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The Impact of Blockchain Adoption on Circular Supply Chain Performance: Mediating Roles of Transparency and Traceability

Dr. Syama K. S.[1], Divyasree M.[2]

[1,2]*CET School of Management, College of Engineering Trivandrum*

Abstract **– Emerging technologies such as blockchain hold significant potential to facilitate the transition from traditional linear supply chains to more sustainable circular supply chains. However, there is only a limited empirical evidence for how blockchain adoption affects circular supply chain performance. Hence, this study aims to explore the effect of blockchain adoption on circular supply chain performance by promoting transparency and traceability within the system. A quantitative explanatory research design was employed, and primary data was collected from 135 supply chain professionals across diverse industries using a structured questionnaire. The data is analysed using Partial Least Squares - Structural Equation Modelling (PLS-SEM) technique with SmartPLS software. The findings of the study reveal that blockchain adoption significantly improves traceability and transparency of circular supply chains and has a direct positive impact on the circular supply chain performance. However, traceability act as the mechanism that mediates the relationship between blockchain adoption and circular supply chain performance and transparency do not influence the circular supply chain performance. These results suggest that the blockchain adoption enhances circular supply chain performance primarily by improving traceability within the system.**

Keywords **- Blockchain Adoption, Circular Supply Chain, Traceability, Transparency**

I. Introduction

In today's world businesses are struggling with piling wastes and reduced resources. According to the UN, by 2050 the solid waste generation is expected to grow from 2 billion to 3.4 billion. The traditional linear supply chain which is based on the model of take, make, use, and dispose contribute a majority to this waste generation (Challa, 2023). Industries around the world that follow the linear supply chain system are struggling with rising waste levels, unsustainable resource consumption, lack of transparency and traceability. This growing waste crisis, along with the concerns over resource constraints has led to a transition towards a more sustainable supply chain. That is organizations should shift from the conventional model of supply chain to a more sustainable circular economy model (El Wali, 2021).

Circular supply chains at the core aims to minimize waste and maximize the usage of resources. The circular supply chain mainly highlights on sustainability and incorporates concepts like reuse, reduce and recycle (Kristofferson et al., 2020), (Parida et al., 2019). Now the concept of circular supply chains has moved from 3R to 9R, they are recycled, reuse, remanufacture, reduce, recover, repair, refurbish, rethink and repurpose (Kazancoglu et al., 2021). The circular supply chain creates a close loop structure where materials are kept on reusing until their end life. This helps in reducing wastes, saves raw materials, and the lowers chances of pollution (Kayikci et al., 2022). It also helps companies in cost cutting by using materials for longer period instead of relying on new. It also ensures that there is no harm to the environment. Thus, moving toward circularity is essential not only for environmental reasons but also for economic and strategic sustainability (Kristoffersen et al., 2020).

Despite having these advantages, the circular supply chain implementation faces challenges in implementing it which includes challenges like ensuring transparency of information where suppliers, manufacturers, regulators, and consumers rarely share a common view of data (Polvora et al., 2020). This can result in inefficiencies, mistrust, and duplication of information. The next challenge is ensuring traceability in which it is often difficult to track how and where recycled or reused materials are sourced and processed. Without reliable data there are chances that organizations may manipulate or fake data. This may affect the consumer trust and reduce the efforts of sustainability.

New studies have shown that integrating Industry 4.0 Technologies like Artificial Intelligence, Blockchain and Internet of things plays an important role in enhancing the functioning of Circular supply chains (Kazancoglu et al., 2021). Hence to address these challenges the blockchain technology has evolved into a tool that can enhance the functioning of Circular supply chains. The Blockchain Technology is a promising technology that can be integrated to support strategy, sustainability and business in overall (Bai et al., 2020). The Blockchain technology with its decentralized, irreversible ledger system, ensures safe, transparent and secure data sharing across the network.

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Blockchain creates tamper-proof digital ledgers that track the origin and movement of materials across the supply chain (Keogh et al., 2021). This ensures that once data is recorded, it cannot be altered or deleted (Upadhyay et al., 2021). Blockchain therefore is a database that contains various information related to transactions with specific protocols (Niranjanamurthy et al., 2019). The decentralization characteristic of blockchain helps to, rather than storing data in a central database, it builds a shared, transparent system where no single party holds all the control. This reduces the risk of fraud and improves stakeholder collaboration. Apart from this blockchain in circular supply chain helps to improve its transparency, traceability, data security and immutability (Tsolakis et al., 2021).

Even though, Blockchain technology has many benefits, its impact largely depends on how well it improves two critical factors transparency and traceability (Paul et al., 2021). Transparency indicates the real-time sharing of information among stakeholders such as suppliers, manufacturers, regulators, and consumers which enhances the monitoring of sustainability efforts (Centobelli et al., 2020). Traceability, refers to the ability to track the movement of materials across the supply chain, from raw material sourcing to using, reusing and recycling (Guercini et al., 2019).

These two variables are important for circular supply chains, because its helps to verify the origin and circulation of materials throughout the supply chains. Even though there are many theoretical papers regarding this there are only a very few empirical studies that have studied the mediating role of transparency and traceability in the relationship between blockchain adoption and CSC performance (Wang et al., 2020). Hence this study aims to explore the impact of blockchain on circular supply chains performance with mediating roles of transparency and traceability.

Research Objectives

The objectives for the study are as follows:

1. To assess the role of Blockchain adoption in enhancing transparency within circular supply chain performance.
2. To evaluate the contribution of Blockchain adoption in improving traceability in circular supply chains performance.
3. To examine the impact of Blockchain technology adoption on the performance of circular supply chain.

II. Literature Review

Circular supply chain is viable solution for the negative effects of linear supply chains (Younis et al., 2020).

The aim of circular supply chain is to attain a zero-waste, resource efficiency by integrating all supply chain functions and collaborating with stakeholders. Blockchain technology is considered as an important driver of circular supply chains because it improves the transparency, traceability, and overall circular supply chain efficiency (Paul et al., 2021; Wang et al., 2023). Blockchain is a database that can be relied on because it contains all the data transactions from a certain period. The Blockchain is secured via fingerprint verification so that there no kind of tampering that can take place and the information validity is assured (Tian, 2016). The Blockchain is also a decentralized network that which helps to keep the data transparent. Blockchain technology is been mainly used to various sectors, such as finance, healthcare, agriculture (Cao et al., 2020). Big companies like Wal-Mart have implemented blockchain onto their Supply chain functions in order to monitor product management, stock tracing, and enhance quality management (Pal and Kant, 2019). In conclusion by integrating Blockchain technology in supply chain management we can say that BCT helps in the evaluating the detailed flow of all financial transactions that is taking place across the whole of supply chain, that is transparency is ensured (Olatunji, 2019).

Since all the processes are taking place over the internet, it helps to reduce any kind of physical transactions are taking place. The transactions happening across the supply chain is always monitored, analysed and approved by the relevant stakeholders. Any kind of unwanted interferences can be avoided, usage of blockchain technology can improve the supply chain in several ways. It increases productivity, shortens lead times, and enhances customer service and relationships with supply chain partners. Additionally, integrating blockchain into supply chain management can boost innovation and support operations (Luay, 2023).

The usage of BCT in supply chain is not only confined to a particular industry but it can be applied to every kind of supply chains. For example, the blockchain-enabled system architecture developed in the work for fast-fashion sector circular supply chain management by Wang et al., 2023. Likewise, Pharmaceutical supply chains (PSC) deliver medicine to various groups, including biotech companies, health regulators, pharmacies, hospitals, and patients (Ghadje et al., 2022). This study looks at how Blockchain can connect with PSC and creates a framework for implementing it in the pharmaceutical industry and identifies the reasons for and against adopting Blockchain, the stages of implementation, and its potential applications based on a thematic analysis. Blockchain is one of the upcoming digital technologies and is known for its number of properties. The study mainly looks into the use of blockchain in the supply chain of healthcare industry.

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The main objective of this study was to understand how blockchain technology (BCT) will help in the improvement of performance of healthcare supply chain management (HSCM) (Vishwakarma at al., 2022). In the production process, traceability is essential, especially in the textile and apparel sector, as it addresses the problems like transparency and information gaps. While stakeholders suffer dangers from unsafe data sharing, customers find it difficult to make ethical purchases or confirm authenticity. This paper suggests that a blockchain-based system for monitoring the supply chain for clothing and textiles. It models network architecture and interactions using smart contracts and transaction validation rules, allowing for improved tracking and transaction verification in a distributed system (Agarwal et al., 2021). In conclusion the usage of BCT in supply chains is very crucial and essential to maintain the transparency and traceability.

Supply chain transparency is about how much a member in the supply chain has the access to information about the fund flow, product flow without any kind of hindrances (Beulens et al., 2005). Tracking of products is essential element as far as a supply chain is concerned. A system that is transparent will allow to access the origin, details of all raw materials, equipment and materials. By doing so it also helps the stakeholders to have an access to the information (Centobelli et al., 2020). Traceability is also another important aspect in the supply chain. All the information that is related to the product can be accessed by offering a traceable supply chain system (Guercini & Runfola, 2009). A supply chain system is found to be effective when it is flexible and responsive to identify any risk elements present and when it is capable of recalling the products that are said to be unsafe (Mc Carthy et al., 2018). Ensuring transparency and traceability within the supply chain is an important criterion, hence integrating BCT within the supply chain helps to enhance the transparency and traceability within the supply chain (Despoudi, 2021), (Treiblmaier, 2018). The study Ghode et al., 2020 explains that using blockchain technology in supply chains creates a decentralized database that allows direct transactions which there by helps to improve transparency in supply chains which leads to coordination between suppliers and consumers.

This document emphasises on these factors and also examines the main barriers in implementation of these, some of which include high costs, lack of specialized expertise, and regulatory issues with a call for further research and practical insights to resolve these challenges (Saberi et al, 2019). The benefits of blockchain for the circular economy (CE) is examined in the article through its enhancement of performance of reverse omnichannel solutions and closed-loop supply chains (CLSC).

Blockchain enhances operational and service capabilities for businesses, increasing corporate performance by enhancing security, transparency, and traceability. Also, it draws attention to how incentives, smart contracts and active return methods, will help to promote CE practices (De Giovanni et al, 2022). The BCT can be applied to various stages of CSCM. According to (Wang et al.,2020) in the procurement process BCT can be used to evaluate the life cycle of the product so that the process of procurement allows the stakeholders to enhance the resource efficiency. Reverse logistics is an important factor in circular supply chain. The BCT technology also helps to enhance the functioning of reverse logistics. Recycling of wastes, recovery and reuse of products and materials are the main factors associated with the reverse logistics. Using the traditional method, it is difficult to get precise information about the materials and products. This issue can be resolved using the BCT technology as all the transactions can be traced out using BCT. This also helps the stakeholders to monitor the transactions (Lo et al., 2018). The circular economy mainly focuses on using resources efficiently and protecting the environment. Blockchain technology supports these principles in supply chains. The paper identifies 10 key factors for successfully implementing blockchain in supply chains. The authors conducted a systematic review and analyzed the factors using fuzzy cognitive mapping and the fuzzy best-worst method (FCM-FBWM) (Kayicki et al., 2022). The study of integrating BCT to CE principles is not only limited to certain industries. The study by (Mukahrjee et al., 2022) investigates the feasibility of integrating this to MSME's in Indian scenario. Sharing, reusing, repairing, refurbishing, and recycling current resources and products for as long as possible is the main concept followed by the circular economy. Although the blockchain-based circular economy is being implemented in many industries throughout the globe, Indian electronic MSMEs have numerous problems when attempting to implement this model. Finding the obstacles that electronic MSMEs encounter when implementing a blockchain based circular economy was the goal of this study.

III. Theoretical Framework And Hypothesis Development

The theoretical framework presented shows the hypothesized relationships among the independent, mediating and dependent variables (Rowley and Slack, 2004). In this study the Blockchain adoption stands for the independent variable, transparency and traceability are the mediating variable and circular supply chain performance is the dependent variable. Blockchain technology which is a distributed ledger technology is a system that helps in

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sharing of data on a point-to-point network (Rejeb et al., 2021). Blockchain technology incorporates various members of a supply chain and it is validated using a cryptographic mechanism (Crosby et al., 2016). Blockchain technology is a safe way to store and preserve data. After being developed and approved by all parties, a blockchain is considered immutable and cannot be altered (Upadhyay et al., 2021). Transparency in a supply chain is the ability through which all the participants in the supply chain and all stakeholders can access the information (Paul et al, 2022). Traceability in supply chain ensures and enables tracking of information about the products from their manufacturing until its distribution. When all stakeholders in a supply chain work together to apply circular economy (CE) principles, they can create new business models and improve supply chain processes to eliminate waste. Ideally, this means reusing and upcycling resources at every stage of the supply chain to achieve a no-waste system. This is called the circular supply chain management (CSCM) (Wang et al.,2020). The figure 1 depicts theoretical framework proposed at a part of this study. It shows that adopting blockchain technology can directly improve circular supply chain performance and also through the mediating variables transparency and traceability.

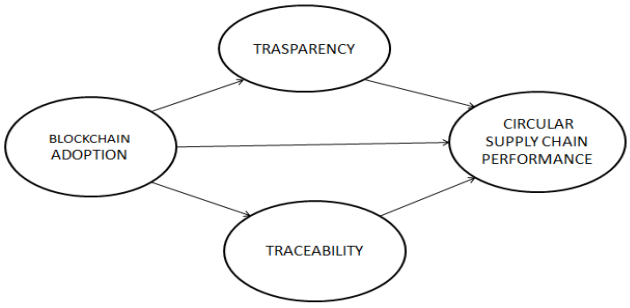

Figure 1. Theoretical Framework

3.1 Research Hypothesis

- H1: Blockchain adoption has a positive effect on enhancing transparency of circular supply chain performance.
- H2: Blockchain adoption has a significant positive effect on enhancing traceability of circular supply chain performance.
- H3: Blockchain adoption has a significant positive effect on achieving circular supply chain performance.
- H4: Transparency has a positive effect on enhancing the circular supply chain performance.
- H5: Traceability has a positive effect on enhancing circular supply chain performance.
- H6: Traceability mediates the relationship between blockchain adoption and circular supply chain performance.
- H7: Transparency mediates the relationship between blockchain adoption and circular supply chain performance.

IV. Research Methodology

A quantitative research design was adopted, with data collected from over 100 supply chain professionals across various industries using a structured questionnaire. The study mainly focused on employees working in the supply chain department across India to gain insights into the role of blockchain in the circular supply chain. The sample size was determined using the formula recommended by (Hair et al., 2010), which suggests that the minimum number of responses should be five times the number of questionnaire items. Since the questionnaire contained 27 questions, the required sample size was calculated as 135 (27*5=135). Primary data was collected through a structured questionnaire, which was designed to capture relevant information on the topic. The questionnaire was distributed via Google Forms to facilitate easy participation and efficient data collection. For data analysis, Partial Least Squares Structural Equation Modeling (PLS-SEM) software.

V. Results And Discussions

5.1 Measurement Model

The factor loadings, AVE value, Cronbach alpha and composite reliability value were analyzed using the PLS SEM software. These measurements are required to establish the reliability and validity of a model. The Cronbach alpha and the composite reliability are tested to measure the internal consistency whereas, AVE is measured to analyse the convergent validity. The Convergent validity is used to measure the statistical relationship between two items that measure the same construct (Ahmed et al., 2019). The Cronbach alpha values for each variable should be greater than 0.70. Also, the AVE value of variable should be greater than 0.50 (Hair et al., 2006). The test results are presented in Table: I.

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Table. I
Construct Reliability and Validity

	Cronbach's alpha	Composite reliability (rho a)	Composite Reliability (rho c)	Average variance extracted (AVE)
BCT	0.925	0.978	0.939	0.721
CSCP	0.938	0.955	0.949	0.704
T	0.960	0.973	0.968	0.811
TRA	0.873	0.87	0.906	0.621

In addition, the discriminant validity of each construct was also analysed. Discriminant Validity was calculated with help of smart PLS software using Fornell-Larcker Criterion. The Discriminant Validity ensures that each model construct is distinct from the other, where one construct is not represented by another in the model. Here the outer diagonal values will be greater than the inner column values (Larcker., 1981). Table II shows the Fornell Larker criterion for discriminant validity measures.

Table II.
Fornell-Larcker Criterion

	BCT	CSCP	T	TRA
BCT	0.849			
CSCP	0.693	0.893		
T	0.650	0.839	0.901	
TRA	0.729	0.397	0.324	0.788

Likewise, the predictive power of the independent variable is measured using the R-squared factor. (Cohen et al., 1988) states that R square value should be greater than 0.26 to be significant. The greater the value, the stronger the predictive power. Table III represents the test results which shows level of predictive power of selected independent variables for the dependent variable.

Table III.
R square

	R-square	R-square adjusted
CSCP	0.819	0.813
T	0.423	0.416
TRA	0.531	0.526

The results give high R-square R-square adjusted values, that is coefficient of determination for circular supply chain performance. It indicates that 81.3% of variability in circular supply chain performance could be explained by block chain adoption, transparency and traceability variables measured under the study. Blockchain adoption explains 42% of the variance in traceability and 53% variation in transparency.

5.2 Structural Equation Model

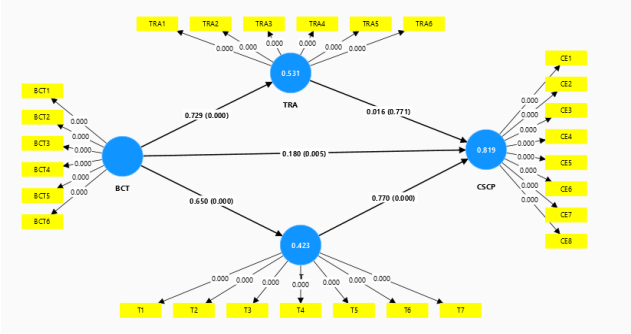

Figure 2. Structural Model

The Figure 2 shows the structural model. The direct association between the variables Blockchain adoption and Circular supply chain performance were evaluated and the results are indicated in the above picture.

The Table 4 shows the hypothesis testing which includes the analysis of direct impact of blockchain on circular supply chains and through the mediating variable traceability. Here it is evident that the direct impact of blockchain adoption on circular supply chain is statistically significant. Also, the adoption of blockchain enhances the transparency and traceability. Furthermore, the traceability has a positive impact in enhancing the performance of circular supply chains. In contrast, the test statistics revealed that transparency does not positively enhance the circular supply chain performance. In other words, transparency alone does not significantly enhance the circular supply chain performance. Results for the PLS-SEM analysis is given in Table IV.

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Table IV.
Hypothesis test results

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
BCT -> CSCP	0.18	0.175	0.065	2.789	0.005
BCT -> T	0.650	0.655	0.036	18.008	0.000
BCT -> TRA	0.729	0.741	0.046	15.985	0.000
T -> CSCP	0.770	0.777	0.049	15.801	0.000
TRA -> CSCP	0.016	0.017	0.056	0.292	0.771
BCT -> T -> CSCP	0.501	0.509	0.041	12.332	0.000
BCT -> TRA -> CSCP	0.012	0.012	0.042	0.283	0.771

The findings are summarized as follows:

- Blockchain adoption has a strong positive impact on achieving Circular supply chain performance (β = 0.180), (p=0.005).
- Blockchain adoption has a strong positive impact on enhancing Traceability of circular supply chain performance (β =0.650), (p=0.000).
- Blockchain adoption has a strong positive impact on enhancing transparency of circular supply chain performance (β = 0.729), (p=0.000).
- Traceability has a positive impact on enhancing Circular supply chain performance (β = 0.770), (p=0.000).
- There is no significant impact of Transparency on circular supply chain performance (β = 0.016), (p=0.771).
- Traceability has a mediating effect between blockchain adoption and circular supply chain performance (β =0.501, p=0.000).
- Transparency does not have mediating effect between blockchain adoption and circular supply chain performance (β =0.012, p=0.771).

VI. Conclusion

This study provides empirical evidence for blockchain adoption significantly enhancing circular supply chain performance. It also considers traceability and transparency as the two mechanisms through which blockchain adoption enhances circular supply chain performance. The results indicate that traceability is the key mechanism having a strong positive effect on performance and a significant mediating role in the relationship between blockchain adoption and circular outcomes. Although blockchain adoption substantially improves transparency, transparency does not have a significant impact on circular supply chain performance and does not mediate this relationship. These findings suggest that the value of blockchain lies primarily in enabling effective traceability rather than transparency alone. Overall, the study highlights traceability as the critical pathway through which blockchain drives circular supply chain performance, offering important implications for both researchers and practitioners.

6.1 Managerial Implications

The findings indicate that blockchain adoption can effectively improve circular supply chain transparency, traceability and more importantly the performance. So, managers should prioritize blockchain implementation for improving circular supply chain performance. They should also keep in mind that it is the traceability factor that act as the mechanism to improve blockchain enabled circular supply chain performance. Hence, organizations should emphasize traceability as the key lever for achieving circular supply chain outcomes and must take initiatives that facilitate and improve traceability of the circular supply chains.

6.2 Research Implications

This study contributes to the growing literature about impact of blockchain adoption on circular supply chains. It highlights the roles of traceability and transparency on blockchain enabled circular supply chain performance and demonstrate that not all blockchain-enabled capabilities equally translate into performance gains. The results refine existing theoretical assumptions by showing that traceability is a critical mediating mechanism, whereas transparency alone may not be sufficient to drive outcomes.

This opens avenues for more nuanced theorization of blockchain capabilities and their performance linkages, particularly within circular supply chain contexts. The study also supports the application of PLS-SEM in examining complex mediation relationships in emerging technology research.

6.3 Societal Implications

Blockchain adoption enhances circular supply chain performance and thereby contributes to boarder societal goals such as waste reduction, resource efficiency, recycling, reusing, environmental sustainability, compliance with ethical standards, responsible consumption and more. The study put forward that when traceability of circular supply chain is improved, its performance can be enhanced. As an integral part of most circular supply chains, society should focus on leveraging traceability of circular supply chains to achieve better performance outcomes.

6.4 Future Directions

Future research can build on these findings by exploring additional mediating and moderating variables that may influence the relationship between blockchain adoption and circular supply chain performance, such as regulatory environments, technological readiness. It should also look into the decentralization, security, smart contracting capabilities brought in by the blockchains and their impact on blockchain performance. Additionally, future work could also apply longitudinal research designs which may provide deeper insights into the long-term impact of blockchain adoption.

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