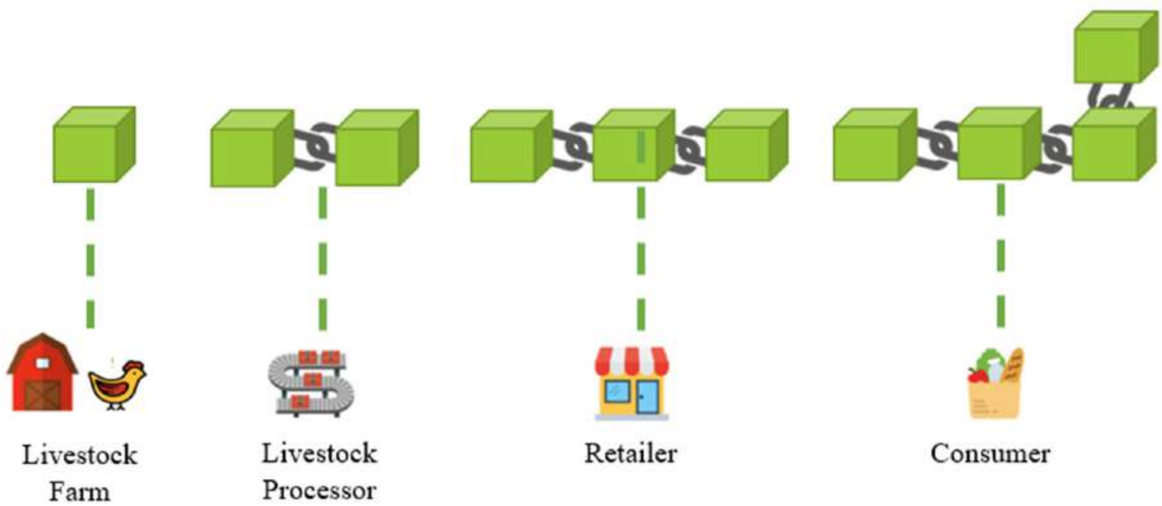

Figure 1. Sketch of a blockchain in a livestock-based supply chain.

In Thailand, blockchain technology began its application to the beef product traceability system in 2019. Blockchain and IoT were integrated in order to enhance traceability and supply chain management, which resulted in increased reliability and awareness in Thailand's food supply chains, especially in the aspects of food safety and quality control [26].

7. Conclusions

Blockchain technology is one of the modern technologies that can be applied to supply chain management in the agri-food industry, as the technology is suitable for improving transparency, reliability, security, decentralization, and information sharing across supply chain actors. It may well help to enhance the competitive advantage of livestock products from Thailand in the international market. To date, however, the adoption of the new technology has yet to be widespread.

This review assessed findings in the literature on blockchain technology in food traceability systems and food supply chains. Table 3 provides a list of papers and the main subjects covered by each. The major findings are summarized as follows: (1) the early paper in 2016 mentioned blockchain technology and food supply chains. Thereafter, an increasing number of research papers demonstrated the adoption of blockchain technology in sectors in Asia, such as China, Vietnam, and Thailand. (2) For livestock-based products, blockchain technology has not been fully adopted and implemented sector-wide. (3) The food industry has observed some changes over time, such as the increased awareness of food quality and food safety based on the new standards and requirements, including the pandemic-induced changes since 2020. (4) The challenges facing blockchain adoption in the food industry have been identified at each stage of the supply chain. The most significant challenge is the lack of awareness of the benefits of the technology among stakeholders in the food industry. Another challenge is the limited adoption capacity, especially among small-scale processors and farmers. Moreover, sector-wide coordination is inadequate for harnessing the potential of product traceability along the entire supply chain. (5) In the ASEAN region, blockchain technology adoption is expanding among the member states, such as Vietnam and Malaysia. There are guidelines for promoting digital technologies, including blockchain use, for the agri-food sector.

Table 3. Papers included in this review and their subject area relevance.

Ref. No.	Author(s)	Year	Blockchain Technology	Traceability System/Supply Chain Management	Food Supply Chain/ Agriculture
[1]	World Health Organization	2020			•
[2]	Caporale et al.	2001		•	
[3]	GS1 Thailand	2019	•	•	•
[4]	Aday et al.	2020			•
[5]	OECD	2001			•
[6]	Choi et al.	2020		•	
[7]	Seok-beom et al.	2022		•	
[8]	Khan	2021		•	
[9]	Pal	2023		•	
[10]	Sarkar et al.	2022		•	
[11]	Research Drive	2020			•
[12]	Jabbar	2016			•
[13]	Ioris	2016			•
[14]	Azzi et al.	2019	•		
[15]	Aung and Chang	2014		•	•
[16]	Opara and Mazaud	2001		•	•
[17]	Opara	2003		•	•
[18]	Shankar et al.	2018		•	•

Table 3. *Cont.*

Ref. No.	Author(s)	Year	Blockchain Technology	Traceability System/Supply Chain Management	Food Supply Chain/ Agriculture
[19]	Bosch et al.	2018			•
[20]	Department of Livestock	2003		•	
[21]	FAO and WHO	2012			•
[22]	Food Chain Strategy Division and Food Standards Agency	2002		•	•
[23]	Zheng et al.	2021	•		•
[24]	Iftekhar et al.	2021	•	•	•
[25]	Yong and Montesclaros	2017			•
[12]	Jabbar	2016			•
[26]	Kumperščak et al.	2019		•	•
[27]	Tian	2016	•	•	•
[28]	Odintsov et al.	2021			•
[29]	Kelepouris et al	2007		•	•
[30]	Badia-Melis et al.	2015		•	•
[31]	Ortiz	2006		•	
[32]	Haselsteiner and Breitfuß	2016		•	
[33]	Banerjee et al.	2020		•	
[34]	Anand	2015		•	
[35]	Attaran	2017		•	
[36]	Singh et al.	2015			•
[37]	Tinacci et al.	2018			•
[38]	Zhang et al.	2019	•		•
[39]	Hu et al.	2018	•		
[40]	Ahmad et al.	2021	•		
[41]	Mougayar	2016	•		
[42]	Xu et al.	2017	•		
[43]	IBM	2017	•		
[44]	Azaria et al.	2016	•		
[45]	Casey et al.	2017	•		
[46]	Christidis and Devetsikiotis	2016	•		
[47]	Condliffe	2017	•		
[48]	Sloane and Bhargav	2021	•		
[49]	Zhao et al.	2019	•		•
[50]	United Nations Global Compact	2016	•		
[51]	Berman	2018	•		
[52]	Townsend	2018	•		
[53]	EU	2002		•	

Table 3. *Cont.*

Ref. No.	Author(s)	Year	Blockchain Technology	Traceability System/Supply Chain Management	Food Supply Chain/ Agriculture
[54]	Sander at al.	2018	•	•	•
[55]	Kamilaris	2019	•		•
[56]	Caro	2018	•	•	•
[57]	ICT4Ag	2017	•		
[58]	AgriDigital	2018	•		•
[59]	Hoffman and Munsterman	2018	•		•
[60]	Bai et al.	2017	•		•
[61]	Hu et al.	2009		•	•
[62]	Lewis and Boyle	2017		•	•
[63]	Patelli and Mandrioli	2020	•	•	•
[64]	Vu and Trinh	2021	•		•
[65]	Thu	2021	•		•
[66]	Sylvester	2019	•		•
[73]	Yuan et al.	2019	•		
[74]	Pearson et al.	2019		•	•
[75]	Creydt and Fischer	2019	•	•	•
[70]	Lee et al.	2017			•
[67]	Chinaka	2016	•		
[68]	Rejeb	2018	•		•
[69]	Perboli et al.	2018	•		
[71]	Mohapatra et al.	2021	•		•
[72]	Neethirajan et al.	2021	•		•
[76]	Surasak et al.	2019	•	•	•

The key challenges identified in this review imply the need for concerted support and coordination across the public and private sectors. It is recommended that research be extended to more specific areas of application and actual practices of blockchain technology in the agri-food industry. The key challenges and limitations discussed in this paper would inform policy makers in designing programs to support and facilitate the application and adoption of blockchain technology in the agri-food industry, especially by promoting sector-wide coordination for blockchain application along the supply chain, awareness building among stakeholders to induce investments, and capacity development among users to facilitate usage.

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