

The Integration of Blockchain Technology and Internet of Things in realising Sustainable Agro food Supply Chains: An insight into small to medium scale Soya Beans farmers in Mashonaland Central Province, Zimbabwe

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Abstract— The world population is projected to reach 9 billion by 2050, which is 34% higher than it is now and the demand for agricultural food is expected to increase as well. Research has shown that the demand for soya beans is on the increase owing to its contribution in cooking oil, stock feed and other by-products. On average, Zimbabwe's soya bean national output production is only enough to meet 30% of national demand, which is supplemented by imports from South Africa, Zambia and Malawi. Constraints in information gathering, storage, safeguarding, and sharing, environmental changes and escalations in input prices has become a catch phrase for soya bean supply systems failure. This study's objective is to explore strategies which can be adopted by soya bean small to medium scale farmers to realise sustainability in their supply chains and build food security in Mashonaland Central Province of Zimbabwe. This study therefore proposes the integration of Blockchain Technology (hereafter: BCT) and Internet of Things (hereafter: IoT) to improve sustainability in the soya bean supply chain systems in Zimbabwe. The researchers adopted a pragmatism research philosophy premised on the mixed methods research approach because quantitative data alone is not sufficient to answer the research questions. Quantitative data were analysed using STATA 15 and NVivo version 16 was used to analyse qualitative data. Using Krejcie and Morgan (1970) a sample size of 375 farmers was randomly selected to respond to questionnaires. Six (6) AGRITEX officers and two (2) Agronomists were purposefully selected from the six (6) districts of Mashonaland Central Province and were interviewed. Findings from the research showed that there is minimal uptake of Artificial Intelligence (hereafter: AI) technologies in soya bean supply chains in Mashonaland Central Province which has slowed the improvements in production and sustainability of agro-supply chains. The study recommends the integration of blockchain and IoT technologies to improve sustainability in soya bean production in Zimbabwe.

Index Terms— Block chain technologies, IoT technologies, Agro food, Supply chain

I. INTRODUCTION

Soya bean is known to be a strategic crop in the agricultural sector due to its various benefits when compared to other crops. Worldwide, the United States of America is the largest soya bean producer, contributing 32 % while Brazil, the second largest producer contributes 29% with Argentina producing 17% (Hamza, Basit, Shehzadi, Tufail, Hassan, Hussain & Hayat 2024; Pagano & Miransari 2020) Food and Agriculture Organization of the United Nations (FAO) 2023; Food and Agriculture Organization Statistics (FAOSTAT), 2023). In Africa, production of Soya beans contributes 1.3 percent of the total production in the World with South Africa being the biggest producer of soya beans. In Zimbabwe soya beans is an important crop that calls for more production to satisfy rising domestic and international demand (Tang et al., 2024). The demand outstrips the supply, opening opportunities for farmers to take advantage of. The growing of soya bean in Zimbabwe by small and medium scale farmers was catapulted by the fast-track land reform in 2000 where land that once belonged to commercial farmers was shared among small and medium farmers (A1 and A2) (Moyo, 2011; Chingwaru, Jaravaza, Mukucha, Risiro & Dangaiso, 2025). Soya bean is largely produced in Zimbabwe's Mashonaland provinces (East, Central and West) which fall under national regions i, ii and iii characterised by good soils and annual rainfall averaging 700mm which are conducive for soya bean production (Estehuizen, 2021). Research has shown that the production in 2019/2020 was estimated

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at 30 000 metric tons, while the demand was estimated to be 240 000 metric tons (U.S. Department of Agriculture, 2020). This translates to the amount of 200 000 metric tonnes that are required by the country for food, feed and other industrial uses are far from being met (Basera, & Mushoriwa, 2023). On the other hand, the soya bean contributes between 2% and 3% to the GDP while the whole agricultural sector contributes 30% (Food and Agriculture Organization (FAO), 2022).

Zimbabwean Small and Medium Enterprises (hereafter: SMEs) fill the gap that was left by large production companies (that closed down), by producing services and goods for Zimbabwe and beyond. SMEs are the source of economic development in Zimbabwe constituting 90% of the national economy in Zimbabwe (Musabayana, Mutambara, & Ngwenya, 2022). SMEs contribute significantly to Zimbabwe's GDP highlighting the need to give attention and support to these upcoming important firms. There is a need to increase production of soya beans with the use of new and improved agriculture technologies that include IoT, and BCT (Bhat, Huang, Sofi, & Sultan 2021). Food supply chains and agriculture are inextricably linked since the goods produced by agriculture are the inputs used in various supply chains where consumers are the final clients (Basera, & Mushoriwa, 2023). BCT and IoT integration in agricultural supply chains establishes trust and efficiency along the agricultural supply chains (Sharma, Samad, Chiappetta Jabbour, & de Queiroz 2025; Bosona & Gebresenbet, 2023; Bhat, Huang, Sofi, & Sultan 2021; Loukos, & Arathoon (2021). Global food chain supplies are based on multiple sectors and spread, involving multiple distinct players such as farmers, shipping corporations, distributors, and grocery stores. This involves a lot of data handled by players and hence the need for digital tools like BCT and IoT to manage and analyse it. Due to the changes in the digital landscape the SMEs in soybean production require a paradigm shift towards integrating BCT and IoT to be able to meet the demand of soybean output needed by the economy.

In Morocco, the integration of IoT is still limited to sensors (in agricultural fields, storage facilities, and transportation) with blockchain technology (for immutable, shared ledgers and smart contracts) is becoming a prominent architecture for comprehensive visibility and sustainable logistics in Agricultural and Food Supply Chains (AFSCs), (El Mane, Tatane & Chihab, 2024). This is similar to a recent study in New Zealand that revealed that blockchain, particularly in conjunction with IoT, enhances provenance, diminishes information asymmetry, and potentially facilitates sustainability KPIs, while practical implementation at scale remains constrained (Ellahi, Wood & Bekhit, 2024).

Soya beans are an important component of edible oil and stock-feed chains in Zimbabwe and a crucial rotation crop for soil health (Musabayana, Mutambara, & Ngwenya, 2022). In the 2023–2024 season, Mashonaland Central contributed around one-third of the nation's production, making it one of the top producing areas. This highlights the need for this region to pilot traceability initiatives among small and medium-sized farmers (IPAD, 2024). However, official figures show a year-over-year reduction in national output throughout the 2024–2025 season, highlighting the need for efficiency and market confidence through reliable data flows (ZIMSTAT, 2025). Similar data from other southern Africa regions demonstrates that smallholders have enduring digital obstacles, such as device access, connectivity fees, and digital skills, which are necessary for any IoT-blockchain implementation to be successful (Nxumalo & Chauke, 2025; Choruma et al., 2024).

The technological potential of blockchain-IoT stacks for Agro-Food Supply Chains (AFSCs) has been described in international studies, but little empirical research has been done to evaluate integrated deployments for soybean value chains in Zimbabwe, and none of it has examined small and medium-sized farmers in Mashonaland Central (Musabayana, Mutambara, & Ngwenya, 2022). Field experiments that quantify adoption costs, data governance, interoperability, and quantifiable sustainability results (e.g., waste, energy, GHGs) in low-connectivity conditions are few in the research currently in publication, which mostly relies on conceptual models and simulations (Tang et al., 2024; Ellahi et al., 2024). Furthermore, there is a void in studies that look at how these systems work with local organisations, assess the welfare effects and inclusion of farmers and assess compliance with new import traceability regulations, evidence that is becoming more and more important to international markets (Huang, Li, Xu, & Ma, 2025). Therefore, this study seeks to produce evidence-based information on the viability, adoption factors, and sustainability

effects of a blockchain-IoT traceability paradigm among small to medium-sized soya bean farmers in Mashonaland Central Province in Zimbabwe.

The rest of the paper will be organised as follows: Section 2 outlines the theory that guides this study and reviews the literature, section 3 presents the research method that guides this study and section 4 presents and discusses the results, while Section 5 concludes.

II. LITERATURE REVIEW

A. Theoretical framework

The study adopted a Transactive Memory Systems (TMS) theory perspective (Wegner, 1995) which is not confined to IoT only but includes issues such as transparency, trust, coordination of personal performance as well as group and the competitive advantages gained in the process. The theory also involves describing the combined structure that people in inter-relationships exercise to convert, store and retrieve information (Ren, 2010). It resonates well with the integration of BCT and IoT in the supply chain by linking customers and suppliers to realize benefits that come from purchasing, issuing and marketing of goods and services in a bid to create desired outputs (Keller, 2019).

B. Sustainable supply chains in soya bean Agro-food systems

Sustainable agro-food supply chains are defined as the full range of farms and firms and their successive coordinated value-adding activities that produce particular raw agricultural materials and transform them into particular food products that are sold to final consumers and disposed of after use, in a manner that is profitable throughout, has broad-based benefits for society, and does not permanently deplete natural resources (El Mane, Tatane & Chihab 2024). Sustainable food supply chains can alternatively be defined as food supply networks that provide food security and nourishment for everyone while ensuring that the economic, social, and environmental foundations for future generations are not jeopardized (Ellahi, Wood, & Bekhit 2024).

However, agro-food supply chains contribute to many environmental and social problems (Nxumalo, & Chauke 2025). The cultivation of agro food grains is usually associated with environmental effects such as soil erosion, loss of natural resources, excessive water consumption, deforestation, land pollution by pesticides and herbicides and logistical challenges (Awan, Ahmad, Khan, Safwan, Qurashi & Hashim 2021). This has created enormous pressure on the environment making it difficult to achieve sustainability in most agro-food supply chains in Zimbabwe (Nxumalo, & Chauke 2025). Currently the supply chains of agro food systems in Zimbabwe are not sustainable from an environmental and social point of view, as they are vulnerable due to climate change and poor supply chain performance. In order to solve these challenges, it requires a move towards more sustainable and inclusive supply chains in agro-food production using new and improved agricultural technologies (Kumarathunga, Calheiros and Ginige 2022). Therefore, sustainable agro food production requires collaboration along the supply chain as it allows organisations on different stages of the value chain to interact and share resources for the achievement of common goals (Bhat, Huang, Sofi & Sultan 2021).

Noteworthy, agro-supply systems are extremely complex, necessitating extensive information sharing throughout the value chain (Mukherjee, Singh, Mishra & Bag 2022). The adoption of emerging digital technologies enhances traceability which assures food safety across the supply chain (Awan, Ahmad, Khan, Safwan, Qurashi & Hashim 2021). In support to this, Choruma, Dirwai, Mutenje, Mustafa, Chimonyo, Jacobs-Mata & Mabhaudhi (2024), proposed that one of the facilitators for sustainable agricultural supply chains is the integration of scientific and technological applications like BCT and IoT, as well as the simple transfer of technology across stakeholders.

C. BCT in soya bean Agro-food supply chains

SMEs in the agro-food sector play a significant part in the expansion and growth of the global economy (Kumarathunga, Calheiros, & Ginige 2022). SMEs are said to be a solution to problems with economic growth and development, particularly in developing economies, as they transform and enhance communities (Omowole, Olufemi-Phillips, Ofodile, Eyo-Udo, & Ewim, 2024; Edobor & Sambo-Magaji, 2025). Technologies like blockchain, the IoT, and cloud computing have been developed in the fourth industrial revolution of today to provide limitless potential for a variety of applications and frameworks (Jain, Jain, Jaiswal, Ahmad, Kapse, & Bisht, 2025). Due to its many advantages, which include ease of task completion, control, process streamlining, cost reduction, efficient and effective record-keeping, transparency, and efficiency, blockchain has become the most widely accepted transformative technology (Stroumpoulis & Kopanaki, 2022). By 2025, 10% of the global economy, according to projections, will be utilizing blockchain technology (Karnaushenko, Tanklevska, Povod, Kononenko, & Savchenko, 2023). In Saudi Arabia, the use of blockchain technology is especially appealing to small businesses because it gives them a cost-effective and accelerated way to send and receive payments, access investment and savings products, and establish a credit history (Alshareef, & Tunio, 2022).

More so, blockchain is a new digital technology that enables widespread financial transactions between dispersed, interconnected networks of computers, and facilitates trustless and transparent data exchange without the use of middlemen like banks (Dong, Abbas, Li, & Kamruzzaman, 2023). According to Kamilaris, Cole, & Prenafeta-Boldú (2021), blockchain technology is a digital transaction record that is maintained by a network of several computer devices without the assistance of a reliable third party. This implies that specific software platforms are used to manage the individual transaction data files (blocks), allowing the data to be communicated, processed, stored, and represented in a way that is human readable. This is enhanced by Haskell (2022) who defines BCT as a digital system for securely storing trade transactions between numerous trading parties. Given that many SMEs in Zimbabwe produce grains, the soya bean supply chain requires the application of BCT and IoT technologies because they provide a dispersed and decentralized system of record keeping. Furthermore, incorporating BCT to IoT would significantly improve the efficiency and sustainability of SMEs' soya bean supply chains tracing how food from an agricultural field ends up on the table. Production, refinement, delivery, selling, consumption, and disposal are all topics covered by food supply chain management (Hugos, 2024; Jia, Peng, Green, Koh, & Chen 2020). Scholars argue that BCT enables the development of a distributed and forgery-proof record of transactions and has even been dubbed a "revolution" likely to be helpful in many industries, including the food industry. Greater access to this technology can encourage the expansion of SMEs, which in turn leads to the creation of jobs and economic growth (Hinojosa, Sanchez, Camacho & Arguello, 2023).

Furthermore, blockchain technologies can be used to support the trading and finance in supply chain management to improve the efficiency and dependability of supply networks in soya bean SMEs (Hugos, 2024). Regarding the status of soya bean harvests, inventory, and contracts, the BCT networks can be a trustworthy source of information (Sharma, and Singh, 2022). For instance, BCT is autonomous, open-source, decentralized, transparent, immutable, irreversible, ownership, provenance (authenticity and origin), and it automates tasks (Dong, Abbas, Li, & Kamruzzaman, 2023). Due to these features, different parties can conduct business at any time and from any location with absolute security.

When used in conjunction with smart contracts, BCT also enables timely payments among stakeholders and offers transparent traceability. This improves food supply networks by enabling stakeholders and consumers to follow the origins and handling of food items, (Bosona, & Gebresenbet, Ellahi, Wood, & Bekhit 2023;). Quick recall procedures and unchangeable records that guarantee information integrity increase safety. Additionally, by automating transactions and encouraging cooperation among supply chain partners, the system lowers costs and streamlines operations, Awan, Ahmad, Khan, Safwan, Qurashi & Hashim (2021).

In addition to the benefits already mentioned, BCT is special and has a lot of potential to establish swift confidence amongst the important players participating in the supply chains for disaster relief. Ellahi, Wood, & Bekhit (2023) developed a theoretical model to examine the effects of blockchain on operational supply chain transparency and collaboration. The author explored the transformative potential of smart contracts

within blockchain technology. They highlighted how these self-executing contracts, with the terms directly written into code, can automate and streamline various processes across multiple industries, including finance, supply chain management, and legal sectors. They also discussed the benefits of enhanced efficiency, reduced costs, and increased trust among parties due to the transparency and immutability of BCT (Ellahi, Wood, & Bekhit 2023).

Collaboration between partners made possible by blockchain smart contracts promotes effective and efficient real-time information exchange and offers many benefits, including increased transparency, flexibility, and short lead times, as well as assisting in the improvement of supply chain resilience (Hernandez, 2023). The proposed BCT adoption would assist strengthen the whole supply chain by transmitting all transactions and pertinent information throughout the entire network, resulting in secure, accurate, and open transactions as well as increased player confidence and efficiency (Awan, Ahmad, Khan, Safwan, Qurashi, & Hashim, 2021).

On the other hand, Pavithran, Al-Karaki, & Shaalan, (2021) focused on how supply chains are becoming less resilient in the era of information asymmetry, which occurs when one of the supply chain's players possesses a disproportionately large quantity of product knowledge compared to the others. They agreed that inaccurate or inconsistent data might lead to bad judgments and an increase in technological dangers like cybercrimes, hacking, and theft, all of which could be damaging to the reputation of the business (Ellahi, Wood, & Bekhit 2023). One of them, according to the authors, is fostering "confidence" among participants in the supply chain by using a decentralised system (Pavithran, Al-Karaki, & Shaalan, 2021). BCT can help address these issues with transparency, traceability, efficiency, and security by using smart contracts that are automatically activated when certain conditions are satisfied (Omowole, Olufemi-Phillips, Ofodile, Eyo-Udo, & Ewim, 2024).

Nonetheless, the implementation of BCT in supply chains is rife with challenges, including those relating to hardware and software needs, educational requirements, cost and security concerns, as well as a number of other issues (Jarial, 2023)). Also, the absence of a variety of resources, such as a skilled labor scarcity, a lack of capital, technological penetration, power outages, lack of proper infrastructure might make it difficult for SMEs to use BCT in soya bean supply chains (Dong, Abbas, Li, & Kamruzzaman, 2023). The vast amount of paper documents used in traditional supply chains can also lead to ineffective tracking and theft. So, it is important to figure out what influences SMEs' decisions to utilize blockchain technology and capitalising on the value produced by various technologies (Ayanwale, Adekunle, Kehinde, & Fatunbi, 2023). As a consequence, the shortcomings of one technology can be solved by another. The purpose of this chapter is to emphasise the benefits of integrating BCT with the IoT. Since increased access to these technologies can help SME growth and contribute to economic expansion and sustainability.

D. IoT in soya beans supply chains

The IoT is a new shift in digitisation which generates a lot of interest in current information communication technology spaces. It encompasses a range of disruptive digital technologies that impact on the lives of businesses and individuals as noted by Nanda & Kumar, 2024; Zengeya, Sambo & Mabika 2021)). IoT is basically made up of various interconnected devices that are joined together via the internet for facilitating the transfer of information without necessarily relying on the intervention of human beings (Khan et al 2021). The technology of IoT has been harnessed to connect computers to networks for communications and information exchange. A few billion smart things (devices) can be connected via the IoT. These intelligent objects may connect with some systems online and gather data at the same time.

The IoT has developed into a cutting-edge technology with many potential applications in agricultural settings. Agriculture has experienced a paradigm shift from precision to smart agriculture as highlighted by Saiz-Rubio & Rovira-Más (2020). IoT augers well with supply chains and specifically, logistics training has become a vital sector of IoT (Eltrinharn, 2022). The process of supply chain management is difficult and costly especially if things go wrong because this can have ripple effects affecting the whole industry. IoT facilitates the collection of data by logistics partners for improved incident response, improved inventory management

and improved transportation. Such capabilities can provide a platform for enabling machine learning models to come up with developed supply management solutions which can foretell challenges and help to save money and time while at the same time increasing the speed of responding to incidents (Pan & Zhang, 2021).

Zengeya, Sambo & Mabika (2021) postulates that using IoT in soya bean production enables SMEs to monitor their farms using soil moisture sensors and this was also supported by other writers, (Sujadi, Marina, Koswara, Indriana, & Sukmawati, 2023; Arditi, Camio, Velazquez, & Errandosoro, 2023). These provide an opportunity for farmers to make plans concerning the times for watering as well as which parts of the farm to irrigate. IoT enables effective remote monitoring of farms through timely monitoring of activities such as pest control, logistics and process operations using actuators and sensors. IoT may for instance enable accurate application of fertilizers and pesticides and also facilitate automatic weeding of soya beans using robots (Sujadi, Marina, Koswara, Indriana, & Sukmawati, 2023). IoT can help in monitoring of soya bean quality right from the time soya bean crops are transported from the field. This is done through monitoring, controlling and accessing the exact geographic location and shipment conditions of products (Saiz-Rubio & Rovira-Más, 2020).

Supply chain management is a process that involves many stages and many actors which can benefit from particular IoT facets (Sallam, Mohamed, & Mohamed 2023). IoT solutions may be adopted by soya bean producers for the monitoring of operations during production and checking the condition of equipment in time. Continued supervision may be helpful in picking out challenges and making the needful rectifications that may help in cutting downtimes and improving the utilization of assets and increase in production and also make useful contributions to sustainability (Sujadi, Marina, Koswara, Indriana, & Sukmawati, 2023).

IoT can be used in tracking the power and water used, IoT like BCT gives precision and transparency to the business of logistics since those who operate logistic companies can access real-time data concerning the location and status of assets (Sallam, Mohamed, & Mohamed 2023; Arditi, Camio, Velazquez, & Errandosoro, 2023). This data may be used to optimize the whole process of deliveries and thus avoiding delays in product delivery. IoT provides ways of effectively managing perishables and cold chains through the identification of changes from the recommended conditions of transportation. IoT also benefits producers as they utilize IoT for the effective handling efficiency and picking accuracy when loading and unloading goods and when tracking items on shelves thereby helping to make inventory more visible and helping to check and optimize traffic stores to improve the display of goods and utilization of space (Zengeya, Sambo & Mabika 2021; Sujadi, Marina, Koswara, Indriana, & Sukmawati, 2023). The diagram by Zengeya, Sambo & Mabika (2021), Figure 1 below shows some functions of IoT in agriculture:

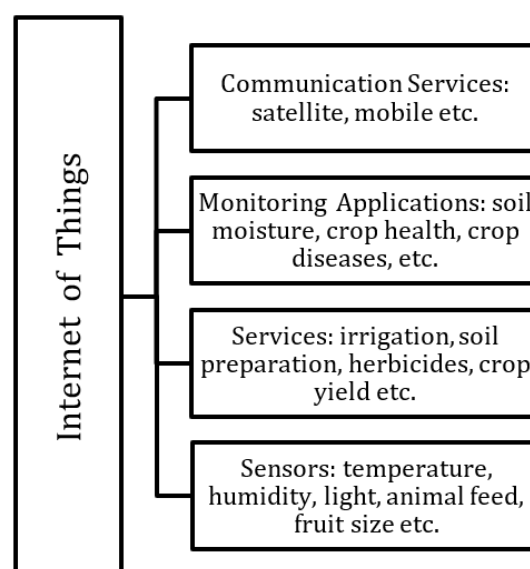


Figure 1 Functions of IoT in agriculture (adopted from Zengeya et al., 2021)

Figure 1 shows how IoT is applied and this is made up of four aspects which include sensors, communication services, services and surveillance services. Communication services comprise fixed mobile networks and internet data provided through satellite network services (Zengeya, Sambo & Mabika (2021). IoT devices enable a variety of data transmission methods, including 2G to 5G cellular networks that enable farmers to gather and communicate data without the assistance of humans. Sensors can be attached to farming equipment such as tractors, combine harvesters and irrigation equipment, (Saiz-Rubio & Rovira-Más, 2020). Implementation of this technology by Zimbabwean SMEs can go a long way in increasing productivity sustainably in agriculture.

E. Integration of BCT and IoT in Soya bean supply chains

Blockchain and IoT have emerged as smart technologies which provide sustainability in various supply chains. Integrating the two technologies results in transparency in supply chains (Hellani, Sliman, Samhat, & Exposito 2021). Transparency was a major issue in agro-food systems as there was no traceability therefore it was difficult to trace any kind of food contamination in the supply chain (Mukherjee, Singh, Mishra, & Bag 2022). When integrated, BCT and IOT allow organizations in the supply chain to track movement of products throughout the value chain. The efficiency of sustainable supply chains relies on trust which has led to many disruptions in the supply chain (Hellani, Sliman, Samhat, & Exposito 2021). Therefore, the integration of BCT and IOT acts as gate keepers of trust in the supply chain to increase traceability and reliability which will lead to greater sustainable supply chains (Hrouga, Sbihi, & Chavallard 2022; Hellani, Sliman, Samhat, & Exposito 2021).

III. METHODS

The researchers adopted a pragmatism research philosophy premised on the mixed methods search approach because quantitative data alone is not sufficient to answer the research questions. Pragmatism increases credibility of the results and strengthens the validity of findings through triangulation (Gobo, 2023; Meydan & Akkaş, 2024). An explanatory sequential design was adopted. This design was adopted by the researchers as they collected and analysed quantitative data before qualitative data. This was done to allow qualitative data to help explain and contextualize quantitative results. These researchers analysed the extent to which BCT and IoT has helped in realizing sustainability in the soya bean supply chains. Interviews were held with small scale Soya bean farmers to undertake a qualitative analysis. Qualitative data was used to explain the level of BCT and IoT integration by small scale Soya bean farmers involved in the agro-food industry in Zimbabwe. An inference to the problems they face was done using quantitative results.

A population of 16500 small scale soybean farmers was targeted and using Krejcie and Morgan (1970) sample calculator a sample of 375 respondents comprising farmers, Agritex officers and agronomists were selected from Mashonaland Central Province. Questionnaires were distributed to 367 small scale farmers and 350 were successfully completed giving a response rate of 95%. To save time and resources, from the total suggested sample of 375, purposefully, 6 AGRITEX officers and 2 Agronomists from the 6 districts in Mashonaland Central Province were interviewed to collect relevant data in exploring deep insights into the extent of BCT and IoT integration in the agro-food supply chains in Zimbabwe. Using questionnaires and Key Informant Interviews, the data collected in November, 2024. The information collected was for for the current and previous 10-year farming seasons of soya beans in the Province which is one of the key region in soya bean production in the country. Key informant interviews were done with AGRITEX officers, Agronomists and farmers from the selected sample. Quantitative data was analysed using STATA and NVivo was used to analyse qualitative data. A simple regression analysis was carried out to help analyse the relationship between the integration of BCT and IoT and realizing the sustainability of Soya bean supply chains and predicting the future outcomes of implementing BCT and IoT in the Agro-food industry in Zimbabwe (Kafle, 2019) OLS regress model was used to determine the relationship between the integration

of BCT and IoT and realizing sustainable supply chains in Mashonaland Central, Zimbabwe. For robustness check, OLOGIT and OPROBIT regression models were also used.

Regression model

$$SSSC = \beta_0 + \beta_1 BCToT_IntIndex + \beta_2 6_{10year} + \beta_3 Above_{10yrs} + \beta_4 "O_Level + \beta_5 Cert + \beta_6 Dipl + \beta_7 Degree + \beta_8 PostGrad + \varepsilon$$

Dependant Variable

SSSC is Sustainable Soya-bean Supply Chains which is anticipated to improve the quality management of soya-beans produced in Mashonaland Central province through transparent and techno-efficient agri-food supply chains. The dependent variable is measured on a 3-point likert scale with 1 representing lower extent, 2 middle and 3 greater extents.

Independent Variables

BCTIoT is the integration of BCT and IoT as disruptive technologies in the soya-bean supply chains, in order to increase their efficiency and innovativeness through knowledge flows and information gathering from all the supply system players.

Exp is the number of years the farmer has been farming soya beans. The number of years were grouped into three categories, 0-5 years, 6-10 years and 11 years and above into soya beans farming. Ed is the level of education of the farm owner/manager that may affect the decision to implement the integration of BCT and IoT in their supply chain. Experience and level of education are control variables used to test the robustness of the simple linear regression results.

IV. RESULTS AND DISCUSSION

In analyzing the questionnaire, the researcher used the respondent characteristics as a set of controls to examine how integration of BCT and IoT variables affected sustainability in agro-food supply chains in soya bean production. It should be highlighted that respondent information may have an impact on how sustainable agro-food supply chains in soya bean production are; as a result, their impact needs to be isolated (Tang et al, 2024). Experience and level of education of research respondents were all controlled for. As a result, neither an interpretation nor a discussion of the results for these variables shown in Table 2 will be made.

Table 1 presents the results of regression analysis for BCT on sustainable agro food supply chains. The Table displays the OLS, OLOGIT, and OPROBIT estimations that were obtained when the questionnaire data was analysed. The model's robustness was tested using OLOGIT and OPROBIT regression analysis (Gobo, 2023). The OLOGIT and OPROBIT models in Columns 2 and 3 of Table 1, respectively, revealed that the findings did not change substantially, indicating that the model is appropriately defined. This is also confirmed by a high R-squared of 0.758.

Table 1: OLS, OLOGIT and OPROBIT estimates: Impact of integration of Blockchain technology and IoT on sustainability of Soya bean supply chains

	OLS	OLOGIT	OPROBIT
VARIABLES	(1)	(2)	(3)
IBCTIoT_Integration Index	0.714***	0.682***	0.692***
	(0.169)	(0.528)	(0.723)
6-10 years	-0.0262	0.0876	-0.0783
	(0.276)	(0.761)	(0.793)
11 years and above	-0.0638	-0.3190	-0.742
	(0.112)	(0.791)	(0.533)
O Level	0.318	0.669	0.562
	(0.207)	(0.736)	(0.197)
Certificate	0.378***	1.219***	1.020***
	(0.275)	(0.482)	(0.319)
Diploma	0.0882	0.397	0.567
	(0.287)	(1.413)	(0.583)
First degree	0.0306	0.596	0.817
	(0.5887)	(1.027)	(0.076)
Post Graduate	0.267	0.227	0.336
	(0.265)	(1.003)	(0.771)
Constant	0.423***		
	(0.670)		
Observations	350	350	350
R-squared	0.658	0.567	0.678

Robust standard errors in parentheses

*** $p < 0.01$ (Significant at 1%), ** $p < 0.05$ (Significant at 5%), * $p < 0.1$ (Significant at 10%)

The results in Table 1 reveal a significant positive correlation between the Integration Index variable and sustainability in agro-food supply chains in soya bean production variable at 1 % level of significance. It follows that the larger population also exhibits the association found in the study. This indicates that as the value of integration of BCT and IoT variables improves by 1 unit, the sustainability of agro food supply chains variable tends to improve by 71%. This is in tandem with Sujadi, Marina, Koswara, Indriana, & Sukmawati (2023) and El Mane, Tatane, & Chihab (2024) who indicated that the emergency of BCT and IoT has potential

to improve supply chain operations' flexibility and agility resulting in more sustainable ways of cultivation of soya beans. In other words, the integration of IoT and BCT into sustainable soybean supply chains presents numerous positive effects that enhance efficiency, transparency, and environmental stewardship. IoT devices, such as sensors and smart devices, enable real-time monitoring of various factors throughout the supply chain, including soil health, crop conditions, and transportation logistics. This data-driven approach allows farmers to optimize resource usage, reduce waste, and implement precision agriculture techniques. Leveraging IoT, stakeholders can make informed decisions that lead to higher yields and improved sustainability, (Happy, Chowdhury, Scerri, Hossain, & Barua, 2023; Pabitha, Benila & Suresh, 2023; Reddy, 2021). Blockchain technology complements IoT by providing a secure and transparent ledger for all transactions and activities within the supply chain. This immutable record fosters trust among all participants, from farmers to consumers. Tracking the origin of soybeans and verifying sustainable practices, blockchain enhances traceability and accountability. Furthermore, the synergy between IoT and blockchain facilitates better collaboration among supply chain partners. The combined power of IoT and blockchain fosters a more resilient and sustainable soybean supply chain, benefiting both the environment and the economy (Madumidha, Ranjani, Vandhana, & Venmuhilan 2019).

This was further supported by informant no.1 an AGRITEX officer who confirmed that the quality of soya bean they are receiving from contract farmers is of high-grade quality. He attributed this to the integration of BCT and IoT into the supply chain system that has been put in place by private contractors. The private contractors work in collaboration with insurance companies to monitor plant progress, soil moisture content, leaf quality, pests and diseases and time management to ensure double cropping. This results in real time harvesting of high-quality soya beans. There is monitoring and tracking of the field from the office using UV indexing which sends signals for any anomaly resulting in proactive responses. For example, if crops are affected by a crop disease outbreak or flooding affecting crop yield the insurance will be aware as they are able to check the fields of all their contracted farmers in real time. This has eliminated conflicts during claim settlement.

Key Informant 4, an agronomist was in support of the above when he explained the type of IoT that they employ in their farming to monitor progress. He indicated the extent of integration between farmers, private contractors and insurance through the use of software packages like Soil Procs which provides real time satellite images to view the extent of damage caused by perils on soya bean fields. This is in agreement with Jia, Peng, Green, Koh, & Chen (2020) who state that the use of BCT enables all stakeholders in the soybean ecosystem to actively engage, share, and verify all types of information and data provided by farmers to come up with more sustainable methods of cultivating soybeans. The positive relationship between BCT and agricultural production is well supported by many writers, (Lin, Huang, Fang, Wang, Hua, Wang, & Yau 2020; da Silva & Sehnem, 2025; Camel, Belhadi, Kamble, Tiwari, & Touriki, 2024; Jain, G., Jain, Jaiswal, Ahmad, Kapse, & Bisht 2025).

Informant no 5 from the AGRITEX department expounded that the integration of BCT and IoT in their supply chain has resulted in the interconnectedness of their farming control systems in detecting low soil moisture levels. They use a remote-control sensor which is linked to the irrigation system. A pivot sensor sends signals that trigger the irrigation motor whenever the soil moisture content drops below recommended levels. Zengeya, Sambo & Mabika (2021) weighed in support and added that the use of IoT enables SMEs to monitor their fields through the use of softwares like dielectric soil moisture sensors that enable farmers to plan irrigation times. Informant no.8, another AGRITEX officer further explained that the use of remote sensors has resulted in effective quality control and output when it was done physically.

One informant, another AGRITEX officer, indicated the use of Whatsapp platforms as a form of technology used by AGRITEX officers and farmers to share information reminding each other of the onset of the farming season, advice on outbreaks of pests and diseases. They use Open Data Kit (ODK), an internet data collecting software loaded to a server. Information on area planted, estimated yield and post-harvest evaluation can be shared on the website to ensure a quality harvest. It is a form of private blockchain that integrates only users with login details. He further elaborated that IT infrastructure development in terms of BCT and IoT technologies is still at its minimal as there is no platform that allows for the tracing of movement of soya

beans along the supply chain. Once the commodity leaves the farmer, there is no information sharing along the value chain. The product cannot be traced back to its point of origin like it is the case with the Tobacco value chain. This has resulted in soya bean farmers receiving low payment from private buyers who will come back and complain about low moisture and nutrients content after delivery of supply. This is as a result of the absence of AI powered equipment for detection at point of production. This is supported by Loukos, & Arathoon (2021) who states that the integration of BCT and IoT in the agricultural supply chain establishes trust and efficiency. The case is different with contracted farmers as they are linked with bigger reliable buyers like Grain Marketing Board (GMB) who allow tracking of product movement, inputs quality, verification and insured transporters. Insignificant variables were not discussed however, education level tends to positively affect the dependent variable, sustainable soybean supply chains. The certificate was found to be significant at 1% level of significance. Education plays a crucial role in enhancing sustainable soybean supply chains by equipping stakeholders with the knowledge and skills necessary to implement best practices in agriculture, resource management, and environmental stewardship, Lei & Yang (2025). Educating farmers about sustainable farming techniques, such as crop rotation, integrated pest management, and soil conservation, they can improve yield while minimizing environmental impact. Additionally, training programs can raise awareness about the importance of traceability and certification, enabling producers to meet consumer demand for responsibly sourced products. Moreover, educating supply chain partners, such as distributors and retailers, about sustainability practices fosters collaboration and innovation throughout the chain. As a result, a well-informed workforce can drive the adoption of sustainable practices, ultimately leading to a more resilient and eco-friendly soybean supply chain that benefits both the economy and the environment.

V. CONCLUSIONS AND RECOMMENDATIONS

Therefore, it is prudent for this study to conclude that there is insignificant integration of BCT and IoT in the SMEs soya bean supply chain except for the few under contract farming. This is as a result of the unavailability of AI powered infrastructure in Mashonaland Central Province, Zimbabwe. There is potential for the adoption of the integration of BCT and IoT in the soya bean supply chain as evidenced by the use of soil moisture sensors, though they only integrate a few supply chain players. However, the high costs associated with setting up BCT and IoT infrastructure remains a deterring factor. The soya bean supply chain still lags behind in the development and adoption of BCT and IoT technologies and this has left a gap in building sustainability and food security in the agro food supply chain. The researchers further recommend that the policy makers should craft a 4IR policy that ensures efforts to exploit current opportunities to deploy emerging technologies in Soya bean farming provinces and reinforce industrial productivity. This should begin with compliance standards regulations being stipulated by the relevant department of agriculture. It should be a requirement for a farmer to operate at large scale and qualify to supply big buyers.

There is also a need for future researchers to explore the challenges and solutions that reduce the pace of the implementation of BCT and IoT in the soya bean farming in Zimbabwe. This is necessitated by the fact that there are various factors that need to be ironed out for the implementation to be a success. This requires a holistic approach that will incorporate all stakeholders in the agro value chain system.

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Integracija tehnologije veriženja blokov in interneta stvari pri uresničevanju trajnostnih oskrbovalnih verig s kmetijskimi proizvodi: vpogled v majhne in srednje velike pridelovalce soje v provinci Mashonaland Central v Zimbabveju

Povzetek — Po napovedih bo svetovno prebivalstvo do leta 2050 doseglo 9 milijard, kar je 34 % več kot zdaj, prav tako pa se bo povečalo tudi povpraševanje po kmetijskih živilih. Raziskave so pokazale, da se povpraševanje po soji povečuje zaradi njenega prispevka v kuhinjskem olju, krmi za živino in drugih stranskih proizvodih. Povprečna nacionalna proizvodnja soje v Zimbabveju zadostuje le za 30 % nacionalnega povpraševanja, ki se dopolnjuje z uvozom iz Južne Afrike, Zambije in Malavija. Omejitve pri zbiranju, shranjevanju, varovanju in izmenjavi informacij, okoljske spremembe in povečanje vhodnih cen so postali ključni dejavniki za neuspeh sistemov oskrbe s sojo. Cilj te študije je raziskati strategije, ki jih lahko sprejmejo mali in srednji pridelovalci soje, da bi dosegli trajnost v svojih oskrbovalnih verigah in zagotovili varnost preskrbe s hrano v provinci Mashonaland Central v Zimbabveju. Ta študija zato predlaga integracijo tehnologije BlockChain (BCT) in interneta stvari (IoT) za izboljšanje trajnosti v sistemih oskrbovalne verige soje v Zimbabveju. Raziskovalci so sprejeli pragmatični raziskovalni pristop, ki temelji na kvantitativnih in kvalitativnih podatkih, saj kvantitativni podatki sami po sebi ne zadostujejo za odgovor na raziskovalna vprašanja. Kvantitativni podatki so bili analizirani z uporabo programa STATA 15, za analizo kvalitativnih podatkov pa je bila uporabljena različica 16 programa NVivo. Na podlagi Krejcieja in Morgana (1970) je bila naključno izbrana vzorčna skupina 375 kmetov, ki so izpolnili vprašalnike. Šest (6) uradnikov AGRITEX in dva (2) agronoma so bili namensko izbrani iz šestih (6) okrožij province Mashonaland Central in so bili intervjuvani. Rezultati raziskave so pokazali, da je uporaba tehnologij umetne inteligence (AI) v oskrbovanih verigah soje v provinci Mashonaland Central minimalna, kar je upočasnilo izboljšave v proizvodnji in trajnosti kmetijskih oskrbovalnih verig. Študija priporoča integracijo tehnologij blockchain in IoT za izboljšanje trajnosti proizvodnje soje v Zimbabveju.

Ključne besede – Tehnologije verižnih blokov, tehnologije IoT, kmetijsko-živilski sektor, dobavna veriga

APPENDIX 1: QUESTIONNAIRE

QUESTIONNAIRE

THE INTEGRATION OF BLOCKCHAIN TECHNOLOGY AND INTERNET OF THINGS IN REALISING SUSTAINABLE AGRO FOOD SUPPLY CHAINS IN SOYA BEAN PRODUCTION. AN INSIGHT INTO SMALL SCALE TO MEDIUM SCALE FARMERS IN MASHONALAND CENTRAL PROVINCE, ZIMBABWE

Section A: Organisational Characteristics

1. Number of years in Soya bean production/manufacturing

0-5 years	01
6-10 years	02
11 years and above	03

2. Educational Level

Grade seven	01
O'Level	02
Certificate	03
Diploma	04
Degree	05
Masters	06
PhD	07

Section B: Realising Sustainability in Soya bean Supply Chains in Mashonaland Central Province

Exploring the extent of sustainability of Soya bean supply chains in Mashonaland Central Province

In the following section, please indicate the sustainable supply chain practices that are being implemented by your organisation.

(1=Strongly Disagree 2= Disagree 3=Neutral 4=Agree 5=Strongly Agree)

Statement	Please tick against relevant response				
	1	2	3	4	5
2.1. Our organisation turnover has been on the increase in the last five years.					
2.2. Our organisation has been experiencing constant growth for the past five years.					
2.3. Our organisation has been developing new infrastructure in the last five years					
2.4. Our organisation has an effective environmental management system					
2.5. Our organisation has a functional waste management system.					
2.6. Our organisation has a waste reduction system.					
2.7. Our organisation ensures operations reduces energy consumption and emissions.					
2.8. Our organisation has a functional corporate social responsibility performance system					
2.9. Our organisation has a functional health and safety performance system					
2.10. Our organisation priorities long term relationships with our suppliers.					

2.11. Our organisation priorities long term relationships with our customers.					
2.12. Our organisation ensures upholding customer relationship management.					
2.13. Our organisations has a system in place to cater for demand uncertainties.					
2.14. Our organisations has a system in place to cater for supply uncertainties.					
1.15. Our organisation has a system in place to measure business process effectiveness.					

Section 3: Integration of BCT and IoT

Estimate the degree of integration of BCT and IoT in the soya bean supply chains in Mashonaland central province.

For the following question use the below scale to respond to the questions, tick against the chosen number:

(1=Not at all 2= Slightly 3=Average 4=Significant 5=A great deal)

Statement	Please tick against relevant response				
	1	2	3	4	5
2.1. Our organisation uses ledger technology to ensure integrity.					
2.2. Our organisation uses ledger technology to improve transparency.					
2.3. Our organisation uses ledger technology to improve traceability.					
2.4. Our organisation uses ledger technology to ensure security and privacy.					
2.5. Our IoT system is uniquely identifiable remotely to ensure scalability.					
2.6. Our IoT system is heterogeneous, capable of connecting devices from different systems and protocols.					
2.7. Our IoT system is has the ability to support increasing number of connected devices without degradation in quality of service.					
2.8. We pay particular attention to the security risks of our IoT system.					
2.9. Security of our IoT systems is very important to us.					

2.10. Information of our supply chain operations are protected sufficiently.					
2.11. Our traceability system can effectively identify and trace product purchase to delivery.					
2.12. Our supply chain partners can be identified through our traceability system.					
2.13. Our traceability system is able to identify and trace product purchase to delivery.					

Thank you