Enhancing Transparency in Agri-Food Supply Chain by Securing IoT-Generated Data with Blockchain

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Abstract

Background: The agri-food supply chain is crucial for a nation's sustenance and economic stability but faces challenges such as lack of transparency, inefficiencies, and information asymmetry. Integrating Blockchain Database (BCD) technology, along with Internet of Things (IoT) technologies, offers transformative potential. This combination can enhance the Transparent Physical and Information Flow (PHF), thus improving Transparency in the Agri-food Supply Chain (TASC).

Objective: This research examines how integrating BCD affects PHF and, in turn, influences TASC in Bangladesh. It is based on two main hypotheses BCD significantly impacts PHF, and a BCD-enhanced PHF subsequently affects TASC.

Methods: An analytical framework was designed to explore the integration of BCD technology and its effect on the transparency of Bangladesh's agri-food supply chain. Data analysis followed five stages: Preliminary Data Examination, Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), Structural Equation Modeling (SEM), and Hypothesis Testing, utilizing IBM SPSS and IBM AMOS. Data were gathered from 400 stakeholders in the Bangladesh agri-food supply chain.

Results and Conclusion: The findings support both hypotheses, showing a significant and positive impact of BCD technology on PHF and, consequently, on TASC. The results highlight the essential role of BCD in enhancing supply chain transparency and operational efficiency.

Implications of the Research: This study offers empirical evidence on how blockchain technology can effectively address transparency and efficiency challenges in the agri-food supply chain. It highlights the potential of BCD to enhance decision-making, operational efficiency, and consumer trust within the agricultural sector, particularly in developing countries such as Bangladesh.

Originality/Value: This research provides fresh insights into how BCD technologies can enhance transparency and efficiency in the agri-food supply chain. By concentrating on the context of Bangladesh, it offers significant implications for policymakers, industry professionals, and researchers, highlighting the transformative potential of blockchain in managing agricultural supply chains.

Keywords: Agri-food Supply Chain (ASC), Blockchain Database Technology, Transparent ASC, Structural Equation Modeling (SEM)

1. Introduction

Agriculture remains a cornerstone of global economic stability, contributing significantly to the GDP of many nations. In Bangladesh a recently LDC-graduated country, this sector is especially crucial, accounting for a substantial portion of the national economy and sustaining approximately 70% of the population [1]. Agriculture in Bangladesh is not just an economic activity but a lifeline for millions. Despite its pivotal role, the agri-food supply chain (ASC) in Bangladesh faces numerous challenges that hamper its efficiency and transparency. The traditional ASC is mired in a complex web of intermediaries, making it exceedingly difficult to trace product origins, verify quality, manage demand forecasting, and prevent fraudulent activities. Such inefficiencies often lead to significant price escalations—prices can increase up to 350% beyond the farmer's original selling price [2]. This not only affects the farmers' livelihoods but also impacts consumer access to affordable food.

The lack of transparency in the ASC leads to substantial economic losses and affects critical areas such as food safety, nutritional access, and public health. Transparency is instrumental in reducing inefficiencies, lowering consumer costs, and increasing farmer profits, thereby bolstering food security and economic stability in Bangladesh [3]. Enhanced transparency can also promote fairness in the market, ensuring that profits are equitably distributed along the supply chain, from farmers to consumers.

1.1 Integration of IoT and Challenges in Data Security

To address these endemic issues, the integration of advanced technologies like the Internet of Things (IoT) has been increasingly explored to enhance data accuracy and operational efficiency in agricultural processes. IoT enables real-time monitoring and data collection at various stages of the supply chain, facilitating improved tracking of product origin, quality control, demand estimation, inventory management, and monitoring of financial transactions. Previous studies have demonstrated that IoT can significantly mitigate many traditional challenges of the agricultural supply chain [4].

However, while IoT offers transformative potential, it also introduces new vulnerabilities, notably the risk of data manipulation. With IoT infrastructure, anyone with access to the database might alter or falsify information, potentially undermining the very transparency and efficiency it seeks to enhance [5].

Blockchain as a Solution to Enhance Data Integrity

To counter the vulnerabilities introduced by IoT, blockchain technology presents a promising solution. Known for its decentralized nature and tamper-evident ledger, blockchain technology ensures that once data is entered, it becomes immutable, thereby safeguarding the integrity of data generated from IoT devices [6]. This integration of blockchain can revolutionize the ASC by enabling a secure, transparent, and immutable record of all transactions and data exchanges within the chain.

By facilitating an environment where data cannot be altered once registered, blockchain not only enhances the security of the data but also builds trust among all stakeholders, including farmers, distributors, retailers, and consumers. This trust is crucial for the effective adoption and scaling of IoT technologies in critical sectors like agriculture.

How Blockchain Leads to Transparency in Agri-food Supply Chain

The integration of Blockchain Database (BCD) into the agri-food supply chain (ASC) represents a transformative approach to addressing longstanding issues of transparency and efficiency. By utilizing BCD technology, all stakeholders gain access to an incorruptible and verifiable data source. This integration facilitates Transparent Physical and Information Flow (PHF), whereby each transaction and transfer within the supply chain is recorded and made accessible to authorized parties only. This level of documentation and transparency significantly reduces the opportunities for fraud and errors, which are commonplace in more traditional ASC models. Moreover, this visibility inherently promotes trust among all stakeholders—from farmers and distributors to retailers and consumers—fostering a more collaborative and secure supply chain ecosystem [7].

The effective use of blockchain can revolutionize the supply chain by making data accessible and immutable, which means that once data is entered into the blockchain, it cannot be altered without the consensus of the network. This aspect is crucial for maintaining the integrity of the data across the entire supply chain. Furthermore, blockchain's ability to provide a transparent audit trail ensures that all goods can be traced back to their origins, thereby enhancing quality control and consumer trust. These features are particularly important in the context of Bangladesh's ASC, where concerns over product quality and origin have historically posed significant challenges.

The core aim of this chapter is to scientifically validate the impact of BCD technology on enhancing transparency and efficiency within Bangladesh's ASC. Considering the pivotal role of agriculture in the national economy and the urgent need for improved transparency, this research is both timely and crucial. The potential of blockchain technology to reform key economic sectors by enhancing transparency and reducing inefficiencies presents a significant opportunity for development, particularly in less developed economies that are similar to Bangladesh.

This study is guided by two primary research questions, which are articulated as hypotheses:

1. **Hypothesis 1:** There is a significant relationship between Blockchain Database (BCD) technology integration and Transparent Physical and Information Flow (PHF).
2. **Hypothesis 2:** There is a significant relationship between Blockchain Database infused Transparent Physical and Information Flow (PHF) and Transparency in Agri-food Supply Chain (TASC).

These hypotheses are tested through a rigorous methodological framework that employs various statistical tools to analyze data obtained from a representative sample of 400 stakeholders involved in the agri-food supply chain. The selection of such a diverse and substantial sample is intended to ensure the robustness of the findings and to support the generalizability of the study results.

This research paper aims to scientifically validate the impact of Blockchain Database (BCD) technology on enhancing transparency and efficiency in Bangladesh's agri-food supply chain. It explores how blockchain can act as a foundational technology that complements IoT by providing a secure framework for data integrity, ultimately leading to a more transparent, efficient, and equitable agri-food supply chain.
Through detailed analysis and empirical research, this paper will contribute to the broader discourse on agricultural technology integration, offering insights that could guide policy decisions and practical implementations in developing countries similar to Bangladesh. This investigation not only furthers the academic understanding of blockchain applications in agriculture but also provides a real-world blueprint for leveraging technology to solve longstanding challenges in global food supply chains.

2. Literature Review

2.1 Transparent Physical and Information Flow of Bangladesh ASC

The agri-food supply chain (ASC) in Bangladesh is characterized by its complexity and the significant role of intermediaries, who bridge the gap between farmers and consumers. This complexity is a major contributing factor to the substantial price escalation observed in the market, often reaching 300 to 350 percent beyond the farmers' original selling price [2]. The ASC involves multiple stages and participants, each adding layers of transactions that, while necessary for the functioning of the market, also introduce opportunities for inefficiency and lack of transparency.

Intermediaries in the Bangladesh ASC

The structure of intermediaries in the Bangladesh ASC is multifaceted illustrated in figure 1, consisting of several key players: Input Suppliers, Growers/Farmers, Farias, Beparies, Aratdars, and Retailers [8].

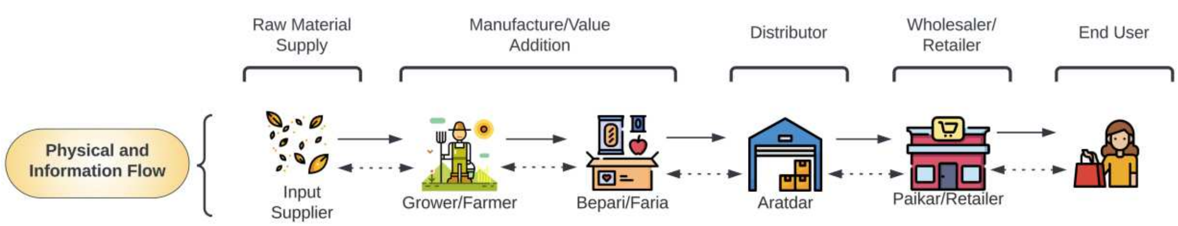

Figure 1: Physical and Information Flow of the Agri-Food Supply Chain (ASC) in Bangladesh).

- **Input Suppliers** are the initial providers in the supply chain, supplying necessary raw materials to the growers or farmers.
- **Growers/Farmers** are the producers of the agricultural products. Once the cultivation is complete, they sell their produce to the next level in the supply chain.
- **Farias**, often landless laborers or small-scale farmers who do not engage in farming full-time, play a crucial role as minor merchants. They operate within three to four local markets and manage small quantities of agricultural products, purchasing directly from the farmers and selling to the Beparies [9].
- **Beparies** are specialized merchants who handle a larger volume of agricultural goods. They buy from the Farias at local markets or directly in the villages, undertake the sorting and packing of these goods, and then sell them to Aratdars.

- **Aratdars** act as the pivotal middlemen in this chain. Operating on a fixed-commission basis, they are key to the storage and distribution processes, providing space and logistical support for perishable goods and acting as a conduit to the Retailers.
- **Retailers** represent the final link in the chain, purchasing goods from Beparies through Aratdars and selling them directly to the consumers.

The traditional ASC in Bangladesh is fraught with challenges due to its dependency on numerous intermediaries. Each layer not only increases the cost to the consumer but also obscures the flow of information, making it difficult to trace product origins, verify quality, and manage inventory efficiently. This opacity and the resultant lack of accountability enable fraudulent practices and contribute to significant inefficiencies and food waste [10].

Furthermore, the dependence on multiple intermediaries can lead to delays and a degradation in product quality by the time it reaches the consumer. This system's inefficiency is exacerbated by the lack of modern technological integration, which could otherwise help streamline operations and improve transparency.

The Need for a Transparent Physical and Information Flow

The need for transparency in the ASC in Bangladesh cannot be overstated. Transparency would not only enhance the efficiency of the chain but also ensure fairer pricing, better quality goods, and increased trust among all stakeholders, from farmers to consumers. Moreover, a transparent system can significantly reduce the opportunities for corruption and loss, directly benefiting the economic and nutritional health of the nation.

The integration of Blockchain Database (BCD) technology proposes a transformative shift in the ASC by creating a Transparent Physical and Information Flow (PHF). BCD offers a decentralized and immutable ledger, which ensures that once data is recorded, it cannot be altered without consensus from all parties involved. This would make every transaction within the supply chain traceable and verifiable, significantly reducing the likelihood of fraud and errors [11].

In a blockchain-infused ASC, the roles of intermediaries could evolve to become more streamlined and focused on adding real value rather than merely acting as links in a chain of custody. For example, Farias and Beparies could use blockchain to provide proof of provenance and quality, thus gaining a competitive edge and fostering trust with both farmers and consumers. By recording each transaction on the blockchain—from the farmer to the retailer—every stakeholder would have access to reliable and timely information, enhancing the overall efficiency of the supply chain. This documented, immutable history of transactions would significantly mitigate risks associated with perishable goods and optimize inventory management.

By embracing these technological advancements, Bangladesh can pave the way for a more equitable and sustainable agricultural sector, fundamentally enhancing the economic, nutritional, and social well-being of its population.

2.2 Internet of Things (IoT) Technologies Data Manipulation Issue in ASC

The integration of Internet of Things (IoT) technologies in the agri-food supply chain (ASC) has been identified as a promising solution to address the pervasive transparency and efficiency issues within the sector. As previously discussed, the complexity of intermediaries in the Bangladesh ASC leads to challenges in tracking the origin, verifying quality, estimating demand, managing inventory, and monitoring financial transactions, all of which contribute to increased food waste and economic inefficiencies. Recent advancements in IoT technologies, as explored in our last research [12, 13], demonstrate significant potential to mitigate these challenges by enhancing traceability and real-time monitoring capabilities across the supply chain.

IoT in Enhancing ASC Traceability

IoT technologies, such as Radio-frequency Identification (RFID), bio/wireless sensors, artificial intelligence, and high-pressure processing, have been increasingly applied within various segments of the ASC. These technologies facilitate a myriad of functions, from real-time tracking of goods to monitoring the storage conditions, thus ensuring product quality and safety. For instance, RFID tags can store data about the product's origin, batch number, and expiration date, which can be instantly accessed by scanners throughout the supply chain. Similarly, bio-sensors can provide critical data regarding the condition of perishable goods, reducing the risk of spoilage and ensuring the delivery of fresh products to consumers.

Figure 2 [14] illustrates a comprehensive traceability system architecture model, which includes detailed application systems and their functions in supporting ASC business processes. This model highlights the key application concepts required, the logical organization of information systems, and provides an overview of information exchange between systems and the roles of each actor. The architecture encompasses multiple management systems, including user management, knowledge management, communication management, and traceability management, each designed to enhance the operational efficiency of the supply chain.

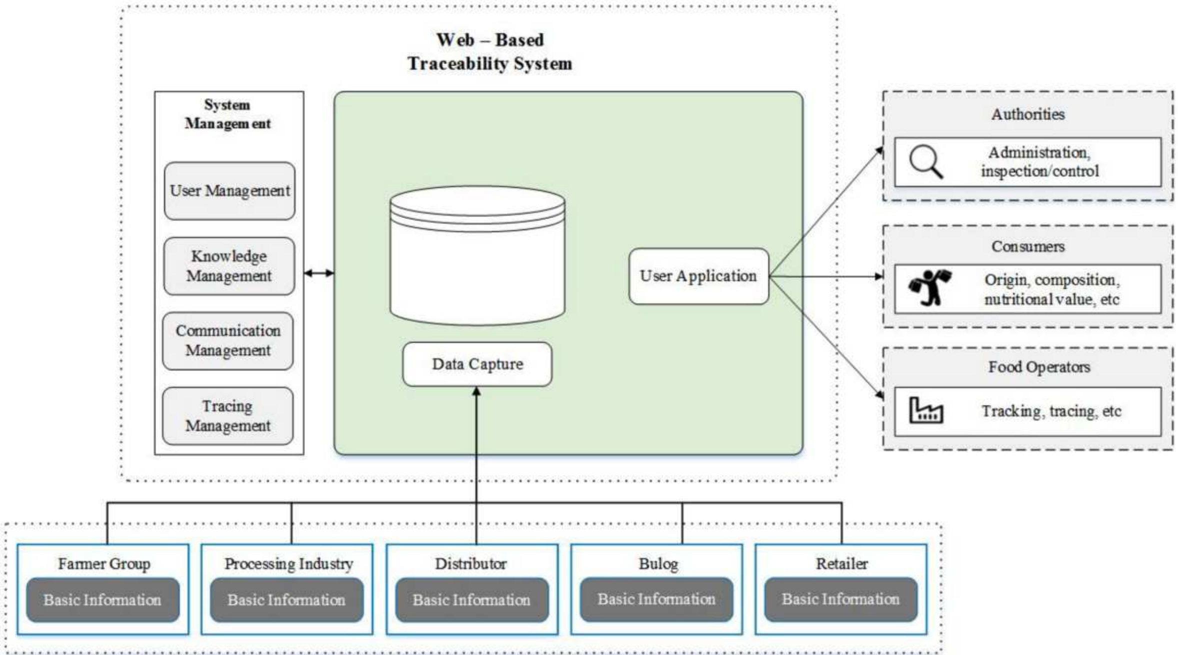

Figure 2: IoT-Based Agri-Food Traceability System Architecture.

Vulnerabilities in IoT-Based Systems

Despite the transformative potential of IoT technologies in addressing transparency and efficiency challenges, they introduce significant vulnerabilities related to data integrity and security. The central issue lies in the data storage and management system. As depicted in the traceability system model, all IoT-generated data, such as payment logs, location logs, quality reports, and inventory statuses, are stored in a centralized database. This centralized nature of data storage presents a critical risk: any individual with sufficient access to the database can potentially manipulate or alter the stored data. This possibility of data tampering undermines the reliability of the IoT infrastructure and, by extension, the entire transparency initiative within the ASC.

The risk of data manipulation is not just theoretical but a practical concern that can have far-reaching consequences on the trust and integrity of the supply chain. Manipulated data can lead to erroneous decision-making, improper inventory management, unfair pricing, and even compromise food safety and quality—risks that are particularly acute in the context of Bangladesh's ASC, where the stakes are inherently high due to the sector's impact on national nutrition and food security.

The Need for Robust Data Security Measures

To counter these risks, it is imperative to implement robust security measures that can safeguard data integrity in IoT-based systems. Traditional security measures, while necessary, are often not sufficient to address the unique challenges posed by the complex and dynamic nature of IoT environments. The implementation of advanced cryptographic techniques, regular security audits, and strict access controls are essential to enhance the security of IoT data.

Moreover, integrating blockchain technology with IoT offers a promising solution to these security challenges. Blockchain's decentralized and tamper-evident ledger can ensure that once data is recorded, it cannot be altered retroactively without detection. This integration can provide an additional layer of security and trust, ensuring the integrity of data throughout the supply chain.

In conclusion, while IoT technologies present a transformative opportunity for enhancing transparency and efficiency in the ASC, the vulnerability to data manipulation poses a significant risk that must be addressed.

Implementing stringent security measures and considering innovative solutions such as blockchain are critical to leveraging the full potential of IoT in the agri-food supply chain. By ensuring the integrity and security of data, we can build a more resilient, efficient, and transparent ASC in Bangladesh, ultimately benefiting all stakeholders, from farmers to consumers.

2.3 Blockchain Database (BCD)

The introduction of the Blockchain Database (BCD) in the agri-food supply chain (ASC) presents a pivotal advancement in combating data manipulation issues, as detailed in our systematic literature review (SLR) of approximately 100 papers [15]. This section outlines the fundamental principles of blockchain technology and discusses its application and benefits in enhancing transparency and security within the ASC, especially in contexts where IoT-generated data is prevalent.

The Genesis and Fundamentals of Blockchain

The concept of blockchain was introduced by Satoshi Nakamoto in 2008, initially as a public ledger for Bitcoin transactions [16]. This innovative technology is characterized by its decentralized and distributed ledger system, which records transactions across multiple computers in a peer-to-peer network, ensuring that no record can be modified retroactively without consensus across the network [17].

A blockchain is essentially a continuously growing series of records, called blocks, which are linked and secured using cryptography. Each block typically contains a cryptographic hash of the previous block, a timestamp, and transaction data, forming a chain that is inherently resistant to data modification [18]. This structure not only facilitates the integrity and veracity of data but also allows users to independently and transparently audit and verify transactions.

As detailed in Figure 3 [6], each block within a blockchain is made up of two primary components: the block header and the block body. The block header includes several key elements that ensure the security and continuity of the blockchain:

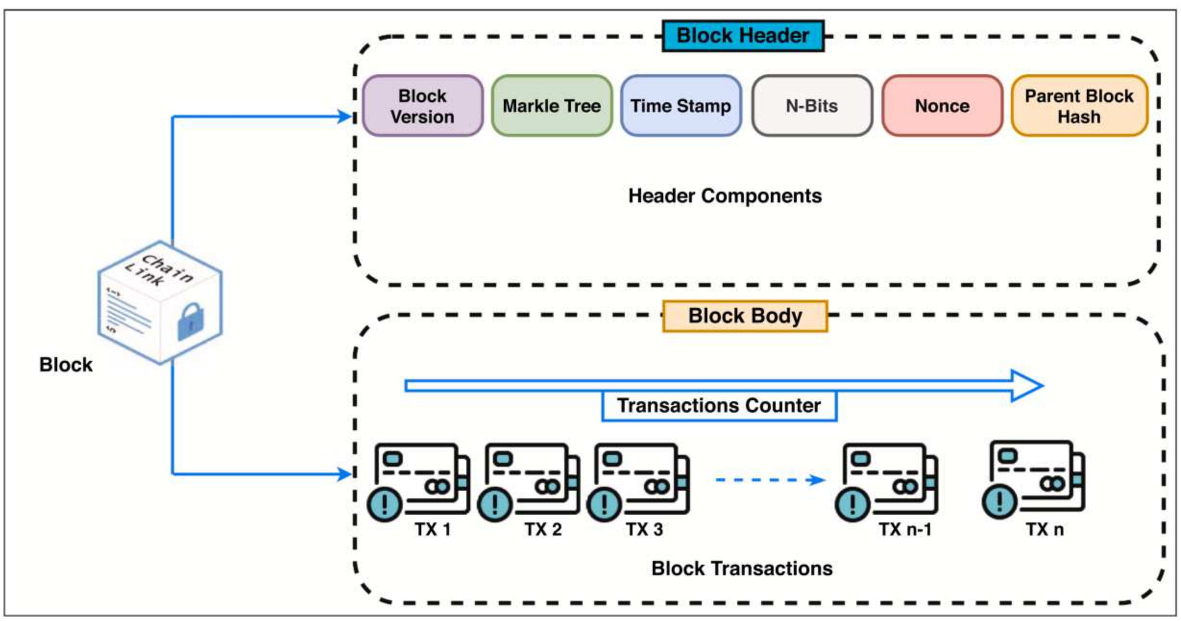

Figure 3: A Block Design.

- **Block Version Number**: Indicates the set of consensus rules to follow.
- **Merkle Tree Root Hash**: Helps verify the integrity of the block's transactions.
- **Timestamp**: Records the time each block is created to ensure data integrity.
- **N-Bits**: Specifies the difficulty target that must be met by the block's hash.

- **Nonce**: A one-time number used in cryptographic communication to ensure that old communications cannot be reused in replay attacks.
- **Parent Block Hash**: Ensures the chain's continuity by linking each block to its predecessor.

The block body, on the other hand, includes a transaction counter and details of each transaction, ensuring that every data exchange within the network is logged and immutable.

Blockchain Operation and P2P Network Benefits

The operation of blockchain is best exemplified when a transaction occurs—say, user 'A' sends data or digital assets like Bitcoin to user 'B'. This transaction is verified by nodes within the blockchain network and once confirmed, is added to a new block in the chain. This decentralized consensus mechanism ensures that all information on the blockchain is up-to-date and accurate, thereby mitigating risks of unauthorized data alterations or breaches.

The peer-to-peer (P2P) architecture of blockchain showed in the figure 4 provides several critical advantages [11]:

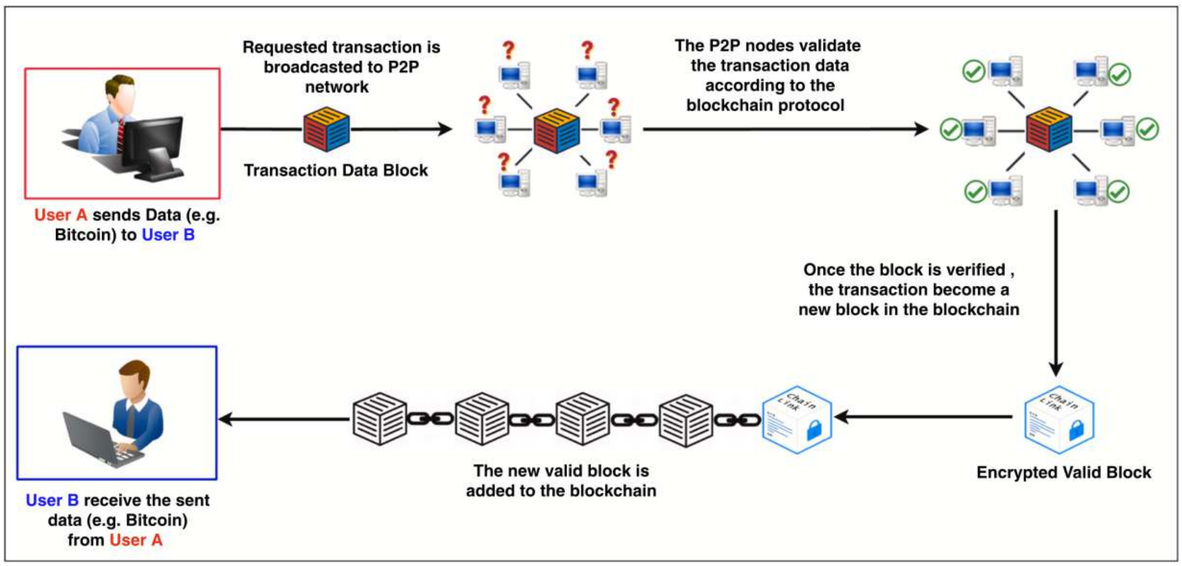

Figure 4: Blockchain System Working.

- **Blockchain Explorer**: Allows users to independently verify the state of the blockchain without third-party interference.
- **Security Against Attacks**: The distributed nature makes it extremely difficult for any attacker to alter data across multiple nodes simultaneously.
- **Data Permanence**: Information on the blockchain cannot be deleted, providing a permanent, unalterable record.

Advantages of Blockchain Over Traditional Systems

Blockchain technology offers several distinctive advantages over traditional centralized database systems:

- **Decentralization**: Eliminates the need for a central authority, enhancing transparency and trust.
- **Persistency**: Once data is added to the blockchain, it is nearly impossible to alter, ensuring data integrity.
- **Anonymity**: Participants interact under pseudonyms, which are recorded on the blockchain, protecting their identities while ensuring accountability.
- **Auditability**: Blockchain's design makes it easy to trace and verify transactions, enhancing transparency and security.

These features make blockchain particularly suited to applications within sectors like agriculture, where the integrity of data and transparency are critical for operational efficiency and trust across the supply chain.

In summary, the integration of Blockchain Database (BCD) technology within the ASC can profoundly impact the management of IoT-generated data, enhancing both transparency and reliability. By leveraging blockchain's robust security features and its decentralized nature, stakeholders in Bangladesh's ASC can overcome longstanding challenges associated with data manipulation and transparency issues.

2.4 Transparency in Agri-food Supply Chain (TASC)

The concept of transparency within the Agri-food Supply Chain (ASC) is a multifaceted notion, encompassing the clarity, openness, and accountability of information from the point of origin to consumption. In the context of Bangladesh's agriculture-driven economy, enhancing transparency in ASC is not merely a logistical aim but a critical economic and social imperative. This section explores the importance of transparency, its impact on various stakeholders, and how technological interventions can significantly enhance TASC.

Transparency in the ASC has gained considerable attention due to its potential to revolutionize the agricultural sector by improving efficiency, reducing losses, ensuring food safety, and increasing trust among consumers and other stakeholders [19]. The current lack of transparency can lead to numerous challenges, including food fraud, unnecessary waste, inefficiency in supply chain operations, and distrust among consumers due to the inability to verify the origin and handling of food products.

In Bangladesh, where the agriculture sector is a cornerstone of the economy and livelihood, the implications of transparency reach beyond economic metrics to affect national food security and public health. The World Bank has emphasized the role of transparent supply chains in improving food systems in developing countries, highlighting that transparent practices can help reduce poverty and boost economic development by creating fair market conditions [25].

Challenges to Transparency in Bangladesh's ASC

Despite its importance, achieving transparency in the ASC is fraught with challenges. The traditional supply chain in Bangladesh is characterized by its length and complexity, involving numerous intermediaries between the farmer and the consumer, as previously discussed. Each intermediary layer potentially obscures data and information, complicating traceability and accountability [24].

Furthermore, issues such as the manipulation of scales, adulteration of products, and informal fee impositions are prevalent practices that compromise the integrity of the supply chain. Such practices not only affect the economic returns for farmers but also pose significant health risks to consumers, highlighting the critical need for enhanced transparency.

Technological Advancements Facilitating TASC

The advent of technologies like the Internet of Things (IoT) and Blockchain Database (BCD) offers groundbreaking opportunities to address these transparency challenges. IoT devices can monitor and record real-time data at every step of the supply chain, from the farm to the retail shelves. This data includes information on the product's location, temperature, handling, and transport conditions, which are crucial for perishable agricultural products [22].

Blockchain technology, on the other hand, provides a secure and immutable ledger for storing data recorded by IoT devices. Since blockchain data cannot be altered retroactively without detection, it ensures the integrity of the data and thus the transparency of the entire chain. These technologies combined can create a Transparent Physical and Information Flow (PHF), significantly reducing the potential for fraud and ensuring that stakeholders have access to reliable and accurate information [23].

Benefits of Enhanced TASC

1. **Improved Food Safety and Reduction in Waste**: Transparency helps in identifying inefficiencies and contamination sources in the supply chain, thereby enhancing food safety and reducing waste due to spoilage or recalls [20].
2. **Fair Pricing and Reduced Exploitation**: With better transparency, exploitation by intermediaries can be minimized, ensuring that farmers receive a fairer share of the profit. This can lead to more sustainable practices and enhance the livelihoods of farmers [21].
3. **Increased Consumer Trust**: When consumers have access to information about where and how their food is produced, their trust in the food quality and the overall brand increases. This can lead to higher consumer loyalty and potentially higher sales [19].

In conclusion, enhancing transparency in Bangladesh's ASC is not just about adopting new technologies but about transforming the economic landscape for farmers, increasing the safety and quality of food available to consumers, and ensuring a more sustainable agricultural practice. The integration of technologies such as IoT and blockchain into the supply chain holds the promise of making these benefits a reality, marking a significant step towards a more transparent, efficient, and equitable food system.

3. Methodology

3.1 Research Design

The cornerstone of a research project is its research design, serving as the scaffold that holds together the entire study. It provides a systematic plan for conducting the research and collecting data, ensuring a smooth alignment with the objectives of the investigation. In this context, the research design is meticulously curated to scrutinize the role of Blockchain Database (BCD) technology in bolstering transparency within Bangladesh's agri-food supply chain.

In alignment with the guidance of [26], our study adopts an exploratory approach, laying the foundation to venture into uncharted territories of agri-food supply chain transparency and its potential enhancement through technology. The exploratory nature of this study is pivotal, as it allows for a deep dive into the intricate relationship between Blockchain Database technology and the transparent flow of physical goods and information, a concept largely untapped within the Bangladeshi context.

The cross-sectional aspect of the research design is employed to capture a snapshot of the variables at a single point in time. This approach is ideal for our study as it provides an avenue to integrate both qualitative insights and quantitative data, thereby enabling a multifaceted analysis of the proposed hypotheses. By surveying a broad spectrum of stakeholders, including both internal and external entities within the agri-food industry, the study garners a diverse array of perspectives.

The instrument of choice for data collection is a meticulously crafted self-administered questionnaire, which follows a comprehensive review of pertinent literature, engaging focus group discussions, and insightful face-to-face interviews. This blend of data collection methods is selected to ensure the breadth and depth of the collected data, offering a 360-degree view of the industry's stance on transparency. The questionnaire is designed to probe into the nuances of the Blockchain Database's influence on the agri-food supply chain and is distributed to a cross-section of the industry, ranging from producers to consumers, thereby encapsulating the entire spectrum of the supply chain.

Furthermore, the research design embraces the positivist research philosophy, asserting that knowledge is gained through observable and measurable facts. Therefore, the study is anchored in empirical evidence, gathered through a combination of primary and secondary data sources, reinforcing the credibility and rigor of the findings.

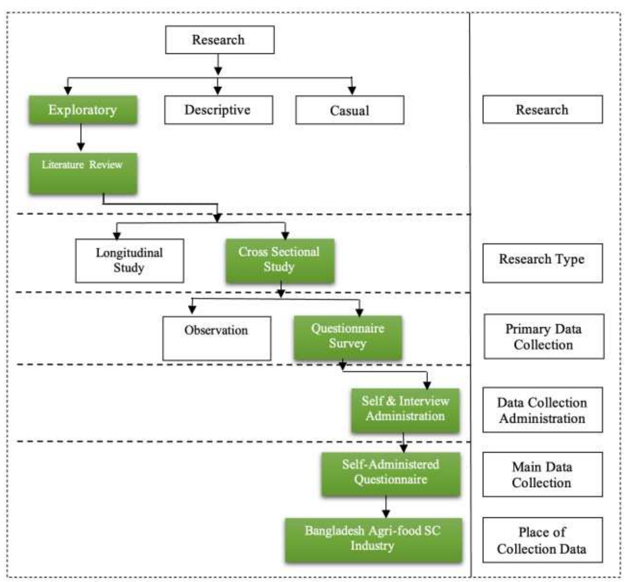

Figure. 5. Research Design

In Figure 5, we have elucidated the detailed mapping of the research design, which [27] recommend as a critical visual aid for readers to comprehend the structure and flow of the research methodology. The figure graphically represents the systematic approach undertaken, highlighting the connections between the IoT, Digital Financial Flow (DFF), and Blockchain Database Technology (BCD), and their synergistic effects on Transparent Physical and Information Flow (PHF) in the agri-food supply chain in Bangladesh.
The resultant research design stands as a robust framework, designed to not only assess the direct impact of Blockchain Database technology on transparency but also to navigate through the complexities that surround the digital and physical flow of information and commodities in the agri-food sector. It is a conduit for achieving the end goal of this study: to scientifically validate the assertion that the integration of Blockchain Database technology can indeed enhance transparency in Bangladesh's agri-food supply chain.

3.2. Population and Sampling Procedure

The population under study in this research encompasses a wide array of individuals and groups involved in the Agri-food Supply Chain (ASC) in Bangladesh. According to the latest estimates, Bangladesh has a population of approximately 168.8 million, with around 50% engaged in agriculture directly and nearly 70% depending on it indirectly for their livelihood [29]. Considering every individual as a participant in the ASC either through production or consumption, the study targets a broad population of about 118 million.
Given the diversity and vast number of individuals involved, this study employs a Probability Sampling Method to ensure each member has an equal and known chance of being selected, which aids in generalizing the findings across the entire population. The sampling strategy involves Stratified Sampling, where the population is divided into three distinct strata: Growers/Farmers, Middlemen, and Consumers [27]. This division helps in addressing the different roles and their impact on the transparency of the ASC.

Table 1 Respondent's Portfolio.

Respondents	Percentage of the Respondent
Customers of Agri-food (Agri-food: Vegetables, Fruits, Cooking Oils, Meat, Milk, Eggs, and Fungi)	45%
Intermediary of Agri-food Supply Chain (Agri-food value addition business, Distributor, Retailer)	25%
Farmer	30%
Total	100%

Each stratum is proportionally represented in the sample, as detailed in Table 1, allowing for a nuanced analysis of each group's influence on the supply chain's transparency. This methodological approach facilitates an in-depth understanding of the intersections between technology and ASC processes, enhancing the generalizability and relevance of the findings.

Sample Size

To determine an appropriate sample size, the Taro Yamane formula is utilized, providing a balance between comprehensive data representation and practical constraints of time and resources. For a population size (N) greater than 100,000 and aiming for a margin of error (e) at ±5%, the formula $n = \frac{N}{1+N(e)^2}$ is applied, yielding a sample size of 400 illustrated in Table 2. This size is considered sufficient to achieve a confidence level of 95% in the research findings, reflecting both statistical power and feasibility [30, 31].

Table 2. Taro Yamane: Sample Size

Sample Size	**Sample Size (n) for Precision (e) of:**			
	+-3%	+-5%	+-7%	+-10%
400	a	200	135	80

3.3. Instruments

The primary instrument used for data collection in this study is a structured questionnaire, designed to assess various aspects of IoT, PHF, and TASC within the ASC. The questionnaire utilizes a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), allowing participants to express the intensity of their perceptions and experiences. This scale is selected for its proven effectiveness in capturing nuanced attitudes and feelings towards complex statements and scenarios related to technological integration in supply chains [28].
The questionnaire's design ensures that it captures a wide range of information about the integration of Blockchain Database (BCD) technology and its impact on the transparency and efficiency of the supply chain processes. It also measures the mediated role of Transparent Physical and Information Flow (PHF) between the

technological integration and the transparency in ASC. This comprehensive tool is pivotal for testing the hypothesized relationships and gathering data that supports robust statistical analysis.

3.4. Data Analysis Method and Tools

The analytical framework of this study is carefully constructed to dissect and understand the intricacies involved in the integration of Blockchain Database (BCD) technology and its impact on the transparency of Bangladesh's agri-food supply chain. The data analysis is divided into five primary stages: Preliminary Data Examination, Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), Structural Equation Model (SEM) Analysis, and Hypothesis Testing. Each stage plays a critical role in uncovering different dimensions of the collected data, thus providing a thorough understanding of the underlying phenomena.

The initial stage of the data analysis process, Preliminary Data Examination, is fundamental in ensuring the quality and integrity of the data. This phase involves meticulous data cleaning which includes tasks such as data editing, coding, and transformation to ensure the data's readiness for advanced analysis [32]. It also involves checking for standard method bias to confirm that the findings reflect the true variables of interest and not the artifacts of the measurement process. Techniques to handle missing data, non-normality, and outliers are also applied to maintain the robustness of the statistical tests that follow [33].

Exploratory Factor Analysis (EFA) is used to identify latent factors influencing the Blockchain Database (BCD) on the supply chain, assessing factor loadings, composite reliability, and Average Variance Extracted (AVE) to ensure robustness.[34]. Finally, Hypothesis Testing and Path Analysis empirically test each hypothesis and map causal pathways, confirming BCD's impact on agri-food supply chain transparency [37].

4. Results

This section of the paper presents the findings from the analyses conducted to test the hypotheses regarding the role of Blockchain Database (BCD) technology in enhancing transparency in Bangladesh's agri-food supply chain. The results are organized into five subsections: Preliminary Data Analysis, Reliability Analysis, Confirmatory Factor Analysis (CFA), Structural Equation Model (SEM), and Hypothesis Analysis. Each subsection delves into specific aspects of the data and provides detailed insights into the empirical evidence supporting the research hypotheses.

4.1. Preliminary Data Analysis

The preliminary data analysis phase is crucial for preparing the dataset for rigorous statistical testing, ensuring the integrity and appropriateness of the data for subsequent analyses. Following recommended methodologies, several steps were undertaken to ensure the data met the necessary assumptions for the selected analytical techniques [34]. Handling missing data is a critical initial step as it can introduce bias and decrease the statistical power of the analyses if not properly addressed [40]. In this study, data was collected using an online Google Form configured to require complete responses to all questions, effectively minimizing the occurrence of missing data. Subsequent checks using SPSS verified the absence of missing values, confirming the effectiveness of the data collection design and adherence to best practices [41].

Prior to analysis, data editing and coding ensured the data was accurate and consistently formatted. Data editing checked for inconsistencies or errors in the responses, and coding was applied to translate qualitative data into a numerical format, facilitating quantitative analysis. Each item in the survey was pre-coded numerically, enhancing the clarity and efficiency of subsequent data handling processes. Data screening was employed to detect non-genuine responses, particularly important in online surveys. Indicators of such responses, such as straight-lining—where a respondent selects the same response across several items—were scrutinized. SPSS was utilized to identify and remove responses exhibiting this pattern, ensuring that the dataset used in the final analyses contained only genuine and considered responses. Outliers, which can significantly affect statistical test outcomes, were identified using boxplots for each variable in SPSS [42]. After careful evaluation, the decision was made to retain these points in the dataset, considering them as genuine variations within the population, thus maintaining a robust sample size of 400 for in-depth analysis. These preliminary steps were essential for ensuring the quality and suitability of the data for the complex statistical procedures that followed, laying a solid foundation for the confirmatory factor analysis and structural equation modeling required to test the study's hypotheses.

4.2. Reliability Analysis

The reliability analysis section is pivotal in assessing the trustworthiness and accuracy of the measurement instruments used in this study. The Exploratory Factor Analysis (EFA), a technique essential for uncovering the underlying relationships among survey items, was employed to evaluate the internal consistency and convergent validity of the constructs within the research framework [34].

Convergent Validity and Internal Consistency

Convergent validity, a measure of construct validity, was assessed by examining factor loadings, Average Variance Extracted (AVE), and Composite Reliability (CR) [34]:

- **Factor Loadings**: Factor loadings represent the correlations between observed variables and their underlying latent factors. In this study, factor loadings were obtained using SPSS version 27, with a Varimax rotation to aid clarity of interpretation. All retained items showed factor loadings greater than 0.4, which is above the minimum acceptable threshold and indicative of satisfactory convergent validity.
- **Average Variance Extracted (AVE)**: AVE assesses the amount of variance a construct captures relative to the variance due to measurement error [43]. In this study, AVE values exceeded the 0.5 benchmark, suggesting that the constructs adequately captured more than half of the variance of their indicators.
- **Composite Reliability (CR)**: CR measures the internal consistency of a set of items, considering varying item loadings. Values above 0.7 indicate good internal consistency, and the constructs in this study all met this criterion, demonstrating robust internal reliability.

Internal Reliability

Cronbach's alpha was utilized to assess the internal consistency of the constructs. A Cronbach's alpha value of 0.7 or higher is generally considered indicative of high reliability [44]. In this research, all constructs displayed Cronbach's alpha values ranging from 0.740 to 0.917, confirming high internal consistency and reliability of the measurement instrument.

Table 3: Exploratory Analysis of the Variables

Construct	Item	Internal reliability Cronbach alpha	Convergent validity: Factor loading (>0.4)	Convergent validity: Composite reliability (>0.7)	Convergent validity: Average variance extracted (>0.5)
RMS (5 items)	RMS_1	0.787	0.809	0.855	0.546
	RMS_2		0.670		
	RMS_3		0.572		
	RMS_4		0.786		
	RMS_5		0.824		
FAR (3 items)	FAR_2	0.792	0.836	5.149	0.633
	FAR_3		0.821		
	FAR_4		0.725		
BNF (5 items)	BNF_1	0.804	0.812	0.860	0.553
	BNF_2		0.661		
	BNF_3		0.710		
	BNF_4		0.730		
	BNF_5		0.794		
ARA (3 items)	ARA_1	0.74	0.793	5.191	0.634
	ARA_3		0.745		
	ARA_5		0.847		
RET (5 items)	RET_1	0.798	0.780	0.862	0.556
	RET_2		0.735		
	RET_3		0.691		
	RET_4		0.670		
	RET_5		0.838		
CON (3 items)	CON_1	0.766	0.887	0.861	0.676
	CON_2		0.851		
	CON_3		0.713		
BCD (3 items)	BCD_1	0.901	0.929	0.925	0.804
	BCD_2		0.849		

	BCD_3		0.915		
PHF (2 items)	PHF_1	0.917	0.903	0.894	0.808
	PHF_2		0.893		
TASC (4 items)	TASC_1	0.911	0.836	0.917	0.735
	TASC_2		0.863		
	TASC_3		0.883		
	TASC_4		0.870		

Table 3 here, details the factor loading scores, AVE, CR, and Cronbach's alpha values for each construct. Based on the EFA, factor loading scores ranged from 0.572 to 0.929, well above the recommended 0.40 level [34]. Consequently, to satisfy the AVE and CR required thresholds we had to drop four items (FAR_1, FAR_5, ARA_2, ARA_4). After that both AVE and CR were within acceptable thresholds, further substantiating the constructs' reliability and validity.
From these analyses, it is evident that the measurement model employed in the study possesses strong reliability and validity. These findings lay a robust foundation for further analyses to test the hypothesized relationships within the structural equation modeling framework.

4.3. Confirmatory Factor Analysis (CFA)

Following the exploratory factor analysis (EFA), confirmatory factor analysis (CFA) was employed to validate the factor structure identified and to confirm the legitimacy of the measurement models used in the study. CFA is a robust statistical technique used to test the hypothesis that a relationship between observed variables and their underlying latent constructs exists. The analysis was performed in two stages: first order and second order measurement models.

First Order Measurement Model

The first order CFA was conducted to validate the four-factor model developed from the EFA. The fit of the model was evaluated using several indices:

- **CMIN/DF (Chi-Square/Degrees of Freedom)**: An index of model fit where values less than 5.0 are generally considered indicative of a good fit [45].
- **CFI (Comparative Fit Index) and IFI (Incremental Fit Index)**: These indices compare the fit of a target model to an independent (null) model, with values greater than 0.90 suggesting an acceptable fit [46].
- **RMSEA (Root Mean Square Error of Approximation)**: An absolute index of fit with values below 0.10 indicating a good fit between the hypothesized model and the observed data.

The results of the first order CFA yielded a Chi-Square/Degrees of Freedom ratio of 2.098, a Comparative Fit Index (CFI) of 0.912, and a Root Mean Square Error of Approximation (RMSEA) of 0.052, all of which suggest that the model provides a good fit to the data.

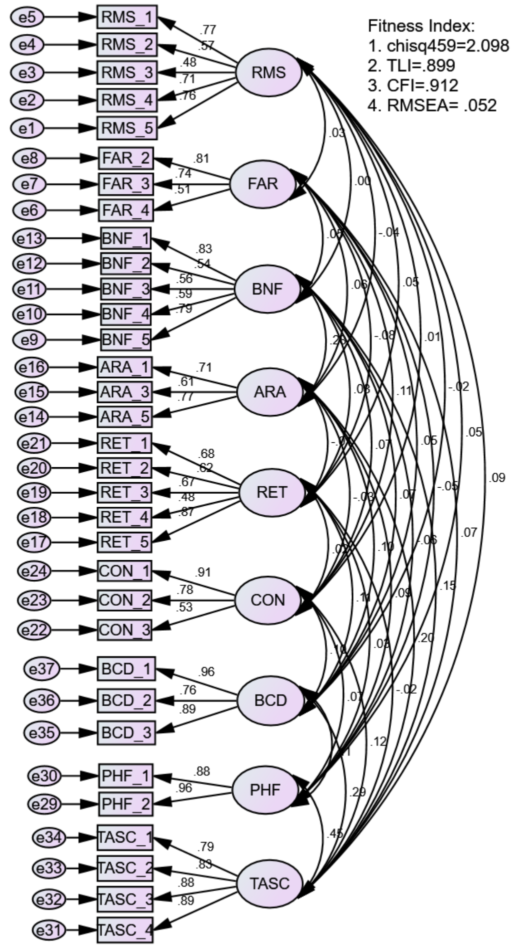

Figure 6: First Order Measurement Model Based on Variables

Table 4: Cut-off Value for First Order Measurement Model

Fit Indices	Recommended Value	Model Value	Interpretation
Chi-sq/df	<5.0	2.098	Good fit
TLI	>0.90	0.899	Good fit
CFI	>0.90	0.912	Good fit
RMSEA	<0.10	0.052	Good fit

Second Order Measurement Model

The second order CFA was necessary due to the presence of mediating and dependent variables within the study. This higher-order analysis was split into two models to adequately represent the complexities of the relationships being tested.

- **Model 1**: The first second order model assessed the mediation structure. The model displayed a Chi-Square/Degrees of Freedom ratio of 1.705, a TLI (Tucker-Lewis Index) of 0.937, a CFI of 0.947, and an RMSEA of 0.042. These indices indicate a very good fit, suggesting that the mediation by the Transparent Physical and Information Flow (PHF) is appropriately modeled.

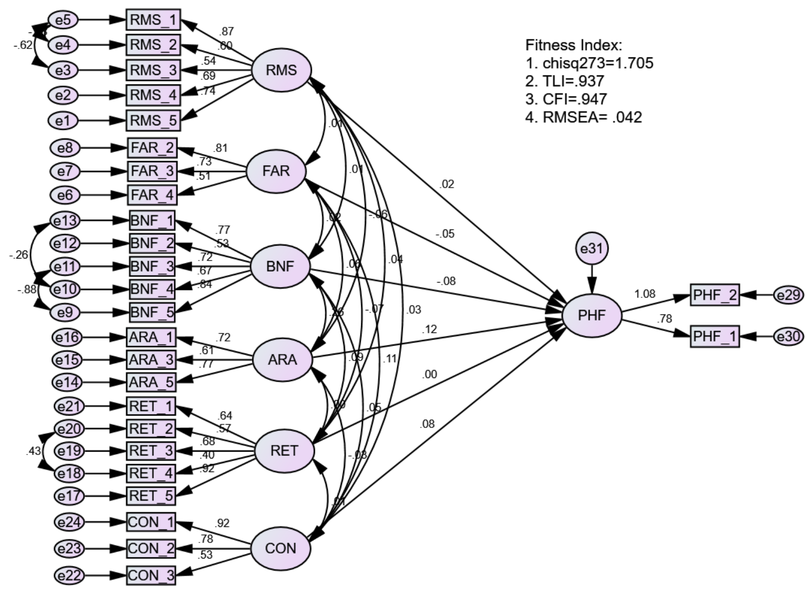

Figure 7: Results of Second Order Measurement Model – Model 1

Table 5: Cut-off Value for Second Order Measurement Model – Model 1

Fit Indices	Recommended Value	Model Value	Interpretation
Chi-sq/df	<5.0	1.705	Good fit
TLI	>0.90	0.937	Good fit
CFI	>0.90	0.947	Good fit
RMSEA	<0.10	0.042	Good fit

- **Model 2**: The model two of second order model examined the impact on the Transparency in Agri-food Supply Chain (TASC). This model reported a Chi-Square/Degrees of Freedom ratio of 1.927, a TLI of 0.987, a CFI of 0.991, and an RMSEA of 0.048. These results further substantiate the fit of the model, indicating robust support for the hypothesized relationships.

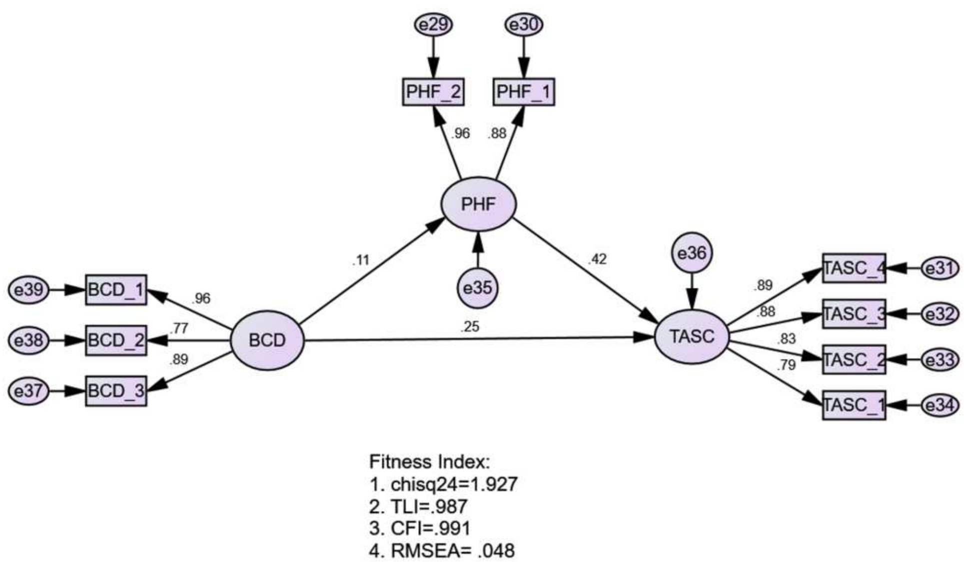

Figure 8: Results of Second Order Measurement Model – Model 2

Table 6: Cut-off Value for Second Order Measurement Model – Model 2

Fit Indices	Recommended Value	Model Value	Interpretation
Chi-sq/df	<5.0	1.927	Good fit
TLI	>0.90	0.987	Good fit
CFI	>0.90	0.991	Good fit
RMSEA	<0.10	0.048	Good fit

Both second order models have shown that the structures proposed in this study aptly correspond to the collected data, with all fit indices well within the acceptable ranges. These results affirm the statistical validity of the measurement models and pave the way for the structural equation modeling to test the hypothesized paths in the study.

4.4. Structural Equation Model (SEM)

The Structural Equation Model (SEM) was employed to assess the structural relationships hypothesized in this study. SEM is a comprehensive statistical technique that allows for simultaneous estimation of multiple and interrelated dependence relationships. It combines factor analysis and multiple regression analysis, making it possible to test complex models that include mediation, moderation, and other interconnected pathways.

The main goal in this section was to evaluate the suggested structural model and compare its fit indices with those of the overall measurement model. This process is crucial for verifying whether the finalized measurement model is consistent with the initially outlined structural model.

Structural Model Fit Assessment

The fit of the structural model was assessed using the same indices as those used in the confirmatory factor analysis and the cut-off value is shown in the table 7:

- **CMIN/DF (Chi-Square/Degrees of Freedom)**: A lower ratio indicates a better fit, with values less than 5 considered acceptable. For the structural model, a ratio of 2.120 was achieved, indicating a good fit.
- **TLI (Tucker-Lewis Index)**: This index rewards model simplicity and penalizes unnecessary complexity. A value close to or greater than 0.90 is typically desired. The TLI for this model was 0.897, which is near the threshold indicating a satisfactory fit.
- **CFI (Comparative Fit Index)**: Measures the relative improvement in fit by comparing the model with a baseline model. Values above 0.90 indicate a well-fitting model. The CFI recorded was 0.909, affirming the model's adequacy.
- **RMSEA (Root Mean Square Error of Approximation)**: Values below 0.06 indicate a good fit, and values as high as 0.08 represent a reasonable error of approximation in the population. The structural model reported an RMSEA of 0.053, suggesting a good fit.

These indices confirm that the structural model provides a good fit to the data, implying that the hypothesized relationships are appropriately represented, and the model structure is robust.

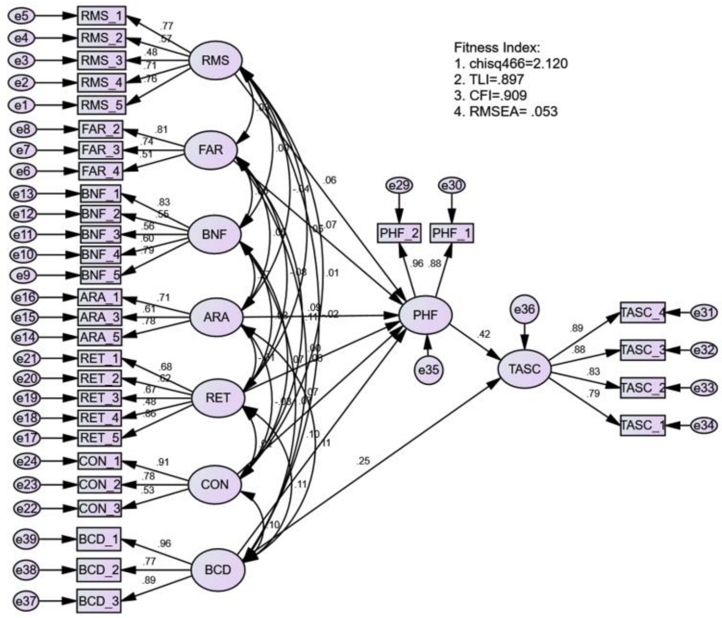

Figure 9: Results of Structural Equation Model

Table 7: Cut-off Value for Structural Equation Model

Fit Indices	Recommended Value	Model Value	Interpretation
Chi-sq/df	<5.0	2.120	Good fit
TLI	>0.90	0.897	Good fit
CFI	>0.90	0.909	Good fit
RMSEA	<0.10	0.053	Good fit

The figure 9 illustrates the finalized structural model with path coefficients and significance levels, visually representing the relationships among the constructs. This visual representation is integral for interpreting the model's ability to reflect the theorized relationships within the data.

4.5. Structural Equation Model (SEM) Analysis

The Structural Equation Modeling (SEM) was employed to examine the relationships proposed in the study's theoretical framework. This analysis aimed to test the direct and mediated effects specified in the research hypotheses concerning the integration of Blockchain Database (BCD) technology in enhancing transparency in Bangladesh’s agri-food supply chain.

Analysis of Hypotheses

The SEM provides a comprehensive examination of the direct paths and mediated relationships within the proposed model. This involves assessing the impact of BCD technology on Transparent Physical and Information Flow (PHF) and its subsequent effect on Transparency in Agri-food Supply Chain (TASC). The path coefficients, standard errors, critical ratios, and significance levels were calculated to determine the strength and significance of these relationships.

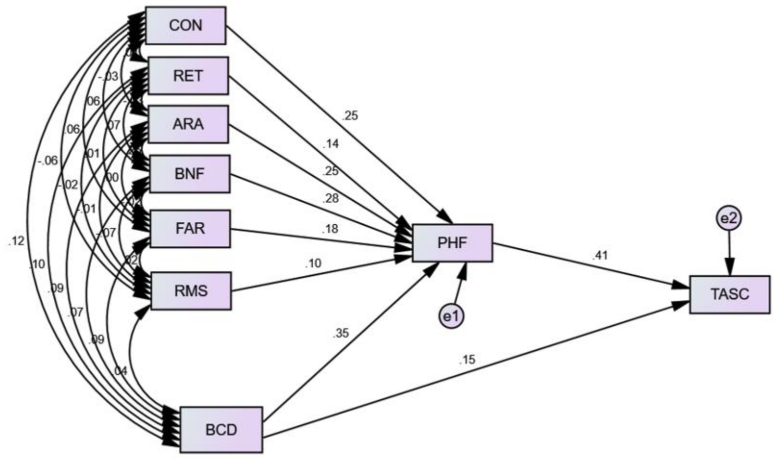

Figure 10: Results of the Hypotheses

The figure 10 illustrates the estimated path coefficients and significance tests for the hypothesized relationships. Each pathway's contribution is visually represented, highlighting both significant and non-significant paths within the model.

Table 8: Hypothesis Testing

The results of the hypothesis tests are summarized below:

Hypotheses	Paths	Estimate (β)	S.E.	C.R.	p	Results
H1	BCD--->PHF	0.123	0.013	9.651	***	Supported
H2a	PHF--->TASC	0.837	0.101	8.281	***	Supported
H2b	BCD--->TASC	0.107	0.036	2.978	**	Supported

Summary of Hypothesis Testing Results

- **H1: Significant Relationship between BCD and PHF**
  The result indicates a positive and significant impact of Blockchain Database (BCD) technology integration on Transparent Physical and Information Flow (PHF) with a path coefficient ($\beta = 0.123$), a critical ratio (CR = 9.651), and a high level of statistical significance ($p < 0.001$). This supports Hypothesis 1, confirming that BCD technology contributes significantly to enhancing transparency through improved physical and information flow.
- **H2a: Significant Relationship between BCD imputed PHF and TASC**
  The analysis shows a strong positive relationship between BCD-imputed PHF and Transparency in Agri-food Supply Chain (TASC), with a substantial path coefficient ($\beta = 0.837$), critical ratio (CR = 8.281), and statistical significance ($p < 0.001$). This finding supports Hypothesis 2a, demonstrating the critical mediating role of PHF in the influence of BCD on TASC.
- **H2b: Direct Impact of BCD on TASC**
  Blockchain Database (BCD) technology integration also shows a direct and positive impact on TASC, albeit with a smaller path coefficient ($\beta = 0.107$), but still significant (CR = 2.978, $p < 0.01$). This result supports Hypothesis 2b, indicating that BCD can directly influence transparency in the agri-food supply chain aside from its mediated effect through PHF.

The results from the SEM analysis consistently supported the proposed hypotheses, underscoring the significant role of Blockchain Database technology in enhancing transparency in the agri-food supply chain in Bangladesh. These findings validate the study's theoretical framework and confirm the effectiveness of BCD technology integration in achieving the desired transparency outcomes.

5. Conclusion

This study aimed to investigate the impact of Blockchain Database (BCD) technology on the transparency and efficiency of Bangladesh’s agri-food supply chain. The findings from our analyses confirm significant enhancements in Transparent Physical and Information Flow (PHF) and Transparency in the Agri-food Supply Chain (TASC) due to the integration of BCD technology. Specifically, the research validated the hypotheses positing that BCD technology integration significantly improves PHF, and that improved PHF substantially enhances TASC.

Blockchain technology significantly enhances the transparent flow of information and physical goods across the agri-food supply chain. This integration helps reduce fraud and errors, thereby optimizing supply chain operations and ensuring a secure tracking system. The use of blockchain database for the Supply Chain, boosts transparency in the agri-food sector, facilitating the tracking and verification of food product quality and origin. This heightened transparency is crucial for building trust among consumers and other stakeholders, reinforcing the reliability of the food supply chain.

A Structural Equation Modeling (SEM) analysis shows that BCD has both direct and mediated positive impacts on the transparency of the agri-food supply chain. While blockchain directly improves transparency, its effects are further amplified through enhanced physical and information flows, leading to more effective supply chain management.

Limitations

The study was conducted within specific regions and involved certain stakeholders in Bangladesh, which might limit the generalizability of the findings to other areas or countries that have different agricultural and technological contexts. Additionally, the potential technological and logistical challenges associated with implementing blockchain technology, such as high setup costs, the complexity of the technology, and the necessity for stakeholder education, were not empirically assessed in this research. This omission could affect the feasibility and applicability of the study's recommendations in various settings.

Suggestions for Future Research

Future studies could explore the scalability of blockchain technology across other segments of Bangladesh's economy or in other countries with similar economic profiles. Research could also assess the long-term economic impacts of blockchain integration, weighing the initial costs against the long-term benefits. Additionally, further investigation into the resistance or challenges from existing intermediaries in adopting new technologies could provide deeper insights into the transition to more transparent systems. This broader approach would help understand the comprehensive implications of blockchain technology in different economic and cultural contexts.

Contributions of the Study

The findings from this research are anticipated to contribute valuable insights into the scalability and applicability of blockchain technology in enhancing supply chain transparency. By demonstrating the practical benefits of BCD integration in a critical sector of Bangladesh's economy, this study could serve as a model for other similar economies facing transparency and efficiency challenges. Additionally, the study aims to stimulate further research and discussion around the adoption of blockchain technology in other sectors and industries where transparency and efficiency are of paramount importance.

Furthermore, by addressing both theoretical and practical aspects of blockchain technology in the context of the ASC, this paper aims to bridge the gap between technological potential and its actual implementation on the ground. It also seeks to provide policymakers, industry stakeholders, and technology developers with a clear understanding of how blockchain can be strategically deployed to enhance not only economic outcomes but also societal well-being by ensuring food security, reducing waste, and promoting fair trade practices within the agri-food supply chain.

This comprehensive approach to examining the effects of blockchain technology in agriculture promises not only to advance the academic discourse but also to offer tangible solutions to some of the most pressing challenges facing the agri-food sectors in developing countries.

The agri-food sector is critical for a nation's economy, safety, nutrition, and health. However, transparency in the Agri-food Supply Chain (ASC) in Bangladesh is fundamentally lacking and plagued by numerous problems. The ASC process relies heavily on complex intermediaries, making it challenging to track origin, verify quality, estimate demand, manage inventory, and monitor fraudulent financial transactions, which increases food waste. Previous research has demonstrated that Internet of Things (IoT) technologies can address these concerns. However, a major vulnerability in the IoT system is that anyone with database access can potentially manipulate or change the data. This study scientifically proves that blockchain technology can protect IoT-generated data, thereby enhancing transparency in Bangladesh's agri-food supply chain. The integration of Blockchain Database technology into Bangladesh's agri-food supply chain holds significant promise for enhancing transparency and efficiency. While there are challenges to be addressed, the potential benefits of such integration, as demonstrated by this study, could catalyze broader economic and social improvements within the country.

Ethics approval and consent to participate: Before distributing the questionnaires, approval was obtained from the Graduate School of Business, Universiti Tun Abdul Razak (UNIRAZAK), Kuala Lumpur, Malaysia. Consent forms were signed to ensure ethical compliance. Respondents participated voluntarily. Ethics clearance was secured from UNIRAZAK. The privacy and confidentiality of respondents' information were maintained, and participation was not coerced. Formal measures ensured respondents understood the academic purpose of the study.

Data availability: Data generated for this study is available from the corresponding author on formal request.

Competing interests: The authors declare that they have no conflict of interest.

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