Blockchain on the Farm: A Systematic Literature Review

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The safety, availability, and cost of a nation's food supply is of vital importance to its citizens and government. One type of technology with the potential to cause widespread change in the food production process is blockchain. This paper provides a systematic review of the academic literature surrounding the application of blockchain to the production, transport, and protection of food. This review also includes some recommendations for future research directions and provides a strong foundation for further research in the application of blockchain to the agriculture industry.

Keywords: blockchain, distributed ledger, digital ledger, agriculture

INTRODUCTION

It might never be known if Nakamoto (2008) envisioned the use of blockchain (BC) beyond the Bitcoin application introduced in his paper, but the last few years have seen interest in this specific means of data organization and storage extend to a number of other industries far beyond cryptocurrencies. Treblmaier (2018) notes its application to supply chains, Sehgal (2017) to insurance, and Kasten (2019a) to engineering and manufacturing. Each of these applications has been described within the last few years and the same can be said for the application of blockchain to agriculture (Lin et al, 2017).

There are few aspects of civilization more important than its ability to provide food for its citizens. The growing population of the planet, in addition to accelerating changes in the climate, makes this task increasingly difficult and expensive. In this challenging environment, the use of various technologies has become a vital tool to improve food production, safety, and availability. Information technology has played an important role in improving the quality and availability of food, from Global Positioning Satellites (GPS) directing the harvesting of wheat to the use of the World Wide Web to help farmers find the best price for their produce. This paper examines the research surrounding use of another breakthrough technology, blockchain, in the production and distribution of food.

The value of blockchain in agriculture stems from its ability to secure data such that it can be read by any party with the proper permission but cannot be altered without the knowledge of the other blockchain participants. This is an invaluable property when the sanctity of data must be protected such as in the movement of goods, protecting the provenance of products, and preserving the dates that certain processes (i.e. harvest) take place.

The paper is organized as follows: The next section provides an overview of blockchain technology and extends the discussion as to its application to agricultural processes, the following section describes the methodology followed in the review, the findings of the review are detailed next, and that is followed by a discussion and conclusion including the limitations of the study and directions for additional research.

BLOCKCHAIN OVERVIEW

Blockchain was introduced as the data-organizing mechanism built into the Bitcoin system of cryptocurrency (Nakamoto, 2008). The primary benefits of blockchain are that the data contained on the chain formed by blocks of data can be secured if that is appropriate, but more importantly, can be made tamper-proof (Drescher, 2017). This feature of blockchain is derived from the nature of how blocks are added to the chain. When a data block is to be added, the data is first run through a hashing algorithm that applies a cryptographic hash to the data that results in a hash reference value that cannot be reasonably reverse engineered or used to find the original data. These hash references are then combined into another hash reference that includes both the hash from the data to be added, the hash reference from the data preceding the new block, and an unknown variable, which is known as the nonce. In order for the block to be added, the nonce must be found that results in a hash reference that meets certain requirements (e. g. has two zeros as the two leading digits). Because the hash value cannot be reverse engineered to find the nonce, the only method available is to guess and check. These computations require significant computing effort, which can be adjusted by easing the hash reference requirements. This is known as mining in the Bitcoin vernacular.

Once added to the chain, the data on this or any block in the chain cannot be adjusted because of the interconnected nature of the blocks and their joint hash references. If the data on a block that was added to the chain earlier is changed, the hash reference between that block and the next one added must be recomputed as does the hash value for each subsequent block on the chain. Each block added to the chain effectively buries the data below it, making changes to those buried blocks, whether authorized or not, impossible to accomplish without notice by all other stakeholders on the chain.

It is important to note that there are many modifications that can be made to the blockchain architecture that make it more easily implemented, such as storing only the hash reference values on the chain instead of the actual values (known as off-chain storage) or predetermining whether all entities in the business environment can make additions to the chain or only certain entities have this permission (permissionless vs. permissioned blockchain). In the case of off-chain storage, the hash values stored on the blockchain act as immutable "official" values that can be used to check whether the values stored match those in other repositories. These and other options are clearly described by Drescher (2017). Xu et al (2016) provide a framework to assist in developing a blockchain-based system that contains the features appropriate to the needs of the organization.

With these capabilities, blockchain-based tools are currently being explored and developed that can provide improvements in a wide variety of agricultural settings. The rest of this paper describes the current state of the literature surrounding these developments.

METHODOLGY

In order to perform a systematic literature review, a repeatable and verifiable process must be in place (Briner & Denyer, 2012). For the present research, the process used consists of the following steps:

- Identify the research question(s).
- Locate and select relevant studies
- Critically appraise the studies
- Analyze and synthesize the findings
- Disseminate the findings

The research question for this study is "For what aspects of agriculture and food production does research suggest blockchain technology can improve?" Within this research question, two secondary questions are addressed:

- Within the blockchain/agriculture literature, what research methodologies are being employed?
- How long has the blockchain/agriculture topic been examined in the academic literature?

To locate the appropriate studies that address these questions, a set of "ground rules" are created to provide structure. For the present study, only the academic literature is examined. This will provide a better picture of the academic effort being expended on this topic. These outlets will include peer-reviewed journals, academic conference proceedings, Master's and PhD theses, and chapters from edited volumes. Book length treatments of the topic are also permissible, though the relative recency of the topic combined with its specificity and the dynamism of blockchain development in general render the existence of these books unlikely. Perhaps they will become available after the topic matures. Future studies should also include an examination of the "gray" literature as well as industry periodicals as a means of understanding the business perspective on the use of blockchain in agriculture. At this early point in its development, any reference to blockchain in the practitioner literature is likely to be a general exploration of its possible benefits without exercising any scientific rigor. As with books, maturity in the topic might bring about additional rigor in this arm of the literature.

To be systematic, a review must specify a specific, repeatable methodology. For this study, searches were performed in the ABI/Informs, Emerald, IEEE Explore, JSTOR, Science Direct, Scopus, Springer, Taylor & Francis, Web of Science, and Google Scholar databases as well as a detailed search of the Senior Scholars Basket of Journals provided by the Association for Information Systems (aisnet.org). For each repository, a combination of keywords were used that provide adequate coverage of the topic. The keywords blockchain, "digital ledger," "distributed ledger," and "shared ledger" were combined with agriculture, farm(ing), and food to produce a matrix of 12 search combinations. These searches were conducted in the metadata to include the article title, keywords, and abstract. A full-text search with these keywords, while possible in most databases, would produce a much larger response but with very low precision. Studies were included in the analysis only after they were examined and found to actually focus on the topic at hand. All searching was completed by November 1, 2019.

Each candidate study was subjected to content analysis to determine the major topic of the paper as well as to uncover any themes and/or sub-themes that exist in the text. The initial analysis was performed on the abstract, introduction, and conclusion sections of each study. In some cases in which the major topic of the paper was unclear or multiple topics existed, the entire paper was examined to determine its major topic.

FINDINGS

The findings section is divided into two subsections. The first provides descriptive statistics that describe the articles that are included in the study. The second subsection describes the research themes evident in the body of literature accumulated for this study. Within these themes, a number of sub-themes are described that became evident during the analysis of the literature.

Descriptive Statistics

A total of 214 studies are identified using the search protocol outlined above. After evaluation, 200 were included in this study. The others did not have blockchain or its application to agriculture at their core.

- Thirty-four studies constructed prototypes of varying complexity and performed some form of evaluative process.
- Nine studies contained some form of empirical evaluation, often exploring the feasibility of a blockchain-based agricultural system.
- All of the remaining studies were descriptive or prescriptive in nature.

Three research themes emerged from the papers:

- Blockchain applied to improve food supply chain processes (152 papers)

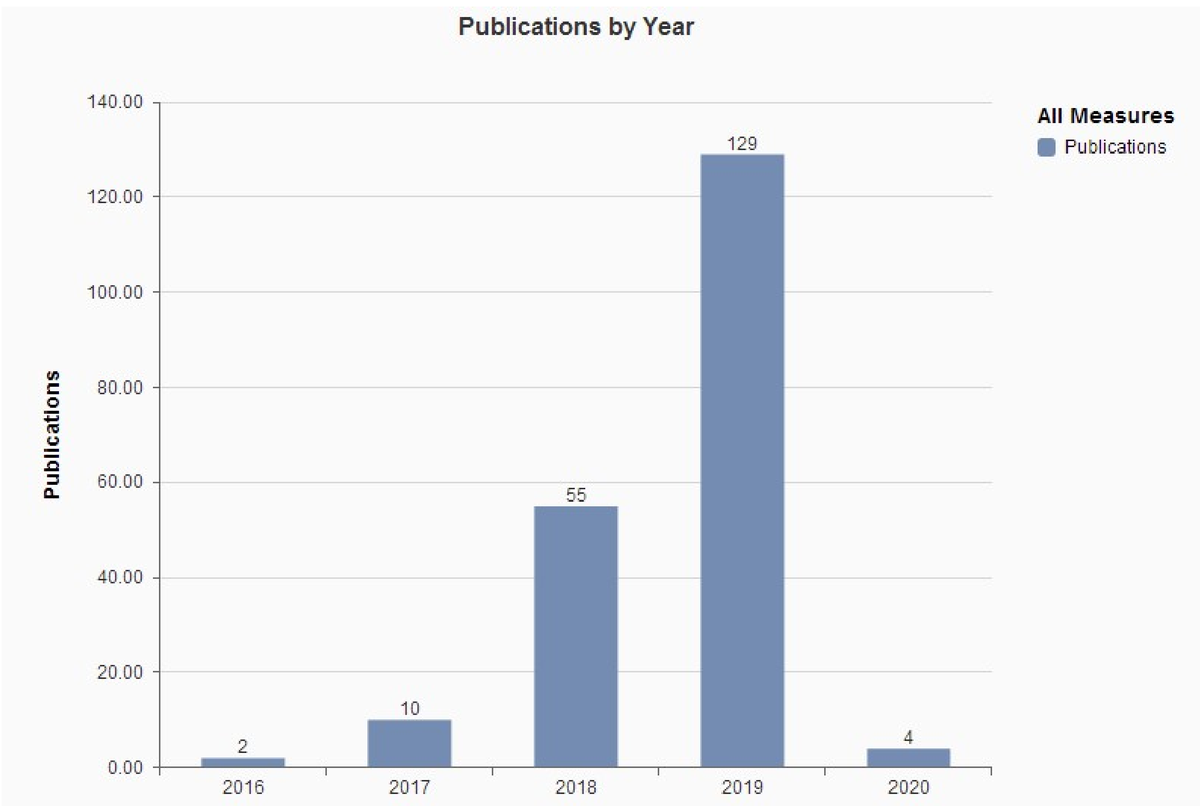
- Blockchain to improve various aspects of the business of food (39 papers)
- Blockchain to improve the actual process of food production (9 papers)

The articles are published in one of five forms:

- conference proceedings (98)
- journal articles (82)
- theses (13)
- book chapter (11)
- report (5)

The article location protocol does not specify a time period to search in, however, no papers were found prior to 2016. This is undoubtedly due to the relative immaturity of the blockchain literature in all but the financial services field. However, the number of papers published since then has risen dramatically. Since the papers for this study were accessed just before the end of 2019, it can be reasonably expected that the number of publications for 2019 will continue to grow, thereby steepening the curve even further. Figure 1 shows the publication trends for the papers included in the study.

FIGURE 1
PUBLICATION RATE OF BLOCKCHAIN/AGRICULTURE ARTICLES



Research Themes

During the analysis of the papers included in the study, three primary research themes emerged and are described in this subsection. These themes are food supply chain, the business of food, and the process of food production. As might be expected, there is significant overlap in some of these studies such that they might be categorized in multiple themes simultaneously. However, the studies are categorized based on what appears to be the primary focus of the author(s) after reading the abstract, introductory and concluding sections, or in some cases analyzing the entire work. In each case, every effort is made to accurately slot the paper in one of the research themes that emerged during the process.

Research Theme #1: Food Supply Chain

The largest theme in this body of research is, by far, the use of blockchain to support and improve the food supply chain (147 papers). The food supply chain (FSC) includes the components (people, organizations, vehicles, etc.) and the processes involved in moving food products from the point of creation to the point of consumption, including any intermediate processing or gathering points, and also including the movement of information that represents these movements and enables the FSC to operate more effectively. Because there are so many different facets of the concept of supply chain, there are a number of sub-themes that emerge within this body of literature. The first examined in this section is that of using blockchain to improve data validity in the FSC.

FSC Data Validity Sub-Theme

A number of authors provide a substantial overview of the use of blockchain in the improvement of data validity in the FSC and these studies are very useful as an orienting tool. Ge, et al (2017) discuss what aspects of the FSC are appropriate for the use of blockchain and how these might be identified. Shyamala Devi et al (2019) and Wu et al, (2019) provide an in-depth survey of the core details of blockchain and how these might deter the access of the data by unauthorized users. Bermeo-Almeida et al (2018) provide a similar service by surveying ten papers from the literature and showing that 60% of the blockchain/agriculture papers were focused on the FSC.

The general concept of traceability, how it is enhanced by blockchain, and how enhanced traceability is useful, are central to a number of papers that are reviewed in this study. Sander, Sameijn & Mahr (2018) investigate how meat traceability is a particular challenge and find that the use of blockchain has a positive influence on consumers' purchasing decisions. Faye (2017) demonstrates the areas of the FSC that could most benefit from the application of blockchain to enhance traceability, while the relationship between traceability and food quality control and management is discussed by Nene et al (2019). Finally, Mohan (2018) discusses several benefits to enhanced traceability in a global FSC environment including satisfying asymmetrical food regulations across international boundaries and a reduction in food illnesses.

Trust is the focus of many of the papers in this theme, especially trust between the consumer of food and the provider, whether a producer or a retailer. A number of authors evaluated how blockchain might increase the trust of the consumer by allowing the identification of the origin of the food they consume (Yeh et al, 2019; Sharma et al, 2019). Zambrano, Young, & Verhulst (2018) demonstrate the use of blockchain to ensure that food destined for refugee relief is not plundered by corrupt practices and people. Johng et al (2018) provide a framework for the use of blockchain in the Business Process Reengineering environment to increase trust among the various stakeholders by increasing visibility and eliminating unauthorized revision of important data. Last, the international aspects of trust, or lack of it, are addressed by Bordel et al (2019).

Data security, in terms of the FSC, is the ability of a FSC network to maintain the safety of the data that describes the food chain processes from both intentional threats such as hacking and digital vandalism as well as unintentional threats such as hardware or communications failure. Many researchers see blockchain as a potential asset in this struggle. Mistry et al (2019) suggest the use of 5G-enabled Internet of Things (IoT) as a backbone for an number of applications, including FSC, that benefit from enhanced data security. Security of data in the cacao supply chain is a problem addressed by Arsyad, Dadkhah, & Köppen (2019) using a two-factor blockchain, and Wu & Tsai (2019) suggest the use of dark web technologies for the protection of data in the FSC.

The authenticity of the food making its way to the consumer is of paramount importance to most consumers and in many cases to the producer. Olive oil from Italy, fish from approved fisheries, and meat from free-range cows are all attributes that are important selling points to various producers. Therefore, many researchers have turned to blockchain to help protect the authenticity of food origins and provenance as it progresses through the FSC. A framework for the application of blockchain to protect authenticity is an important starting point for this area of study (Montecchi, Plangger & Etter, 2019; Yakavenka, Vlachos & Bechtsis, 2018). Shih et al (2019) propose an Ethereum-based tool that will provide a guarantee of the authenticity of food marketed as organic. The identification of meat species flowing through the FSC must be identified and can sometimes be a time-consuming process. Rao, Chakraborty & Satya Murthy (2019) provide an overview of how blockchain can improve that process. Finally, Arena et al (2019) put forth BRUSCHETTA which is an IoT-based framework for certifying the authenticity of olive oil produced in Italy, a target of substantial fraudulent activities.

The role of specific technologies is discussed by a number of research teams. Violino et al (2019) detail the role of Radio Frequency Identification (RFID) in protecting the authenticity of Italian olive oil, as well as the level of acceptance of this technology by potential customers. Figorelli et al (2018) apply blockchain and RFID to the tracing of wood in the supply chain from standing timber to the final user. Hilt, Shao, & Yang (2018) describe the possible vulnerabilities inherent in using RFID in the FSC. And, Baralla, Pinna & Corrias (2019) describe a QR-based system that uses a blockchain-based approach to allow a European consumer to reconstruct the entire history of the food they purchase and consume. Gopalakrishnan & Behdad (2019) provide an example of how videogrammetry can be used to solve data verification problems in the organic meat processing process. Ko, Hong & Chiu (2019) present a SpectroChip designed specifically for use in the protection of food safety. An interesting insight is made by Kuang et al (2019) noting the lack of coupling of the physical food product to the data that describes it and its movement. They provide a solution to this digital-physical parity issue. Also importantly, Amin, Zuhairi & Saadat (2020) provide an approach to reduce the amount of data created during a typical FSC transaction, while Moudoud, Cherkaoui & Khoukhi (2019) describe a method to reduce the power consumed during a transaction, both of which will likely improve blockchain's data processing speed issues.

The final two areas of interest in the supply chain theme involve the use of blockchain to ensure regulatory compliance and to reduce information asymmetry. Casino et al (2019) show how blockchain can provide proof of regulatory compliance to European union regulators that require that final products can be traced back to their raw materials and basic ingredients and dos Santos et al (2019) use a token-based system to assist in gaining certification at the time of harvest. Returning to Italy, we find Scuderi, Foti & Timpanaro (2019) discussing the information asymmetry and lack of transparency that afflicts small producers in many food areas and how blockchain can improve their ability to compete with larger producers and the various components of the supply chain. Likewise, the sustainability of the agricultural supply chain in India is improved by the application of blockchain by Kamble, Gunasekaran & Sharma (2019).

The role of blockchain in the safeguarding of data validity in the FSC has a number of wide-ranging aspects, from the protection of food provenance to the securing of data from unauthorized viewing or revising, to maintaining the authenticity of a nation's signature product from corruption. In each of these many applications, the data immutability inherent in blockchain architecture provides protection to the data stored either on or connected to the blockchain. With this capability, the many members of the supply chain, including the end consumer who is arguably the most important member of the FSC, can have confidence that the food produced and consumed is what it purports to be and the business conducted by FSC members can be done in a fair and transparent manner. Table 1 lists the papers contained in the "BC to promote data validity" sub-theme.

TABLE 1
PAPERS FOCUSED ON THE USE OF BLOCKCHAIN TO PROMOTE DATA VIABILITY

Research Emphasis	**Authors**
Overview of the Role of Blockchain in FSC	Bermeo-Almeida et al, 2018; Borah et al, 2020; Davidsson, 2019; Dubey, 2018; Ge et al, 2017; Green, 2018; Heinrich et al, 2019; Kim & Laskowski, 2017; Schneider, 2017; Shyamala Devi, 2019; Wu et al, 2019
Blockchain to Improve Traceability	Baralla et al, 2019; Bettín-Díaz, Rojas & Mejía-Moncayo, 2018; Buttafoco, 2019; Dasaklis, Casino & Patsakis, 2019; Ehrenberg & King, 2019; Faye, 2017; Foth, 2017; Gopi et al, 2019; Holmberg & Aquist, 2018; Kim & Laskowski, 2018; Malik, Kanhere & Jurdak, 2018; Mohan, 2018; Nene et al, 2019; Sander, Semeijn & Mahr, 2018
Blockchain to Enhance Trust Between FSC Participants	Basnayake & Rajapakse, 2019; Bechtsis et al, 2019; Bordel et al, 2019; Coronado Mondragon, Coronado & Coronado, 2019; Cortés et al, 2019; Crew, 2018; Johng et al, 2018; Kale et al, 2019; Kandeeban, 2019; Kang & Indra-Payoong, 2019; Kumar, Liu & Shan, 2019; Lin et al, 2018; Liu, Yan & Song, 2020; Madumidha et al, 2019; Sharma et al, 2019; Yeh et al, 2019; Zambrano, Young & Verhulst, 2018
Blockchain to Provide Data Security on FSC	Arsyad, Dadkhah & Köppen, 2019; Cortez-Zaga, Casas-Llamacponcca & Shiguihara, 2019; He, Chen & Li, 2019; Karlsson et al, 2018; Liao & Xu, 2019; Makarov et al, 2019; Mao et al, 2019; Massner, 2019; Mistry et al, 2020; Patil et al, 2018; Wang & Liu, 2019; Wu & Tsai, 2019; Xie, Sun & Luo, 2017; Xu, Agbele & Jiang, 2019
Blockchain to Promote Food Authenticity and Prevent Fraud	Arena et al, 2019; Galvez, Mejuto & Simal-Gandara, 2018; Lo et al, 2019; Montecchi, Plangger & Etter, 2019; Musah, Medeni & Soylu, 2019; Ohlsson & Davison, 2019; Olsen, Borit & Syed, 2019; Rao, Chakraborty & Satya Murthy, 2019; Shih et al, 2019; Yakavenka, Vlachos & Bechtsis, 2018
Application of Specific Technology to Support the FSC	Amin, Zuhairi & Saadat, 2020; Baralla, Pinna & Corrias, 2019; Bumblauskas et al, 2019; Burke, 2019; Croxson, Sharma & Wingreen, 2019; Figorelli et al, 2018; Gopalakrishnan & Behdad, 2019; Hilt, Shao & Yang, 2018; Ko, Hong & Chiu, 2019; Kuang et al, 2019; Moudoud, Cherkaoui & Khoukhi (2019); Pal & Kant, 2019; Surasak et al, 2019; Violino et al, 2019
Blockchain to Promote Regulatory Compliance	Blakistone & Mavity, 2019; Casino et al, 2019; dos Santos et al, 2019; Tieman et al, 2019
Blockchain to Promote Information Symmetry	Kamble, Gunasekaran & Sharma, 2019; Rathi, Patil & Tribhuwan, 2019; Scuderi, Foti & Timpanaro, 2019

Blockchain for Food Safety in the FSC Sub-Theme

The second largest sub-theme identified in the literature centers on the use of blockchain to promote food safety within the FSC. Two characteristics of this sub-theme vary somewhat from the preceding traceability sub-theme. First, there is a great deal of consistency in the terminology used by the researchers in the traceability realm that is not as evident in the food safety literature. Specifically, the researchers in this area tend to use the terms food safety and food quality interchangeably. This makes some sense in that the quality of the food in the FSC is usually judged in connection with its fitness for use, which can also be thought of as food that is safe to eat. Therefore, in this analysis the terms food safety and food quality will be considered to describe the same concept. The second difference is that, unlike the concept of traceability, this concentration of literature is much more homogenous. Thus, there are not readily identifiable concentrations of the literature on FSC/food safety except for the methodology used and, in some cases, the specific type of product addressed.

There are a number of studies that provide significant overviews of how blockchain could potentially play a role in improving the FSC to improve food safety (Sailaja, 2019; Tse et al, 2017; Kshetri, 2019; Pearson et al, 2019; Johnson, 2019; Yiannas, 2019). A specific discussion of how blockchain can be utilized to improve the FSC in China is provided by Xie, Guo & He (2018) and Berti & Semprebon (2018). Marinello et al (2017) propose a framework for a blockchain-based animal product supply chain control mechanism and Awwad et al (2018) present a few potential case studies for a blockchain-based FSC. A small number of reviews exist that synthesize selected slices of the literature that focus on the use of blockchain to improve food safety (Tan et al, 2018; Zhao et al, 2019; Creydt & Fisher, 2019; Astill et al, 2019). Lastly, Behnke & Janssen (2019) review the boundary conditions necessary for the successful implementation of blockchain to improve food safety.

System designs with more specificity in terms of focus can also be found in the literature (Wang, 2019; Hua et al, 2018; Hong et al, 2018; Shyamala et al, 2019). A number of designs lean on an Internet of Things (IoT) architecture in combination with blockchain to provide a means of identifying and pinpointing food safety problems (Lin et al, 2018; Hao, Sun & Luo, 2018; Huang, Zhou & Liu, 2019). Guo, Liu & Zhang (2018) describe their SafeFood solution using Hyperledger Fabric. Tao et al (2019) consider a multi-domain hierarchical blockchain mechanism with fuzzy evaluation of node reputation and Tian (2016) and Yu & Huang (2018) examine the usefulness of RFID and blockchain to trace food with quality problems. Finally, Suzuki et al (2018) introduce the "proof of Proof" concept, a security enhanced form of blockchain while Tradigo et al (2019) present an information system to provide extended capabilities beyond food tracing such as monitoring land quality.

Systems that address specific agricultural products are designed for dairy (Kasten, 2019b), soybeans (Salah et al, 2019), peanuts (Zhao et al, 2019), wood and wood products (Kim & Hwang, 2018), pigs (Yuan et al, 2020), and fish (Førsvoll & Åndal, 2019). Actual prototype systems are developed and tested by some authors. Some examples of realized systems include one based on the Hazard Analysis and Critical Control Points (HACCP) protocol (Tian (2017), systems implemented to track pork and mangoes by Walmart (Kamath, 2018), and a system based on the Food Quality Index (FQI) to protect the foods bought by restaurants (George et al, 2019). A hybrid on- and off-chain storage process utilizing IoT is put forth by Lin et al (2019), an RFID/IoT solution is built by Mondal et al (2019), Wang et al (2019) make extensive use of logs to verify identities of all FSC participants prior to transacting food data, and Hayati & Nugraha (2018) devise FoodTrail, a blockchain-based system implemented on the Hyperledger Sawtooth platform.

For many of the studies that propose the use of blockchain to support food safety, the underlying theme is the exploitation of blockchain's data immutability characteristic that provides for a single version of the truth and allows the tracking of food shipments throughout the FSC to ensure that product moves through the process at the proper pace. Once in the supply chain, blockchain data can be used to ensure that the food is handled properly to avoid spoilage (i.e. proper refrigeration, segregation from contaminating materials, etc.). Moreover, once dangerous food is identified anywhere between the source and the final destination, its origin and route of travel can be known without ambiguity, thus greatly improving the probability of finding the source(s) of the quality and/or safety problem.Table 2 presents the studies focused on the use of blockchain to enhance food safety and promote food quality.

TABLE 2
PAPERS FOCUSED ON THE USE OF BLOCKCHAIN TO PROMOTE FOOD SAFETY IN THE FSC

Research Emphasis	Author(s)
Overview/review papers	Astill et al, 2019; Awwad et al, 2018; Behnke & Janssen, 2019; Berti & Semprebon, 2018; Creydt & Fischer, 2019; Johnson, 2019; Kshetri, 2019; Marinello et al, 2017; Pearson et al, 2019; Sailaja, 2019; Tan et al, 2018; Tse et al, 2017; Xie, Guo & He, 2018; Yiannas, 2019; Zhao et al, 2019
System Proposals	Guo, Liu & Zhang, 2018; Hao, Sun & Luo, 2018; Hong et al, 2018; Hua et al, 2018; Huang, Zhou & Liu, 2019; Lin et al, 2018; Shyamala et al, 2019; Suzuki et al, 2018; Tao et al, 2019; Tian, 2016; Tradigo et al, 2019; Wang, 2019; Yu & Huang, 2018
Systems to Address Specific Agricultural Products	Førsvoll & Åndal, 2019; Kasten, 2019b; Kim & Hwang, 2018; Salah et al, 2019; Yuan et al, 2020; Zhao et al, 2019
Prototype Systems	George et al, 2019; Hayati & Nugraha, 2018; Kamath, 2018; Lin et al, 2019; Mondal et al, 2019; Tian, 2017; Wang et al, 2019

Blockchain to Improve FSC Efficiency Sub-Theme

The efficiency of the food supply chain can be evaluated in a number of ways. Certainly, the cost of the processes making up the supply chain is one element of its efficiency, as is the amount of waste created during the food transportation process. In this sub-theme, the papers that are focused on increasing the various dimensions of the efficiency of the FSC are enumerated. A number of overview papers have been published that provide the underlying issues that blockchain applications address in increasing FSC efficiency (Antonucci et al, 2019; Mohanty, 2019; Unurjargal, 2018).

Of the various approaches described in this sub-section, the majority chose to address the concept of transparency. A more transparent supply chain is one that allows all parties to access relevant data in a reasonable amount of time, leading to better and quicker decision-making and, presumably, a better functioning supply chain. Forliano & Franco (2020) assess that the application of artificial intelligence, when combined with blockchain technology, can produce a more robust and resilient FSC. Likewise, IoT tools are a logical fit for increasing the efficiency of the FSC (Madumidha et al, 2019, Kim et al, 2018; Caro et al, 2018; Aich et al, 2019). IoT provides a quantum leap in the system's ability to collect data and blockchain provides a better tool for handling and protecting the data collected. Amir Latif et al (2019) suggest that blockchain can provide a means of improving the trust between FSC participants and thus improve their ability to communicate. The Halal food sector is particularly sensitive to the information that travels with food within the FSC because it provides assurance that the food has been procured, processed, and transported according to strict laws. Blockchain is an appropriate tool to ensure those data are also safeguarded and made available (Chandra, Liaqat & Sharma, 2019). Finally, the increased viability of FSC-related information provided by blockchain can help remove intermediaries whose only reason to exist is to verify and disseminate data, thus reducing costs (Mezquita et al, 2020; Kamilaris, Fonts & Prenafeta-Boldú, 2019).

Kaijun et al (2018) focus on the flow of information through the Chinese FSC as they explore the use of a double chain blockchain architecture. The improved flow of financial data through a FSC with the goal of applying blockchain and the Sustainable Development Goal (SDG) framework is addressed by Yousuf, Ratna & Rahman (2019). Finally, the first actual blockchain-enhanced transportation transaction, sending US-grown soybeans to China, is documented by Karry (2018), including the role of smart contracts in executing the deal in a nearly autonomous fashion.

Food waste is a chronic problem in any FSC and the reduction of waste is the objective of three research teams. Kayikci & Subramanian (2018) examine barriers to blockchain adoption in the Turkish dairy food chain. In Ecuador, Pena, Llivisaca & Siguenza-Guzman (2020) point out that at least one third of the food in the FSC is wasted and suggest approaches to reducing this waste with blockchain. In the United Kingdom, certain cuts of beef are considered much more desirable than others and much of the less desirable cuts are wasted. Carey & Subramanian (2019) provide a framework for the use of blockchain to make these wasted cuts of beef more available to the market and thus less likely to end up in the landfill.

A general reduction in logistics costs is the objective of a use case developed by Perboli, Musso & Rosano (2018) to demonstrate how blockchain can be used to reduce the cost of transporting food by creating a design framework that can improve the design of appropriate software. They point out that the design frameworks used to design financial blockchain applications are insufficient for the FSC environment. In a similar vein, Wang (2019) provides a design framework to help produce a tool to improve data integration tools along the FSC. Finally, Kakkar & Ruchi (2020) propose a tool to not only track rice shipments through the Indian FSC but also to improve rice paddy productivity.

The efficiency of the FSC is enhanced by increased access to information for all stakeholders, improved ability to communicate for all FSC participants, and the increased ability to track data at sufficiently low granularities to enable an understanding of item-level product activities. Table 3 presents the papers from this sub-theme.

TABLE 3
PAPERS FOCUSED ON THE USE OF BLOCKCHAIN TO IMPROVE FSC EFFICIENCY

Research Emphasis	**Author(s)**
Overview/Review Papers	Antonucci et al, 2019; Mohanty, 2019; Unurjargal, 2018)
Blockchain to Improve Efficiency by Increasing Transparency	Aich et al, 2019; Amir Latif et al, 2019; Caro et al, 2018; Chandra, Liaqar & Sharma, 2019; Forliano & Franco, 2020; Kaijun et al, 2018; Kamilaris, Fonts & Prenafeta-Boldu, 2019; Karry, 2018; Kim et al, 2018; Madumidha et al, 2019; Mezquita et al, 2020; Yousuf, Ratna & Rahman, 2019
Blockchain to Reduce FSC Waste	Carey & Subramanian, 2019; Kayikci & Subramanian, 2018; Pena, Llivisaca & Siguenza-Guzman, 2020
Blockchain to Reduce FSC Costs	Kakkar & Ruchi, 2020; Perboli, Musso & Rosano, 2018; Wang, 2019

Blockchain to Manage Shelf Life Sub-Theme

The final, and smallest, sub-theme of the supply chain theme is the use of blockchain to manage the food on the shelves at the retail level. One paper (Tsang et al, 2019) describes a system in which blockchain, IoT, and decision support can be used to manage the inventory in a retail location to a sufficient level of granularity that it can decrease the losses caused by spoilage of food on the shelf.

Research Theme #3: The Business of Food

This research theme concerns those blockchain solutions and concepts related directly to the business aspects of the food production, transportation, processing, and selling activities that make up the overall food industry. As with the previous themes, the data immutability characteristic of blockchain plays a vital role in providing assurances of data validity and providing a single version of the truth for all FSC participants to rely upon.

As with other topics covered in this study, this theme also includes a number of effective overviews of the area of study. Lin et al (2019) take a global approach to the use of blockchain to support smart agriculture and how it might help in reducing agriculture's contribution to climate change and environmental pollution. Lin et al (2017), on the other and, start from the local and regional level to describe a system, along with an evaluation tool, that they hope will act as a model for development of future, larger scale, systems. Zhang et al (2019) provide a discussion detailing the challenges facing those wishing to introduce blockchain as an agriculture sustainability and traceability tool. Dakshayini & Prabhu (2020) and Kamble, Gunasekaran & Gawankar (2020) both discuss how specific investments in certain technologies such as blockchain and IoT can result in significant improvements in the sustainability of a region's agricultural industry.

Relationships have always been an important part of agriculture, whether between farmers and buyers, consumers and retailers, or members of a FSC. A number of authors provide insights into the manner in which some of these relationships can be enhanced using technologies such as blockchain. For example, Linsner et al (2019) discuss the fear that local farmers have of losing their traditional local relationships when tools like blockchain are introduced. Pinna & Ibba (2019) suggest that a blockchain-based employment management system might improve the relationship between temporary workers and the growers for whom they work during the harvest season. Finally, many authors recognize the importance of the entire network of relationships that supports the local and national agriculture industry, and suggest that it could be greatly strengthened by blockchain. Some authors assert that the smart contract, or other mechanisms to build executable operations into the blockchain system, is key to building these relationships (Smirnov, Sheremetov & Teslya, 2019; Monet & Meulders, 2019; Nazarov, Shvedov & Sulimin, 2019; Silva, Guerreiro & Sousa, 2019). Others focus their efforts on creating sustainable organizations in more rural environments (Polbitsyn, 2018; Petek & Zajec, 2018; Tripoli & Schmidhuber, 2018, Papandreou, 2019).

There is a wide array of studies that seek to use blockchain to solve some of the basic, and not so basic, financial problems faced by farmers or other FSC participants. Kniepert & Fintineru (2018) apply an institutional economic perspective to the food industry and describe how blockchain fits into this approach. Blockchain applications in the food court payment and wholesale food delivery management systems demonstrate how these basic functions can be better managed and therefore cost less (Yadav et al, 2018; Markovic, Edwards & Jacobs, 2019). The cost of contract coding is addressed using visual and user-defined smart contracts (Mao et al, 2019) and a method for determining the value of the waste products sold by farmers to produce green energy is defined by Dodge (2019). Obtaining credit and insurance is vital to farmers around the world, and blockchain has been employed to assist in credit evaluation (Mao et al, 2018) and to reduce the evaluation costs for drought-based insurance. Junfithrana et al (2018) devise a method to streamline and make transparent the process by which excess rice is donated to orphanages in Indonesia. With all of these capabilities, the question of whether they are worth implementing by the organization must be addressed (Chinaka, 2016). Martindale et al (2018) address this question from the position of a blockchain-based Enterprise Resource Planning (ERP) system and Füzesi et al (2019) from that of a food traceability system.

Researchers have identified that one of the significant issues that makes it difficult to survive in the agricultural industry is the lack, or imbalance, of information (Andreevich & Ivanovich & Ivanovich, 2018). This information imbalance might arise because of systems that do not integrate properly (Lagutin et al, 2019) or perhaps the data is not collected properly (Yadav & Singh, 2019). In either case, the authors discuss blockchain as a means of controlling or eliminating this information asymmetry problem. Blockchain is proposed as a means of providing better information to the consumer (Awan et al, 2019; Maghfirah, 2019; Ghimire, 2019) or between members of the supply chain, making it less difficult to find and negotiate price (Mao et al, 2018; Saji et al, 2020).

A number of authors have sought to use blockchain to deal with other, less common issues in agriculture. For instance, there is significant activity to determine if blockchain can provide assistance in maintaining compliance with various governmental regulations (Krzyzanowski, 2019; Ehmke & Ehmke, 2019; Misra & Das, 2019). Others discuss ramifications of blockchain solutions for specific types of food such as wine (Spadoni et al, 2019) and dairy (Longo, Nicoletti & Padovano, 2019). Finally, the application of blockchain is used to to reduce the use of child labor in West and Central Africa (Senou et al, 2019) and for incentivizing the efficient use of rural waste (Zhang, 2019). Table 4 presents the papers focusing on the use of blockchain to support the business of food.

TABLE 4
PAPERS FOCUSED ON SUPPORTING THE BUSINESS OF AGRICULTURE

Research Emphasis	Author(s)
Blockchain to Promote Sustainability	Dakshayini & Prabhu, 2020; Kamble, Gunasekaran & Gawankar, 2020; Lin et al, 2019; Lin et al, 2017; Zhang et al, 2019
Blockchain to Support FSC Relationships	Linsner et al, 2019; Monet & Meulders, 2019; Pinna & Ibba, 2019; Nazarov, Shvedov & Sulimin, 2019; Papaandreou, 2019; Petek & Zajee, 2018; Polbitsyn, 2018; Silva, Guerreiro & Sousa, 2019; Smirnov, Sheremetov & Teslya, 2019; Tripoli & Schmidhuber, 2018
Blockchain to Support Financial Aspects of Agriculture	Chinaka, 2016; Dodge, 2019; Füzesi et al, 2019; Junfithrana et al, 2018; Kniepert & Fintineru, 2018; Mao et al, 2019; Mao et al, 2018; Markovic, Edwards & Jacobs, 2019; Martindale et al, 2018; Nguyen, Das & Tran, 2019; Yadav et al, 2018
Blockchain to Promote Information Symmetry	Andreevich, Ivanovich & Ivanovich, 2018; Awan et al, 2019; Ghimire, 2019; Lagutin et al, 2019; Maghfirah, 2019; Mao et al, 2018; Saji et al, 2020; Yadav & Singh, 2019
Blockchain to Maintain Regulatory Compliance (and other issues)	Ehmke & Ehmke, 2019; Krzyzanowski, 2019; Longo, Nicoletti & Padovano, 2019; Misra & Das, 2019; Senou et al, 2019; Spadoni et al, 2019; Zhang, 2019

Research Theme #4: Blockchain in the Production of Food

To this point in the study, blockchain has been demonstrated to be an effective tool in moving, selling, and making a profit through the creation of food. In this fourth theme, the actual growing of food is the target of this technology. However, it is not nearly as active a research area as the aforementioned topics. Perhaps it will take a while longer for farmers, who might be more apprehensive of newer technologies such as blockchain, to adopt these tools and the possible changes in farming processes they might bring with them.

The use of water is of tremendous importance to farmers and other food growers, especially where it is not plentiful. Munir, Bajwa, & Cheema (2019) design a smart watering system that uses fuzzy logic and blockchain to optimize the watering process based on environmental and crop characteristics. The system proposed by Bordel et al (2019) performs a similar function that allows the water-using community to develop rules to make the most of their water allotment. Using blockchain to control breeding data such as time of ovulation, Britt (2019) suggests that reproductive management technologies will inevitably produce a sub-breed of cattle bred for specific latitudes and that will produce a more specialized milk product.

Other applications of blockchain range from a tool to track the carbon footprint of various food products in order to control emissions (Shakhbulatov et al, 2019) to controlling access to an image-based plant phenotyping tool (Samaniego, Espana & Deters, 2019) to forecasting dissolved oxygen in aquaculture farms (Cao et al, 2018). Not all applications of blockchain are as exotic, though. Branco et al (2019) propose a blockchain-based tool to remotely control the growing of mushrooms and the growing of tomatoes in Africa is optimized by a blockchain-based tool that monitors solar-powered greenhouses (Busia et al, 2019). Table 5 displays the papers centered on using blockchain to assist in the production of food.

TABLE 5
PAPERS FOCUSED ON THE USE OF BLOCKCHAIN TO SUPPORT FOOD PRODUCTION

Research Emphasis	Author(s)
Blockchain to Promote the Production of Food	Bordel et al, 2019; Branco et al, 2019; Britt, 2019; Busia et al, 2019; Cao et al, 2018; Lamtzidis, Pettas & Gialelis, 2019; Shakhbulatov et al, 2019; Munir, Bajwa & Cheema, 2019; Samamiego, Espana & Deters, 2019

DISCUSSION

It is clear from the papers reviewed in this study that the literature surrounding the application of blockchain in the agriculture sector has only begun to mature. The literature consists primarily of descriptive and prescriptive studies with very few actual systems being created, even at the prototype level. This is not an unexpected occurrence given that the first agriculture/blockchain study only emerged in 2016. However, the rapid increase in the number of papers being produced hopefully foreshadows that the level of empirical research will begin to increase as well. Of course, for the literature to grow beyond the point of describing what might work to how well it works, there needs to be an increase in the number of blockchain-based applications implemented in industry. While firms such as IBM and SAP have been discussing the usage of blockchain technologies, they are only starting to roll these blockchain tools out to industries such as supply chain, agriculture, and finance (www.ibm.com/blockchain). Those that do exist have yet to be studied in any systematic way, but that is exactly what is needed to move the literature to the next level of maturity. Moreover, as more researchers begin to examine these tools as they exist in their various industries, it will likely provide confidence to those firms who have been hesitant to commit resources to the development of blockchain tools, especially if the results of these analyses suggest that the many claims of improved performance, security, and accuracy come to pass.

As the examination of potential and actual blockchain-based tools continues to grow in number, researchers should also begin to consider the shortcomings of blockchain, such as its inability to easily change or delete data from the chain once added. This, and other characteristics, might impose significant changes to organizational processes that utilize this method of data storage and organization. For those applications that require the ability to examine all previously developed data within a process, this aspect of blockchain is very welcome. For others, for whom access to past data is unnecessary or even unwanted, this could prove inconvenient and require that other measures be placed atop the blockchain structure to impose whatever order the firm needs in order to remain compliant with its existing processes.

CONCLUSION

This paper provides a systematic review of the extant literature on the use of blockchain in the agriculture sector. It displays with a number of examples how the use of blockchain can improve the sustainability of agriculture from a financial, environmental, and market perspective. While it appears that there is a vibrant and growing community of researchers examining the benefits of the blockchain process and proposing new ideas to leverage it to improve operations in many facets of agriculture, there has been little research into the actual results obtained by using blockchain instead of more traditional data storage and security mechanisms. The paper identifies a number of themes evident in the body of literature surveyed and provides examples of research efforts within each one. The study also uncovers some shortcomings in the literature that should be addressed as the blockchain environment begins to mature.

This study has a few limitations that must be noted. To this point, all major electronic databases have been examined, but that does not provide a guarantee that this is an exhaustive search. Also, only those research efforts that have been peer-reviewed are included. This is not to suggest that the other areas of literature such as that emanating from trade-focused outlets has no worth, only that the focus in this project is to identify research efforts that are undertaken and evaluated in a systematic, verifiable manner.

It is left for future research to include other, so-called gray, literature in the review. That will be helpful in developing an understanding of where the industries think blockchain is most valuable and to see if academia's research efforts are aligned with the expectations of the practitioner community.

The value of a study such as this is to orient the researcher to the work already done upon which they might build their study and within which they can find their research direction. For the practitioner, it is instructive to know what is being worked on in the academic world and how these ideas might impact, and hopefully improve, his or her ability to bring food from around the world to the plate of hungry people everywhere.

ACKNOWLEDGEMENT

A previous version of this paper has been presented at the Annual Conference of the Southeast Decision Sciences Institute.

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