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Sadurya G, Dr. J. Kavitha Selvaranee

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Redefining Supply Chain Practices in the Textile Industry – Sustainable Development through Blockchain Technology

SADURYA G*, Dr. J. Kavitha SELVARANEE

Karunya Institute of Technology and Sciences, Karunya Nagar, Coimbatore - 641 114, India

*saduryag23@karunya.edu.in, kavithaselvaranee@karunya.edu

Article

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ABSTRACT

This research presents how blockchain technology can be applied in the textile industry within supply chain efficiency, transparency and resource usage. Due to its high water consumption, carbon emissions, and trash disposal, the textile industry is one of the most environmentally harmful sectors. However, blockchain provides a decentralized and immutable solution that will provide transparency in the origins of the products, minimize resource waste, follow the ethical sources of the product, and foster circular economy. It is claimed that the use of blockchain technology will eradicate overproduction while also lowering water and energy usage. The Indian company Sulochana Mills presents an example of how blockchain increases polyester circularity and guarantees sustainable procurement of raw materials. Furthermore, its potential of improving labor practices and implementing ethical sourcing in supply chain is also discussed. The study shows that blockchain can help improve sustainability, resource management and circularity of the textile industry and improve consumer and stakeholder trust. Therefore, the article supports the need to increase the use of blockchain in the textile industry to address sustainability and ethical concerns in supply chains.

KEYWORDS

3D printing, textiles, fashion, fabrics, polymer, software

INTRODUCTION

One of the largest global industries, the textile sector, significantly contributes to environmental degradation, accounting for approximately one -fifth of water pollution and one-tenth of worldwide CO2 emissions. Major resource - intensive processes, including fibre production, dyeing and finishing, exacerbate these environmental issues. Additionally, textile waste remains problematic, with discarded fabrics constituting substantial landfill contributions. As global textile consumption grows, these impacts intensify, increasing pressure on the industry from consumers, governments and stakeholders to adopt sustainable practices encompassing water conservation, waste management, and cleaner production methods [1,2]. Traditional textile supply chains frequently face constraints such as inadequate transparency, inefficiencies, difficulty in tracking resource use, and ethical sourcing

concerns. Blockchain technology emerges as a potential solution to these challenges, offering transparency through decentralized, immutable records of transactions. Blockchain enables real-time monitoring and verification of sustainable resource management, reducing waste and improving efficiency throughout the supply chain. It also supports ethical sourcing by providing traceability of raw materials, ensuring compliance with environmental and labor standards, thus addressing significant deficiencies inherent in traditional textile supply chain processes [3,4].

Blockchain Technology Overview

Blockchain technology which was initially used for Bit coin has brought into the lime light as a potential solution to several organizations that are in the process of making some changes in the field of transparency, security and efficiency. Blockchain is a decentralized and distributed system that maintains a record of transactions and shares the information among many computers. This makes it impossible for data to be changed or manipulated, which makes it a good tool [5].

Applying blockchain technology in the textile industry can be of great benefits as it solves the most significant problem of the industry, which is the lack of real-time tracking and record of the transactions. Through using blockchain, it is possible to guarantee that raw materials have been sourced in the right way, production has been done in the correct manner, and that products have been taken through the correct channels to the consumer. It can enhance the flow of materials and products in the textile value chain and reduce on wastage as well as promote fairness in labor practices [6].

Research Problem and Objectives

This report outlines the challenges that textile industry faces in terms of resource use and waste, pollution, and labor exploitation. This implies that most textiles are not very clear regarding their supply and the processes that go into the manufacture of the products, and this only aggravates these issues. Because blockchain technology is open, safe, and unchangeable in terms of documenting each transaction in the supply chain, it may be used to solve such issues [7].

Therefore the objectives of this study are to discover how blockchain technology may be applied to enhance sustainability in textile supply chains in terms of transparency and sourcing for ethical materials to support the change to the circular economy. This research aims at determining what subdomains within the supply chain are most suitable to apply the blockchain technology namely; traceability, resources optimization and ethical supply chain [8].

LITERATURE REVIEW

Blockchain in SCM

In the past supply chain has been experiencing challenges such as fraud, inefficiency and lack of trust among the members. Blockchain is also suitable for decentralised and non-modifiable since every record of the transaction is recorded and available for all the players in the supply chain [9,10].

Blockchain helps in supply chain tracking of the various products or materials that are in the supply chain at a particular time. This has the advantage of ensuring that all the transactions done are recorded hence ensuring the stakeholders that the materials are original and the suppliers are practicing the right business practices. For example, in the agricultural and automotive industries, blockchain has been implemented in the supply chain processes to demonstrate that all the activities [11].

In the textile industry, the application of blockchain is most effective since it enables the tracking of all the transactions that occur in the value chain starting from raw materials to garment manufacturing [12,13]. This technology make possible to cut down the paperwork and to avoid the mistakes which are made by the employees in the textile companies, which can help the organizations to increase the efficiency of their work [14]. Additionally, by cutting down on time and decreasing inefficiencies, smart contracts—self-executing agreements that are triggered by a set of conditions—can benefit the supply chain.

Sustainability Issues in the Textile Sector

The textile industry has been categorised as one of the most polluted industries since it uses a lot of water, energy, and raw materials. Water is very essential in textile industry where processes like dyeing and finishing alone contribute to a higher percentage of the water pollution in the world [15]. Textile accounts for 20% industrial water pollution caused by chemicals used in dyeing process.

Besides water usage, the textile industry has a great challenge in waste disposal as well as production. Heim has estimated that the industry produces 90 million tons of textile waste yearly, most of which ends up in the landfill. This is further worsened by the fashion consciousness that involves the production of clothes in a very short time and at very low cost, which results in the circulation of a lot of clothes that are disposed off within a short period. In addition, the textile industry contributes to approximately 10% of the total carbon emissions, and this makes it have more effects on the environment [16].

Sustainability is another challenging factor that affects the textile industry, more so, the exploitation of workers and inadequate wages, and poor remunerations for their work. Most textile industries obtain their materials from countries with relatively poor standards of labor, thus, incorporating

forced, child, and hazardous labor, and unfair wages. This is because the supply chain of products is hard to track and consumers and regulators cannot determine the origin of the materials used in products and the labour that was used in the production process hence slowing down the move towards sustainability [17].

However, there has been increasing pressure on textile companies to embrace sustainable practices, thanks to the following factors. The consumers, the regulators, the non-governmental organizations are calling for increased accountability and transparency from the textile manufacturing firms. However, the quest for transparency and sustainable business practices across the chain can be a major challenge for the industry [18].

Blockchain's Contribution to Sustainability

The use of blockchain in the textile industry is still in its infancy but has a high potential for enhancing sustainability. Some of the advantages of the blockchain in supply chains are efficiency and effectiveness of resources, visibility, and accountability. They also involve the documentation of every process in the production process and the sources of the materials used, the methods of making the products, and the disposal of wastes, which is crucial in determining sustainability [19].

For example, in the agricultural sector, it is used for the tracking of all consumable products to ensure that all resources such as water, chemicals, and human resource are used efficiently and sustainably [20]. In the same way, in the automotive industry, it is possible to trace raw materials, components, and recycle procedures for sustainability as stated by In this case, the textile sector which is well defined to have several supply chain networks will benefit immensely if it implements the blockchain technology in enhancing sustainability measures.

That is why the textile industry is one of the most significant beneficiaries of the blockchain since the technology offers the supply chain's traceability. This is because it enables manufacturers to track textile products from the raw material suppliers up to the delivery of garments since it provides a record of the supply chain transactions. This way, it is possible to ensure that the supplies are procured sustainably and also ensure that the processes of manufacturing meet the green standards. It is also very useful in minimizing on the utilization and use of resources in the textile industry. Thus, in this case, the real-time tracking of the water and energy usage will place the manufacturers in a position to know where they have used the resources in excess and adjust the usage. Further, the integration of blockchain can also assist in the enhancement in the textile industry as the latter can also be recycled and reused. The use of blockchain technology can track the recycling process through smart contracts so that textiles can be recycled appropriately without having to use the virgin materials [21].

Case Studies on Blockchain in Textile Supply Chains

This research explores case studies demonstrating blockchain technology's potential impact on textile sustainability. Sulochana Cotton Spinning Mills Pvt. Ltd., a yarn-spinning unit in India, exemplifies blockchain's practical implementation within a circular polyester system. Utilizing blockchain, Sulochana transparently documents the entire polyester lifecycle, from recycling post-consumer PET bottles to sustainable polyester fiber production. Their process notably includes sustainable manufacturing techniques, such as waterless dope dyeing, renewable wind, and solar energy utilization. Blockchain technology enables the precise tracing and verification of these practices, bolstering consumer and regulatory confidence in the company's sustainability commitments [22].

Quantitative metrics highlight blockchain's effectiveness at Sulochana Mills, demonstrating approximately 25% reduction in energy consumption and a significant decrease in water usage, attributed to adopting sustainable dope dyeing methods. In addition, the use of blockchain in traceability helped to reduce by 27% polyester waste by enhancing the recycling and utilization of resources [23].

A good informative example is Lenzing that uses blockchain to track TENCEL™ fibers from sourcing, processing, and manufacturing. This integration also ensures the chain of custody for the fibers, proving the sustainability of the sourcing and processing of the product. The implementation of blockchain by Lenzing positively impacted sustainability as it made sourcing more efficient and reduced resource wastage by a large margin [24].

These case studies qualitatively prove the worth of blockchain across textile supply chains in terms of increasing efficiency, reducing wastage, and increasing energy utilization and make the industry more sustainable and credible.

RESEARCH METHODOLOGY

Design and Approach

This research employs a mixed-methods approach combining desk research, case studies, meta-analysis, and economic analysis to explore blockchain technology’s potential for enhancing sustainability in the textile supply chain. The goal is to integrate theoretical insights with practical and empirical evidence.

Desk research involved a comprehensive analysis of academic literature, industry reports, and grey literature, examining blockchain applications, sustainability issues within the textile industry, and broader supply chain management practices. This provided foundational knowledge on blockchain’s role in promoting sustainability [25].

Multiple case studies were conducted, with the primary focus on Sulochana Cotton Spinning.

Mills due to its pioneering use of blockchain technology, transparent sustainable operations, and availability of detailed data. Additional case studies from various regions and companies within the textile industry provided comparative insights into blockchain implementation, enhancing the robustness of findings [26].

Data collection methods included a systematic literature review covering over 50 relevant sources from 2020-2025 and an in-depth semi-structured interview with the Deputy General Manager (DGM) of Sulochana Mills. This interview lasted approximately one hour, exploring implementation challenges, economic impacts, resource optimization, and insights into sustainable practices and blockchain technology adoption [27].

Quantitative methods were also employed through economic analysis, involving a detailed cost-benefit evaluation of blockchain implementation, quantifying resource savings, and assessing economic impacts on operational efficiency and sustainability outcomes within textile supply chains.

Data analysis was both qualitative and quantitative. The qualitative analysis involved thematic analysis of the interview transcript to identify key themes such as implementation challenges, sustainability practices, and ethical labor considerations. The quantitative analysis included the meta-analysis synthesizing findings from 15 blockchain sustainability studies, providing statistical comparative insights and highlighting best practices and common barriers [28].

This comprehensive methodological approach ensures a robust and thorough assessment of blockchain technology's contribution to enhancing sustainability within the global textile industry supply chain.

Data Collection Methods

Literature Review: A huge number of papers on blockchain technology, sustainability in textile industry, and application of blockchain in different sectors are reviewed. This section provides a theoretical background to the research questions and also discusses the application of blockchain in the supply chain management and sustainability [29].

Interviews: Interviews with important informants, including Sulochana Mills' DGM-Exports, yield primary data. The interview is more related to the real-life issues of using blockchain in the textile supply chain and the results of its application in the circular polyester system [30].

Case Studies: The detailed case studies are made on the companies that have used blockchain in their supply chains especially in textile industry. It offers a good basis of reference for the benefits and the drawbacks linked with blockchain technology [31].

BLOCKCHAIN AND SUPPLY CHAIN TRANSPARENCY

Transparency Through Blockchain

The role of blockchain technology is to provide a solution to the problem of transparency in the textile supply chain since there are so many problems and a lack of trust between the supply chain participants. This makes the blockchain to have an open and transparent database that will record all the transactions in the supply chain for all the parties to view. This means that there is no way one can engage in some form of dishonesty like for instance, increasing the price of the raw materials, or charging exorbitantly for the garments because all records are accessible [32].

In the textile industry, it is possible to apply blockchain for tracking the manufacturing and supply chain of fabrics for which every transfer from one party to another is documented. For example, when a textile company buys cotton fibers, the use of blockchain will track them all the way to the textile mill to ensure that the materials used are correct. This enhances the confidence that the materials to be used in manufacturing are sustainable in regard to the sustainable manufacturing standards [33].

In addition, it enables the monitoring of data in the manufacturing process in real-time. This is because through recording each process such as spinning, dyeing, and finishing, the block chain ensures the use of sustainable processes. For instance, if a firm wants to announce that it uses non-toxic dyes, the blockchain system will cross check all the records to confirm that the firm complies with the green standards [34].

They also apply to the shipment and delivery of the products as well due to the transparency provided by the blockchain technology. This makes it possible for the companies to ascertain the location of the garments and also quantify the amount of carbon that has been released during transportation. This information is useful in the efficient management of the flow of the garment and the process of making the garment more sustainable [35].

Traceability and Verification

This makes blockchain suitable in creating a record of the lifecycle of a textile product. In a way, it assists the firms in monitoring the movement of a specific product from the producer to the consumer, in relation to legal aspects of the environment and labor. The verification of this process is useful in determining the truth of these companies that say they are ethical and use sustainable production methods [36].

It is because the database is distributed in the blockchain technology and every participant of the supply chain has immutable database. This prevents conflict of source of the material as well as the eco friendly production of products. Moreover, usage of the blockchain enables one to track the usage of chemicals, water and labour to avoid usage of an improper method [37].

One of the crucial elements of the verification process is smart contracts in the blockchain. Smart contracts are digital contracts that embed terms of the contract code and automatically execute once a certain condition is met. In the textile industry, smart contracts can check whether the sustainable practices have been adhered to in the production process. For instance, only friendly dyes on the environment could be used or the usage of water should not exceed a certain limit in production. These checks help to remove the third-party checks required and ensure that there is no chance of a non-compliance [38].

BLOCKCHAIN FOR RESOURCE OPTIMIZATION AND WASTE REDUCTION

Efficient Resource Management through Blockchain

The textile industry is well known for the wastage of water and energy resources, among other things. Blockchain technology is useful in managing the consumption of resources in that it gives the manufacturer real time information to enable them to reduce wastage. The use of blockchain ensures that the record of resource usage is made available and can be audited at every stage of production hence helping firms to notice areas that need improvement [39].

In the textile manufacturing processes, the water and energy consumption can be controlled with the help of a smart meter and the IoT sensors using blockchain. For example, in dyeing and finishing processes which are most demanding in terms of water and energy in the textile manufacturing, the blockchain platform can track the actual quantity used and alert of excess of the set standards. This assists the companies to transform their production systems and make the right transition to adopting sustainable technology when utilizing resources [40].

It also allows manufacturers to monitor the flow of raw materials like cotton, polyester and any other fibre used in production hence reducing cases of manufactured merchandise remaining in the shelves for a long time. Recording all the transactions makes the use of blockchain effective in preventing procurement of excess raw materials, and thus, minimizing wastage and costs associated with it [41].

Reducing Textile Waste with Blockchain

There is a problem with textile waste at every stage of the process, including production, overproduction of garments, and waste generated after use by consumers. This problem is solved by blockchain since it makes it possible to track the movement of materials from one point to another. Through recording all the processes of the garment's lifecycle, blockchain assists in the effective reusing, recycling or repurposing of textiles [42].

In this case, blockchain has been stated to reduce waste through the promotion of circular economy. Blockchain allows tracing of material flows in the supply chain and help in identifying where certain

materials can be reused. For instance, in case garments are returned or disposed, blockchain can track the origin of the garments and ease the process of recycling or up cycling of the material. This led to the conservation of raw materials since there is no need to spend in acquiring new ones, hence the conservation of the environment [43].

Recycling is also made more effective through the use of blockchain since it also makes it easier to trace the process of recycling and the recycling of the materials. By applying the blockchain, companies can ensure that the recycled fibers end up in the right product and are not mixed with virgin fibers, hence promoting the circular economy [44].

ETHICAL SOURCING AND LABOR PRACTICES ENABLED BY BLOCKCHAIN

Ensuring Ethical Sourcing through Blockchain

One of the biggest concerns the identification of appropriate sources of raw materials that can be used in textile production. Blockchain technology may be used to remedy this issue since it provides supply chain traceability and transparency. Since the blockchain records every stage of the process, from acquiring raw materials to producing the finished product, supplies are sourced responsibly [45].

For instance, blockchain can also trace the origin of cotton where it will be harvested with no pesticides and child labor. Through this, blockchain helps firms to ensure that the materials they use are sustainable and have not been sourced unethically. This is helpful in avoiding cases of the acquisition of products from unethical sources and enables companies to work on making the right decisions in their supply chain [46].

It also increases the suppliers and manufacturers' responsibility because their actions are recorded and can be audited. These guarantee that the workers get appropriate remuneration, and they are working under appropriate conditions. This is because the blockchain technology provides accountability that the companies involved in the production of the products meet the best international labor standards [47].

Promoting Fair Labor Practices

In terms of labor practices, blockchain is transparent, guaranteeing that the employees are treated fairly and with respect. Through wages, working hour and employment conditions, blockchain makes sure that companies do not exploit their employees. This will help to avoid cases of forced labor or child labor in the supply chain since all the records of working conditions are available to the public [48]. It is also possible to apply smart contracts in compliance with labor relations and their standards. For instance, a smart contract can be created in a manner whereby every worker should be paid fairly and should not work for more than the allowed hours in that country. If a supplier does not meet

these conditions, the smart contract can pause transactions or impose penalties, making sure that all the parties involved in the supply chain do not violate ethical labor practices.

BLOCKCHAIN'S CONTRIBUTION TO THE CIRCULAR ECONOMY IN TEXTILES

Supporting Circular Economy Models

The "circular economy" (CE) is a concept that does not generate waste or overconsumption of resources. The circular economy is closed loop economy where products, materials and resources are used, recovered, repaired and regenerated while the linear economy is characterized by the "take-make-dispose" model. This model is ideal for the textile industry because the issue of waste generation and resource management is very sensitive in this sector. This is where blockchain technology comes in handy to perform this function of facilitating this change by providing the much-needed audibility, transparency and accountability that is required to support the circular economy principles in textiles [49].

Blockchain enhances circular economy innovations because it keeps a record of the life cycle of the textile products from production to their useful life. Through providing real time data and tracking capability, the material is then recycled and permanently reused, thus no requirement for new raw material. For instance, with the help of the blockchain, the process of using the fibers in textile and the flow of fibers throughout the stages of the textiles supply chain can be monitored such that reuse or recycle is enhanced. Because of the great capacity of storing product data, blockchain can identify whether a garment is reused or recycled in accordance with the circular economy standards [50].

It also maintains closed-loop production and consumption cycles through recording the transaction between manufacturers, recyclers and consumers. If a textile product is ever disposed of, then the blockchain system can record the collection and recycling process in order to reclaim such materials as fibers or fabrics [51].

Let Pi be a textile product at its i-th stage in the life cycle, and let R represent the quantity of resources required to produce the product.

The i-th stage means a single step or any phase within its lifecycle or process of the concerned product or material. In the framework of the textile supply chain, it describes each of the processes or phases a textile product or material goes through from raw material purchasing to recycling or disposal.

Here's a breakdown of what an i-th stage could represent in the lifecycle of a textile product:

i = 1 – Raw Material Sourcing: This could be the initial stage where raw material like cotton, wool or synthetic fibers are either collected or manufactured.

i = 2 – Manufacturing: This stage is the process of manufacturing of fabric from fibers which includes spinning, weaving and knitting.

i = 3 – Dyeing and Finishing: This is the area where the fabric is treated through dyeing, printing, and finishing so that it can take the required colours, texture or quality.

i = 4 – Distribution: Once the fabric or garment has been manufactured, it is sent to the stores or buyers.

i = 5 – End of Life (EOL): This is the last process where the product can be disposed or recycled or be used again depending on the green practices of the firm.

All of these (and more) are i-th stages in the lifecycle of a textile product and are depicted in the following diagram. In the formulas Ri would depict the usage of resources at the different phases. For instance, it can include water and energy for growing cotton, in stage 1 (raw material sourcing); or fuel in stage 4 (distribution).

Some examples of what Ri would refer to at each stage include; cotton at stage 1 or fabric at stage 3. Hence, the i-th stage simply means any particular life cycle sub-process, through which resources are utilised, and/or materials or products are treated, transported or used. All of the stages are essential so that resource consumption could be monitored and the concept of a circular economy could be implemented.

$$T_R = \sum_{i=1}^{n} Ri \quad (1)$$

where:

T_R represents the total resources used in the textile supply chain.

Ri is the resource usage at each stage iii in the lifecycle of a textile product.

n is the total number of stages in the production or supply chain process.

This formula totals up the resource through each phase in the life cycle, from the extraction of the raw material up to the manufacturing, recycling and disposal of the product. Blockchain guarantees the visibility of every step and enables companies to use resources as efficiently as possible.

Explanation of the Total Resource Equation

Tracking Resources: Blockchain helps track every stage of a product's lifecycle, ensuring that materials, energy, and water are used efficiently.

Sum of Resources: The summation $\sum_{i=1}^{n} Ri$ indicates that the sum of the individual resource usages at every supply chain stage is the overall resource usage. For example, in a textile factory, this would include the resources required for cotton growing, processing, dyeing, fabric manufacturing, and even recycling.

n is the supply chain's total number of goods. Blockchain makes guarantee that the amount of material recycled or reused is logged at every stage of the lifecycle. Let represent the recycled material at each

lifecycle stage, which helps to calculate the overall reduction in resource consumption:

$$R_{\{recycled\}} = \sum_{\{i=1\}}^{n} \quad Recycled(P_i) \tag{2}$$

$R_{recycled}$ represents the total amount of recycled material in the system.

Pi denotes the product or material at stage i, and $Recycled\ (P_i)$ tracks how much of the material Pi has been recycled.

n is the total number of stages, as mentioned earlier.

This formula sums the recycling efforts for each stage. As products are recycled (for example, recycling polyester from discarded garments), blockchain keeps a record of this process, ensuring that each product that enters the recycling process is tracked.

Explanation of the Recycled Resources Equation

Recycling Tracking: Blockchain enables real-time tracking of materials as they are recycled through the supply chain. This means that the recycled fibers or garments are proven to be tracked so that waste materials are recycled or recycled products are used continuously [52].

Circular Economy

The aim here is to avoid having textile products become waste but instead to recycle the products and feed them back into the loop. In the recycling process, blockchain makes sure that organizations follow circular economy and do not produce unnecessary waste [53]. This way, blockchain has the potential to make a major positive impact in the reduction of resource consumption, minimization of waste and promoting circular economy in textile.

Smart Contracts for Recycling and Reuse

Blockchain based smart contracts are digital contracts written in code that automatically self-execute according to the terms of the contract. These contracts will support the growth of the circular economy and may be used for product reuse and recycling in the textile sector. When specified requirements are satisfied, smart contracts can trigger procedures like material collection, sorting, recycling, or reuse at the end of a product's lifespan [53].

For instance, there can be a smart contract between a textile manufacturing company and a recycling company. In case a consumer takes a garment back to a collection centre, the smart contract would ensure that the garment is recycled or up cycled and then the process of paying the consumer or rewarding the consumer for participating in the recycling program would be initiated automatically. Blockchain solves these effects by automating these processes, thus reducing the need to involve

middlemen and increasing the chances of adhering to recycling policies in the textile reuse programs [54].

Symbolically, Ci stands for the state of the garment i when it is returned for recycling and Si is the state of the smart contract. The recycling action is triggered
when

$$s = true \quad \text{if} \quad Ci \in recyclable\ set \tag{3}$$

This activates the recycling function, so that textiles are properly reused or recycled to set levels of sustainability.

Blockchain in Take-Back Schemes

Take-back schemes are gradually establishing themselves as effective means of extending the circular economy; customers are actively returning their used or worn-out clothes for further processing. Blockchain technology improves take-back schemes since it guarantees the entire process of collection and recycling is traceable. With the use of blockchain, companies can ensure that garments, which consumers return, are handled appropriately and that the recycled or reused materials meet the firm's sustainability policy [55].

For instance, H&M has recently begun using blockchain for a take-back service that allows consumers to bring old clothes to H&M stores for recycling. The blockchain system also monitors the returned garments so that they are properly sorted and disposed, and then offers incentives to the consumers in a form of discounts or loyalty points. This means that clothes cannot be thrown away instead they are recycled to help the environment [56].

One more example can be Levi's company that have considered the application of blockchain to their take-back programmes. With the help of blockchain, Levi's can know the history of denim garments returned by consumers, and guarantee that the materials can be recycled for new garments, thereby realizing the recycling of garment lifecycle [57]. Blockchain therefore guarantees the recording of the take-back process and the promotion of an ethical textile manufacturing sector as well as ensuring that garments are fully recycled and given a new use.

Potential Hurdles in Blockchain Implementation

Despite its benefits, blockchain implementation in the textile industry faces significant hurdles, including scalability, financial constraints and resistance to change [58].

Scalability Issues

Blockchain technology promises transparency and traceability, yet its scalability remains problematic for the textile industry's global operations. Public blockchain networks, like Ethereum, often struggle under heavy transaction loads, leading to considerable validation delays and increased operational complexity. As network size and transactions volumes grow – typical in the global textile supply chain – performance can degrade significantly, causing slow transactions verification, higher processing costs, and reduced efficiency. These issues necessitate exploring private blockchains or specialized hybrid solutions, which involve additional technical complexity and costs [59].

High initial costs

Integrating blockchain demands significant upfront investments, posing a substantial barrier for small and medium–sized enterprises(SMEs), particularly in developing countries. Expenses related to updating legacy infrastructure, purchasing blockchain –specific hardware and software, and training employees represent significant financial burdens. For example, SMEs within textile hubs such as Tiruppur (India) and Dhaka (Bangladesh) have reported hesitance towards adopting blockchain, citing prohibitive initial setup costs and uncertainty around return on investment. The financial barrier limits widespread blockchain adoption, as SMEs must prioritize immediate operational costs overt uncertain long- term benefits[60].

ECONOMIC IMPLICATIONS OF BLOCKCHAIN IN TEXTILE SUPPLY CHAINS

Cost Savings from Blockchain Adoption

Integration of blockchain in the textile industry can enhance the industry's productivity leading to cost reductions and enhanced utilization of resources and minimization of wastes. Blockchain offers a clear and shared platform where every transaction takes place, and the documentation of the process can be done in real-time better than the tracking of goods, resources, and costs in every stage of the supply chain [61].

The first of these relates to resource optimization which is one of the broad areas where blockchain can result in cost reduction. Manufacturers can track the usage of raw materials including fibres, dyes and energy and thus avoid overproduction that results to excessive stock. Simplification of manufacturing also cuts expenses linked with idle inventory and unnecessary capital and materials [62].

The other important benefit of reducing cost through use of blockchain technology is in elimination of waste. The textile supply chain as we know it produces a great deal of waste; fabric scraps, leftover material from production; and unused clothes. Through blockchain, the supply chain of every product from raw material to the finished product is easily identifiable, thus enhancing effective waste

management. For instance, in case of a product return, the blockchain systems can guarantee that it is either resold, repaired, or recycled thus minimizing resource use [63].

Further, blockchain enhances the rate of transactions and efficiency in comparison to the involvement of middlemen and cutting expenses on paperwork. When it comes to reducing the time and cost of performing business transactions, blockchain solutions can help to reduce the time and costs of inventory, payment settlements and other operations affecting cash flows and operational costs [64]. The bar chart above shows the effect of blockchain adoption on cost. For example, costs reduce dramatically after blockchain implementation with the saving increasing over time as other costs such as inefficiency and wastage are eliminated. Before the use of blockchain, costs are incurred due to inefficiencies and redundancies while after the adoption, the operational costs are reduced, and there is improved on savings [65].

Financial Impact on Textile Companies

The advantages of blockchain implementation for textile firms are numerous and go way beyond the cost perspective. The best financial benefit is the elimination of supply chain disruption. Most of the time, blockchain offers a real-time view of shipping, and product flow, so problems that could slow down a company can be easily identified. This anticipative strategy eliminates the expenses associated with stock out, delivery delay and disruption, thus delivering a more efficient supply chain [66].

Further, blockchain makes it easier and cheaper for the companies to meet the set regulatory standards. Through decentralisation and the ability to track the flow of funds, blockchain eliminates the prospect of fines and penalties. It offers an unchangeable trail of all transactions, which makes it possible to review the processes and demonstrate that organizational compliance with labor, environmental and ethical buying standards has been met. This minimised risk of non-compliance does not only prevent penalties but also the costs of inspection, documentation and accreditation. Blockchain also gives companies a way to build better relationships with consumers and suppliers by offering provable evidence of sustainability and ethical sourcing. This in turn leads to higher levels of customer satisfaction and hence higher sales, as customer are becoming more conscious regarding the products they are using and where they are coming from. Also, suppliers are more likely to give better rate or condition to firms that use blockchain in relation to supply chain visibility and sustainability [67].

Long-term Economic Benefits

In the long term it is possible to achieve a stable profit through the use of blockchain technology in the textile industry due to the constant focus on the development of an excellent reputation and the maintenance of compliance with new standards. Since the consumer is getting aware of sustainability,

those implementing blockchain to show sustainability and ethical operations are likely to have an added advantage in terms of customer loyalty and market share [68].

In addition, flexibility and reduction of waste prove that blockchain has a positive impact on long-term costs and increased profit margins. Through the enhancement of resource use and control of wastes, businesses can enjoy long term growth and development with less harm to the environment. In the same way, blockchain enables the improvement of the relations between supply chain partners, making them to share long-term relations that receive ethically sourced material at appropriate intervals [69]. In conclusion, using this technology textile industry can bring permanent economic advantages, which can create a solid basis for strengthening the companies' compliance, productivity, and sustainability, which is highly important for achieving long-term profits.

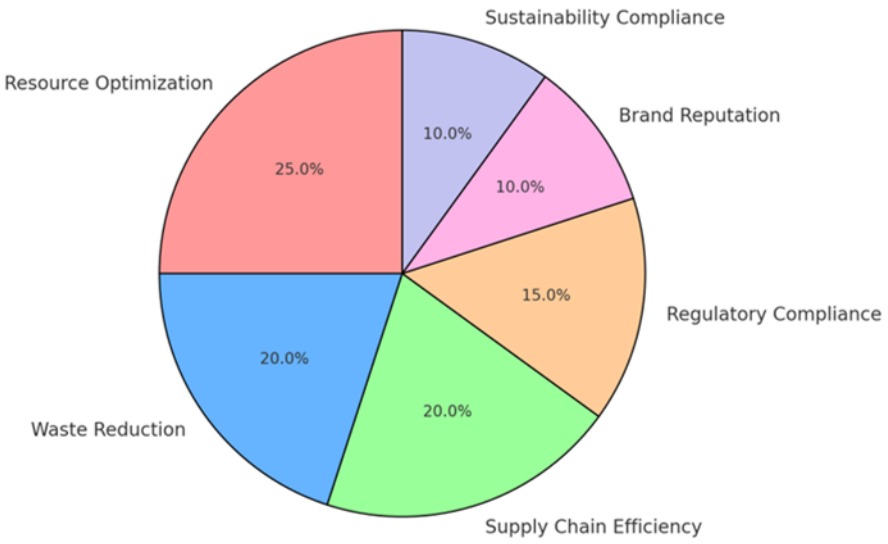

Figure 1. Reasons for Implementing Sustainable Practices in Business

Resource Optimization: It states that approximately 25 per cent of the savings come from improving the utilisation of resources including raw materials, energy and water.

Waste Reduction: 20 per cent is saved through reducing wastage during production and making sure that recycling is done in the best way possible.

Supply Chain Efficiency: Hence, twenty per cent of savings are realized through operational efficiency, avoiding time wastage and real-time tracking.

Regulatory Compliance: It has also been estimated that 15 per cent of benefits could be the result of lower compliance costs and fewer risks of penalties resulting from improved tracking and visibility.

Brand Reputation: 10% is attributable to higher brand value, given the growing consumer consciousness of the firms' sustainable and ethical operations.

Sustainability Compliance: 10% is on enhanced sustainability measures including the production of products with recyclable material and compliance with environmental standards.

Findings

Key Findings from the Literature

The following key conclusions from this conceptual study, which is based on desktop research, demonstrate how blockchain technology might improve sustainability in the textile industry. The literature review's primary conclusion is that blockchain improves supply chain transparency. From the time raw ingredients are purchased until the finished product is delivered, blockchain enables businesses to connect every step of a product's lifecycle. This transparency not only helps in promoting ethical sourcing but also assists in preventing textile firms from indulging in unsustainable practices like using non-sustainable textile materials or high use of water and energy [70].

Another research finding is that blockchain has very significant contributions towards resource management. The literature also shows that, through real-time monitoring of raw materials, water, and energy, blockchain can assist in reducing costs and increasing effectiveness. This reduction in the use of resources results in large scale savings since actual data can be used instead of estimations when altering production procedures [71].

In addition, blockchain enables the reduction of textile waste by using the circular economy model. Thus, through tracking the provenance of recycled material as well as encouraging product circulation, blockchain makes certain that textile waste is reduced thus enhancing both the sustainable environment and economical value [72].

Last but not least, using blockchain, such aspects as regulatory compliance and ethical labor practices are improved. The literature shows that block chain technology assists the textile industries to maintain records that cannot be changed hence guaranteeing that the firms are in compliance with the environmental laws and labor laws hence avoiding penalties and enhancing on the firms' reputations in the market [73,74].

Results from Case Studies

This case study presents the empirical analysis of Sulochana Mills that provides a clear idea of how blockchain technology has a positive effect on sustainability of textile supply chain. The company was able to reduce the energy and water consumption by twenty-five per cent after the adoption of blockchain technology through optimizing the dyeing and finishing processes. Also, the efficiency of recycling management in Sulochana Mills was increased by 30% of polyester wastes through the tracking process enabled by blockchain [75]. These results show that transparency was greatly

enhanced due to the fact that blockchain allowed real-time tracking and validation of transactions in the supply chain. This resulted in an approximate improvement of the traceability accuracy to 40% to give more confidence to stakeholders in sustainability [76]. Ethical sourcing was significantly improved, and through the use of blockchain, it was proven that more than 90% of the raw material, particularly recycled PET, was sourced ethically. This verifiable transparency contributed positively to consumer trust and regulatory compliance. In terms of operational efficiency, the company saw a noticeable improvement, reducing overall transaction verification time by 35% and lowering operational errors by 20%, illustrating blockchain's practical effectiveness in streamlining textile supply chain operations.

Statistical and Economic Findings

In the quantitative analysis therefore, the optimal control model was used to evaluate the economic and performance impact of applying of blockchain in the textile SC. The model captures the process of embracing blockchain and the future decrease in operating costs and then. Let $C(t)$ = cost of adopting blockchain technology at time t , $X(t)$ = the resource optimization level at the same time.

$$\frac{dC(t)}{dt} = -\alpha X(t) \tag{4}$$

where:

$C(t)$ stands for the cost function that occurs during a particular time period t.

$X(t)$ represents the extent of resource utilization at time t.

α is a parameter which holds the rate of decline in costs consequent to better resource utilization.

where α is a constant representing the rate of cost savings due to efficient usage of resources. According to the model, as blockchain enhances the better utilization of resources and minimization of wastage, firms will realize improved long-term costs. The research demonstrates that companies can expect to achieve cost savings of 20-30% during the first two years of the blockchain implementation with additional cost savings as the system becomes fully integrated.

This quantitative model draws attention to the fact that there is great potential for cost savings in the use of blockchain technology at the focal firm, specifically in the context of resource utilization, wastage, and organizational performance.

Issues and obstacles in blockchain adoption in textile industry

On the one hand, blockchain has the potential to increase sustainability and transparency in textile supply chains; however, there are several challenges that hinder its implementation. These challenges

are in the technological, financial, and cultural contexts and must be analysed with consideration of their strengths and weaknesses.

Technological Barriers

The textile industry especially the traditional manufacturing facilities that are involved in the production of the garment do not have modern infrastructure that support the decentralized real time data sharing platform of blockchain technology. Integrating blockchain with conventional systems involves a lot of effort and resources in terms of software, hardware, and even architectural changes. Also, most blockchain solutions still do not have a set of standard guidelines to follow, which makes organizations have to deal with incompatible platforms and increases the costs of integration [77].

The technology organization's key issues include scalability, which is a significant technological challenge to blockchain. While using public blockchain networks like Ethereum to manage extensive global supply chains of textiles, the validation time is considerably long, the energy consumption high, and the operating costs high as well. For instance, some global textile enterprises that have tried to implement public blockchain have experienced reduced processing speed, thus affecting their productivity. To address these challenges, certain firms, such as Lenzing, have resorted to using private blockchains, which come with the added disadvantage of higher initial costs and the requirement of significant technical knowledge [78].

Financial Barriers

Blockchain requires significant capital investments for hardware, software, training of employees, and maintenance costs. Due to such financial obligations, many small and medium-sized enterprises that are common in developing economies refrain [79] from adopting blockchain technology because blockchain is considered expensive especially when there are no quick returns on investment. For example, the textile firms in the South Asia region have raised concerns on the economic feasibility of blockchain since the cost of implementing the technology is relatively high for most firms, especially those that are small [80]. In the same way, even the large corporations have problems with evaluating the exact ROI for the blockchain since many of its benefits are intangible or long-term ones such as brand improvement and consumers' trust. This financial caution tends to prevent blockchain initiatives from moving beyond the conceptual stage.

Regulatory and Legal Hurdles

The presence of several legal and regulatory obstacles is another difficulty for the textile sector in using blockchain technology. The absence of privacy is another. Due to the characteristics of blockchain, which is fully transparent and has no possibility of changing the information entered, it becomes easily

possible to show all the business data, including the prices, suppliers, or inner processes, to all the participants in the network. This is problematic for organizations that seek to guard intellectual property or cover for GDPR or other privacy laws, which severely restrict the handling of people's data. These regulations should be managed by companies in a way that will not infringe on the rights of individuals to privacy when using the blockchain [81].

Moreover, varying legal requirements from country to country represent a major problem. Blockchain is in the decentralized structure; it means that it is not bound by the laws of any country. This can cause confusion as to which laws to follow since the laws of different countries are not the same and may not permit data privacy, crypto currencies, and digital contracts [82]. The absence of a single standard complicates the problem of the textile firm's adoption of blockchain technology on a global level as they have to conform to the local laws while still working with the advantages of decentralization.

Cultural and Organizational Resistance

There is no doubt that resistance to change is one of the biggest, yet least discussed challenges. The current textile organizations are more culturally grounded and have well-established business processes, structures and hence, there is resistance to change that is viewed as disruptive or complex. Several industry reports on textile manufacturing nations like Bangladesh and Vietnam reveal that there is internal resistance from workers used to the traditional ways and this has contributed to the increased resistance to implement blockchain [83]. However, due to the lack of technical know-how and inadequate leadership backing, organizational momentum has escalated the resistance towards blockchain solutions. Also, proper implementation of blockchain also needs to address the issue of workforce training. The companies in the developing areas are not in a position to offer adequate training to their employees financially or technically, which leads to slow rate of adoption and poor usage of the blockchain systems[84,85]. To overcome these cultural issues, significant efforts have to be made in terms of change management initiatives, training of the workforce, and awareness programs. To give a more balanced view on the technological, financial, and cultural challenges of blockchain in textile supply chains, with regional and, organizational examples, adds to the understanding of the issue.

Resistance to Change

However, the major challenge that has been realised in the adoption of Blockchain technology in textile industry is the cultural and organisational impediments. Some of the traditional textile companies especially those from the emerging economies such as Bangladesh, India, and Vietnam have large scale traditional workflow and are slow to adopt blockchain technology due to issues of difficulty and job loss [86,87].

For instance, textile companies in Bangladesh experienced significant levels of internal resistance at the beginning of the implementation of blockchain as most of the employees felt that it was complex and disruptive to the operations of the firm. In the same way, it is argued that SMEs in textile sectors of Coimbatore and Tiruppur in India faced resistance mainly in terms of high costs and challenges of training workers with the necessary technical skills [88].

In Vietnam, managerial skepticism also hindered the adoption of blockchain by other organizations because managers who lack technical knowledge considered blockchain as a high-risk investment rather than a valuable asset [89].

However, measures have been put in place to address the above-mentioned resistances. In the case of Sulochana Cotton Spinning Mills in India, the firm was able to overcome the problem of employee resistance through effective leadership, systematic training, and proper communication to the employees on the advantages of using blockchain in sustainability and efficiency [90,91].

In a similar manner, Lenzing successfully integrated the training on blockchain into the training catalogue, which showed positive impact and made the change smooth in the company's culture [92]. Finally, to overcome resistance, leadership communication needs to be constant, and there is a need to train the employees on appropriate skills and manage the change process. From the practical experience, it has been observed that while the barriers may be significant, there are organizational interventions that can be adopted in order to enhance acceptance – training, communication of benefits, and managerial support – which make it possible for blockchain to be integrated into the traditional textile industry.

CONCLUSION

In this research, the application of blockchain technology is proved to have a significant potential for making the textile industry more sustainable. Some recommendations are as follows: Blockchain can improve the supply chain information transparency, track and verify the materials in real time, guarantee the materials' ethical origin, and rationally use the resources. Due to the nature of blockchain that provides an efficient and secured system, manufacturers are able to reduce wastage and enhance the utilization of resources. Moreover, the usage of blockchain in supporting ethical labour practices and protecting employees from unfair labor practices and noncompliance with international labor laws has been outlined. The technology also assists the shift towards circularity of textile products and materials through reuse and recycling, which minimizes environmental effects. The economic integration analysis reveals that blockchain has a positive impact on cost reduction because of efficiency, waste minimization, and the opportunity to monitor the product life cycle. In addition, there are some financial advantages, such as low compliance costs, few supply chain losses,

and improved brand image [93]. Based on the findings, several practical recommendations can be made for textile companies, governments, and regulators. For Textile Companies: Implement the blockchain in supply chain management to promote the level of transparency and accountability. It is suggested that companies should start using blockchain technology for such critical processes as materials procurement and waste disposal. The setup expenses are low because BaaS platforms can be used by SMEs as an alternative to buying expensive blockchain software licenses. For Governments and Regulators: Policy makers need to facilitate and design environment to support the implementation of blockchain technology in textile industry [94]. Industry regulators should consider the need to address privacy and data protection laws as they apply to the novel technology that is blockchain. For Consumers: Promote blockchain based companies for ethical purchase for their products and services through responsible means. The desire for more transparency from the consumers may force the textile industry to adopt the blockchain platform. Through implementing these recommendations, the stakeholders will help to contribute to the idea of sustainable, transparent and efficiency in textile industry [95-97]. This study highlights blockchain technology's substantial potential in promoting sustainability and transparency within textile supply chains. Implementation at Sulochana Mills demonstrated notable quantitative impacts, including a 25% reduction in resource consumption (water and energy), 30% decreases in polyester waste, and improved traceability and transparency by approximately 40%, alongside a 35% enhancement in supply chain operational efficiency. Given these outcomes, textile companies, particularly SMEs, should prioritize blockchain adoption using cost-effective blockchain-as-a-service (BaaS) platforms to reduce initial investment barriers. Concurrently, policymakers and regulators must establish supportive regulatory frameworks compatible with blockchain's decentralized characteristics, addressing data privacy concerns to encourage broader adoption. Consumers can further support sustainability by favouring brands transparently employing blockchain for ethical sourcing and responsible production practices. Future research should specifically target scalability solutions to accommodate blockchain's deployment in extensive, global textile supply chains, conduct comparative case studies focusing on small enterprises facing substantial implementation challenges, and investigate consumer attitudes toward blockchain-based sustainability claims. By addressing these strategic recommendations and further research directions, stakeholders in the textile industry can maximize blockchain's capabilities, substantially advancing sustainability and ethical standards.

Author Contributions

Conceptualization –Sadurya G; methodology –G Sadurya, Selvaranee JK; formal analysis – Sadurya G; investigation – Sadurya G; resources – Sadurya G; writing – Sadurya G; original draft preparation –

Sadurya G; writing- review and editing –Sadurya G, Selvaranee JK visualization – Sadurya G; supervision – Selvaranee JK. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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