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Traceability Technology in Plastic Waste Management for Recycling Paper Industry: A Circular Economy Review

Rr. Citra Rapati[1] * | Marimin Marimin[2] | Yandra Arkeman[3] | Popong Nurhayati[4]

[1]*IPB University, School of Business, Bogor, Indonesia*
[2]*IPB University, Department of Agro-Industrial Engineering, Bogor, Indonesia*
[3]*IPB University, Department of Agro-Industrial Engineering, Bogor, Indonesia*
[4]*IPB University, School of Business, IPB University, Bogor, Indonesia*

*Correspondence to: Rr. Citra Rapati, IPB University, School of Business, Gedung SB-IPB Jl. Raya Pajajaran, Bogor 16151, Indonesia.
E-mail: citrasoedaryantorapati@apps.ipb.ac.id

Abstract: The global increase in plastic waste generation poses a significant challenge to environmental sustainability. Among major contributors is plastic waste from the recycling paper industry. The circular economy represents an emerging paradigm in the management of plastic waste in Indonesia. Despite growing interest in digital innovations, the integration of traceability technology such as blockchain and IoT remains underexplored. This study explores the role of smart technology in enhancing traceability of plastic waste management within the recycling paper industry in the context of the circular economy framework using the PRISMA protocol. Through a systematic literature review of 40 peer review from Scopus and ProQuest published between 2013 and 2024, the study highlights the current practices, drivers, and barriers in adopting smart technologies, while enabling alignment with sustainability reporting frameworks like the Global Reporting Initiative (GRI) and the Sustainability Accounting Standards Boards (SASB). This review contributes to the field of sustainability accounting by framing digital traceability of plastic waste not only as technical solution but also as a driver of ESG aligned innovation. The findings propose a future research agenda to explore innovative approaches and solutions for optimizing plastic waste traceability in line with sustainable practices and circular economy principles.

Keywords: blockchain, circular economy, plastic waste management, recycling paper industry, sustainability reporting, smart technology, traceability technology.

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INTRODUCTION

The global increase in plastic waste generation poses a significant challenge to environmental sustainability. Plastic waste management has become increasingly complex due to the diverse types and volumes of plastic materials generated globally (Khadke et al. 2021). One of the plastic waste sources is from industrial processes such as the recycling paper industry. The recycling of plastic waste within the recycling paper industry is a critical component of addressing this issue, particularly within the framework of the circular economy (Rapati et al. 2023). The pulp and paper industry holds considerable growth potential, fueled by the abundant availability of raw materials and a robust domestic market, further strengthened by the implementation of advanced technologies. In Indonesia, the industry's development prospects are particularly promising due to the accessible supply of wood raw materials from plantation and community forests. Additionally, Indonesia's tropical climate allows for faster plant growth compared to subtropical regions. As a leading global producer of pulp and paper, Indonesia boasts a national pulp industry capacity of 12.3 million tons per year, ranking 8th globally, and a paper industry capacity of 18.56 million tons per year, ranking 6th worldwide. Currently, 59 industries in Indonesia utilize used paper as raw material, with a combined production capacity of 12 million tons and continually growing investment values. However, an adequate supply of raw materials is crucial, as these industries require over 7.8 million tons of wastepaper annually to operate efficiently. Domestic supply falls short at only 3.5 million tons per year, necessitating imports to meet the shortfall (Ministry of Industry, 2021). The development and expansion of the pulp and paper industry inherently affects environmental quality due to pollution from industrial waste. Given the significant environmental impact of industrial activities, the waste produced by the pulp and paper sector—comprising pulping, bleaching, washing, primary sludge, and secondary sludge—poses considerable risks as potential contaminants of air, soil, and water (Lindholm-Lehto et al. 2015).

The circular economy emphasizes the importance of resource efficiency, waste reduction, and the continual use of materials, thereby transforming waste into valuable resources (Geissdoerfer et al., 2017). The escalating problem of plastic waste is a critical environmental challenge that necessitates innovative solutions. Proper handling of plastic waste produced in paper recycling industry is the key for promoting sustainability and aligning operations with the principles of circular economy (Rapati et al. 2023). In order to achieve what is desired, one needs to put much more effort into and bring about disruptive innovations. Solutions grounded in physical or digital information for tracking plastic materials can facilitate the circular economy and help to address challenges throughout the value chain (Rumetshofer & Fischer, 2023). The circular economic framework emphasizes the continual use of resources, minimizing waste, and re-integrating materials back into the production cycle. In this regard, the implementation of traceability technologies is essential for enhancing the management often fall short in terms of transparency and operational efficiency, hindering progress toward contemporary sustainability.

Recent advancements in traceability technologies, including blockchain, the Internet of Things (IoT), and digital platforms, present promising solutions to these challenges. Blockchain provides a decentralized and secure way to record and verify transactions, which can improve the efficiency and accountability of waste management processes (Liu et al. 2022). Blockchain technology has emerged as a transformative strategy, revolutionizing numerous industries with its diverse applications across various sectors such as manufacturing, construction, supply chain, food, healthcare, energy, transportation, and retail. By providing a decentralized ledger capable of tracking the origins of materials and goods, blockchain facilitates a swift, secure, and transparent information platform. This innovation enhances the reliability and efficiency of data management, fostering greater trust and accountability within these industries (Abbas & Myeong, 2024). Rumetshofer & Fischer (2023) evaluate how physical- or digital-information-based solutions for tracking plastic materials can support the circular economy and help to overcome hurdles along the value chain The integration of various information technologies, such as IoT and AI, is discussed to enhance the tracking and management of plastic materials. These technologies provide advanced capabilities for monitoring, data analysis, and process optimization, which are essential for supporting a circular economy.

Varriale et al. (2023) identify which technologies support sustainable emerging practices from the perspective of the triple bottom line (3BL). Specifically, the analysis considered the following eleven technologies: artificial intelligence, 3D printing, blockchain, digital applications, computing, the Internet of Things, geospatial technologies, immersive environments, proximity technologies, open and crowd-based platforms, and robotics. Moreover, digital platforms enhance stakeholder communication and coordination, thereby reinforcing efforts to implement circular economy initiatives (Martínez-Peláez et al. 2023).

While the potential of these technologies is widely acknowledged their deployment in the context of plastic waste management remains constrained by a range of barriers. Notably among these high initial costs, technical complexities, and persistent concerns over data security (Ma et al. 2024). In addition, the current body of research lacks comprehensive evaluations of the long-term effectiveness and scalability of such technologies in real-world settings. Therefore, conducting a systematic literature review is needed to put together existing findings and identify gaps. Most importantly, it will help provide a coherent agenda for future research.

The circular economy model supports the extended use of products, waste reduction and the ability to put back the products back in the loop. Using traceability technologies enhance plastic waste management by making it easier to track and document the journey of plastic products. The goal of this systematic literature review is to analyze and evaluate technology innovation that supports traceability and sustainability in plastic waste management in the paper recycling industry, the main facilitators of barriers to adoption, and future research directions.

Theoretical background of the uses of blockchain in recycling is important to understanding the functional framework behind the proposal. In the following section we will introduce the main theory, its relevant concepts, and authors, with citations from the literature.

1. Blockchain Technology Fundamentals (Borandag, 2023)
    a. Decentralization: As a decentralized network, blockchain technology does not allow a single entity to have complete control and contributes to greater transparency and lowers the risk of fraud.
    b. Immutable ledger: The immutable ledger of blockchain ensures that information, once logged, cannot be altered or destroyed, creating trust and reliability.
    c. Consensus mechanisms: Consensus algorithms (like Proof of Work, Proof of Stake, etc.) are the foundation of blockchain systems that help validate transactions and ensure consistency across the distributed ledger.
2. Supply Chain Management (Bułkowska et al. 2023)
    a. Supply chain transparency: In theoretical models of supply chain transparency, visibility and traceability is emphasized from the perspective of making sure that material flows through the supply network. Blockchain technology is aligned with these frameworks which help in real-time monitoring as well as keeping tamper-proof records of transactions.
    b. Closed-loop supply chains: Proponents of the closed-loop supply chain model advocate for the incorporation of material repair and reuse into supply chain design. The blockchain provides your support to implement such systems as it serves as a reliable mechanism to track the material flow and verify the material flows which you can thus use to promote circularity and resource efficiency.
3. Circular Economy Principles (Khadke et al. 2021)
    a. Circular economy: Under the circular economy framework, it is important to optimize resource usage and minimize waste through continuous use of materials. Blockchain technology plays a role in this as it enables effective tracking of materials, thus aiding the implementation of sustainable practices.
    b. Resource recovery: Resource recovery is rooted in theoretical traditions emphasizing the importance of reclaiming valuable resources from waste. The openness and reliable traceability offered by blockchain facilitate the identification and processing of recyclable materials.

4. Incentive Structures and Game Theory (Bułkowska et al. 2023)
    a. Smart contracts: Smart contracts are self-executing contracts with the terms of the agreement or transaction directly written into lines of code. They can automatically execute the incentives, ensuring that anyone that takes part in the recycling process is compensated for their recycling efforts appropriately.
    b. Incentive alignment: By applying principles of conventional game theory, systems are structured such that the incentives facing all parties are aligned, promoting collaboration. These models are further solidified through the advent of blockchain technology, which allows for the transparent and immutable enforcement of incentive mechanisms.
5. Technology Adoption and Diffusion Theories (Wong et al. 2023)
    a. Technology Acceptance Model (TAM): This is the most important model in the field of technology acceptance, which explains the adoption of technology by users by perceiving the features of the technology in terms of its usefulness (the extent to which a person believes that using a technology contributes to improved job performance) and ease of use (the extent to which a person believes that it is easier to use the technology). We focus on perceived benefits from improved transparency, security, and operational efficiencies that drives the adoption of new technologies such as blockchain in other industries.
    b. Diffusion of innovations: This theory by Everett Rogers explains how, why, and at what rate new ideas and technology spread. Blockchain technology's diffusion in the recycling industry is influenced by factors such as relative advantages, compatibility, complexity, trialability, and observability.

METHODS

Search Strategy and Inclusion/Exclusion Criteria

This research conducts a systematic literature review incorporating both quantitative and qualitative data. The study employs analytical techniques grounded in both quantitative and qualitative methodologies. The systematic literature review and bibliometric analysis were carried out utilizing data obtained from the Scopus database (https://scopus.com (accessed on 24 May 2024)) included snowball articles related sources from the ProQuest database (https://ProQuest.com (accessed on 1 June 2024)). Scopus and ProQuest were selected due to their status as the largest databases for abstracts, citations, journals, conference proceedings, and books. The following keywords were entered into the Scopus and ProQuest search engines: Circular economy, Plastic waste management, Recycling paper industry, Traceability technology.

First, from the scopus database, when the query ((TITLE-ABS-KEY (traceability AND technology) OR TITLE-ABS-KEY (plastic AND waste AND management) AND TITLE-ABS-KEY (recycling AND paper AND industry) OR TITLE-ABS-KEY (circular AND economy)) was input, and 1553 titles were shown (see Figure 1). The entry was further limited using a time limit of 2014 until 2024 where the results were reduced down to 851. Next screened database was limited to "article", "final", "English" and the result was reduced to 490 articles. Based on 490 Scopus articles analyzed further using research trend number of publications parameters with the themes "traceability technology," "plastic waste management," "recycling paper industry," and "circular economy" over the last 10 years, the research subject areas and countries of origin were identified.

Additionally, the selection process was refined by excluding papers with minimal relevance to the study's focus on technologies for traceability and sustainability in plastic waste management, resulting in 27 key papers (Figure 1). Among these, 13 key papers were sourced from ProQuest.

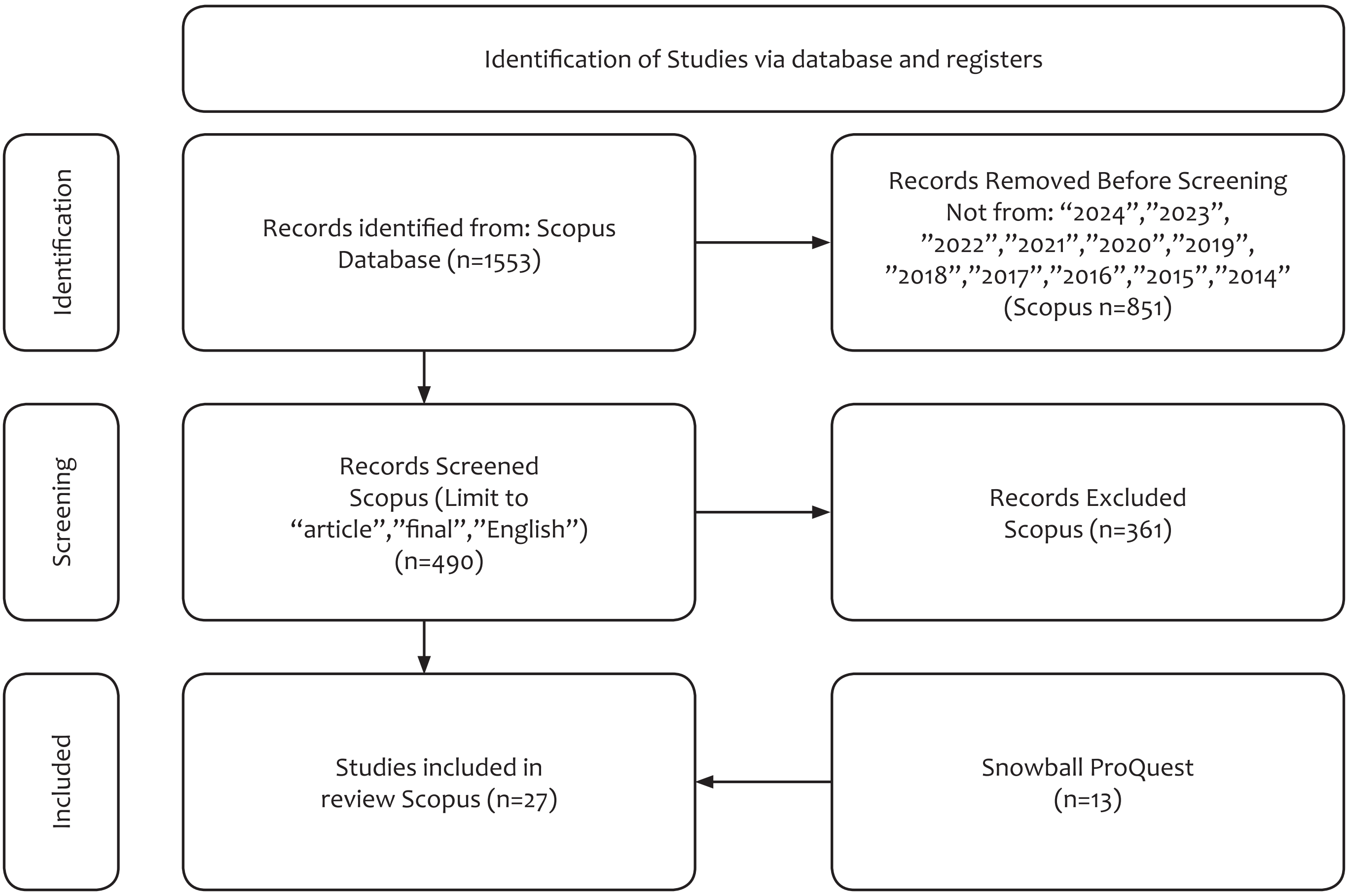

Figure 1 The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) for this study

Inclusion Criteria:

a. Final articles addressing traceability technologies in waste management.
b. Concentrate on the issue of plastic waste in industrial and recycling environments.
c. Published in Scopus-indexed or ProQuest journals between 2014 and 2024 in English.

Exclusion Criteria:

a. Studies unrelated to industrial plastic waste or lacking technology application.
b. Non-peer-reviewed literature or conference abstracts without full text.

Data Extraction and Coding Process

A qualitative synthesis approach was used, categorizing studies based on themes such as technology types, traceability outcomes, sustainability impacts, barriers, the challenges faced, and managerial implications. We analyzed the content manually through open coding, identifying common threads such blockchain, IoT, transparency, regulatory challenges, and stakeholder collaboration.

Operational Definitions

These are operational definitions used in the paper:

a. Traceability Technology: Refers to digital tools and systems, such as blockchain, Internet of Things (IoT), and QR Codes that enable tracking, recording, and verifying the movement of materials across the supply chain.

These technologies ensure transparency, accountability, and efficiency in waste management processes (Regueiro et al. 2024; Borandag, 2023; Ponis et al. 2023).

b. Smart Technologies: Encompass advanced digital innovations such as artificial intelligence (AI), digital twins, blockchain, and automated systems used to optimize waste tracking, processing, and management in industrial operations. These technologies are instrumental in achieving sustainability goals through increased efficiency and data driven decision making (Varriale et al. 2023; Teisserenc & Sepasgozar, 2021).

c. Sustainability Reporting Frameworks: Refers to structured guidelines that help organizations disclose their environmental, social, and governance (ESG) performance in a transparent and standardized manner. Notably frameworks include the Global Reporting Initiative (GRI) and the Sustainability Accounting Standards Board (SASB), both which provide sector-specific metric for evaluating sustainability performance. Thes frameworks facilitate accountability by aligning corporate reporting with stakeholder expectations and regulatory standards (Zamil & Hassan, 2019).

Research questions

RQ1. What are the current applications of smart technology from literature that will ensure and enhance traceability and sustainability in plastic waste management within the recycling paper industry?

RQ2. What are the barriers and drivers associated with the use of traceability technology recommended for sustainable plastic waste management of recycling paper industry in the circular economy framework

RQ3. What future research agenda can be identified for optimizing the use of smart technologies in plastic waste management within the recycling paper industry?

RESULTS AND DISCUSSION

Research Gap

1. Number of Publications

A total of 490 documents related to the keywords "traceability technology," "plastic waste management," "recycling paper industry," and "circular economy" published between 2014 and 2024 were retrieved from the Scopus database. The volume of documents exhibited a consistent upward trend from 2014 to 2022, followed by a slight decline in 2023, as illustrated in Figure 2.

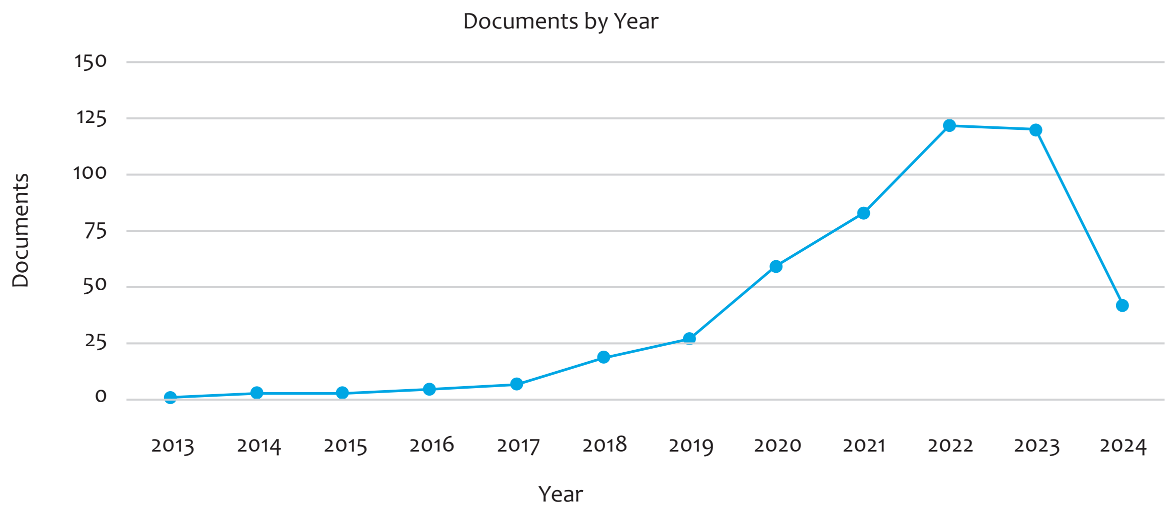

Figure 2 Number of Publication

The rise in research activity during this period may be attributed to the ongoing advocacy for sustainable waste management practices and the increasing utilization of smart and digital technologies to enhance traceability and sustainability in waste management. The steady increase in publications over the past decade reflects a growing interest in this field and the expanding discourse on the role of smart technology in ensuring traceability and sustainability in plastic waste management.

2. The Subject Area Covered

The research utilizes the keywords "traceability technology," "plastic waste management," "recycling paper industry," and "circular economy" spans 11 subject areas, as depicted in Figure 3. The top five subject areas by publication volume are environmental science (32.8%), energy (12.9%), social science (8.8%), engineering (7.6%), and computer science (5.7%).

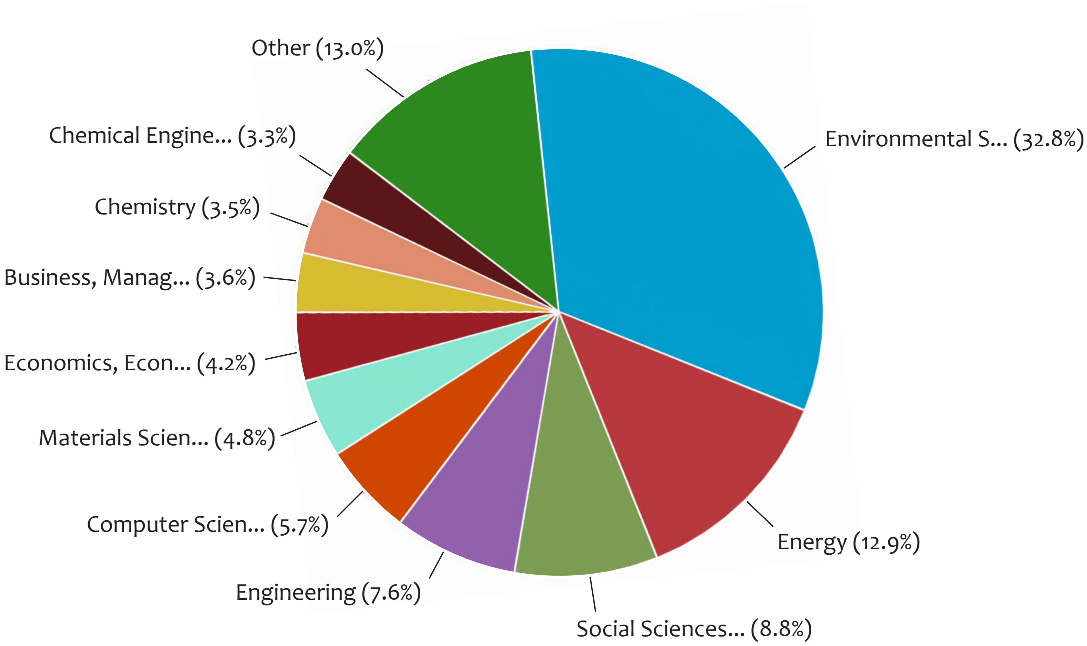

Figure 3 Proportion of Publication Documents by Subject Area

Plastic waste management has become a significant focus for researchers in environmental science. According to energy-related documents, energy recovery from waste is highly regarded as an effective environmental mitigation measure. Given that Environmental Sciences constitute a significant portion of the research, it is likely that topics related to sustainability and environmental impact are well-covered. However, the specific technology used to enhance traceability in the plastic waste recycling process, especially within the paper recycling industry, might not be as thoroughly explored.

a. Lack of Focus in Computer Science and Engineering: With only 5.7% of documents in Computer Science and 7.6% in Engineering, there seems to be a relatively low focus on the technological aspects that are crucial for improving traceability. Technologies such as blockchain, IoT, and advanced tracking systems, which are key to enhancing traceability, may not be receiving adequate research attention.

b. Materials Science (4.8%): Although Materials Science plays a crucial role in developing sustainable materials and improving recycling processes, the low percentage suggests that there may be a gap in research dedicated to understanding and innovating materials that are easier to recycle, including those used in paper and plastic waste streams.

c. Potential Underrepresentation in Social Sciences: 8.8% in Social Sciences might suggest a need for more research into the societal implications, regulatory frameworks, and consumer behavior related to the recycling industry. Understanding these aspects is essential for the successful implementation of traceability technologies and sustainability practices.

As a result, recent research and development initiatives have been launched to determine the optimal conditions and equipment for recycling paper mill waste. The advancement of smart technology within the field of computer science has emerged as a significant breakthrough, enhancing the traceability and sustainability of plastic waste management within the recycling paper industry.

3. Contribution by Territory

The enforcement of regulations specified in European Union directives, such as the zero landfills policy, has driven research into alternative fuels and their application. Consequently, there has been an increased emphasis on energy recovery and the reduction of greenhouse gas emissions from waste within these countries. Figure 4 illustrates the contributions of various countries to the body of knowledge surrounding the keywords "traceability technology," "plastic waste management," "recycling paper industry," and "circular economy." The United Kingdom leads with 84 publications, followed by Italy and Spain, with 45 and 43 publications, respectively, over the past decade. Additionally, Asian countries such as China and India have contributed 29 and 24 publications, respectively. The remaining publications primarily originate from other European countries. This indicates that research in this area is predominantly conducted by Western nations, highlighting a gap in literature from other global perspectives.

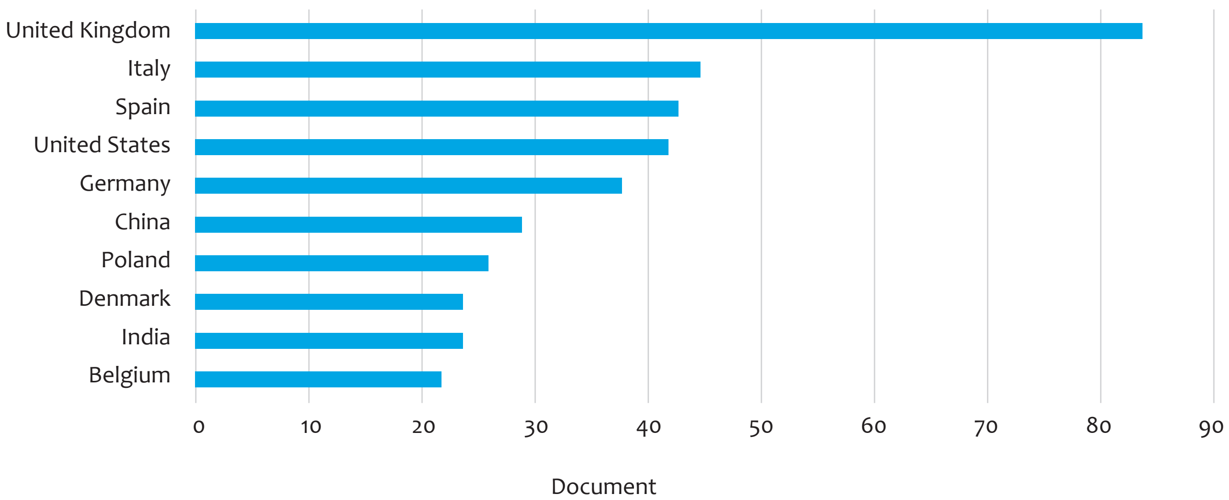

Figure 4 Number of publications by country

The Current Application of Smart Technology to Ensure Traceability and Sustainability

Based on the 40th journal review, there were few smart technologies found in the paper, as shown in Table 1. Table 1 provides a comprehensive overview of various studies that investigate the application of smart technologies to ensure traceability and sustainability in different industries. The table lists the titles of the studies, their authors, the specific smart technologies examined, and whether these technologies effectively ensure traceability and sustainability. This table summarizes recent smart technologies identified from the provided summaries that ensure traceability and sustainability across various industries. The content analysis focused on key aspects such as the technology used, whether it ensures traceability and sustainability, and the source of the information. Below are the key findings:

1. Blockchain Technology:
   Blockchain technology significantly improves transparency and traceability in plastic waste management by recording each transaction in the lifecycle of plastic products. It also supports secure data sharing and collaboration among stakeholders. Example: Blockchain-based refurbishment certification system ensures data integrity and enhances consumer trust in recycled products (Regueiro et al. 2024).
2. Internet of Things (IoT):
   IoT devices, such as sensors and RFID tags, are used for real-time monitoring of waste levels, optimizing collection routes, and reducing the frequency of waste overflow in bins. They enable better tracking and management of waste. Example: IoT-enabled smart waste management systems improve sorting processes and increase recycling efficiency (Barnabas et al. 2021)
3. LoRaWAN and Smart Bottles:
   The TRACKPLAST smart bottle uses a LoRaWAN-based wireless sensor network to track the movement of plastic waste. This technology is being used for real-time monitoring and visualization of the locations of waste. Such as: A pilot deployment of the TRACKPLAST system on Syros Island, Greece, had shown the potential of the system to track and analyse the movement patterns of plastic waste (Ponis et al., 2023).
4. Digital Twins:
   Incorporating digital twin technology through blockchain enables the creation of virtual projections of physical assets, which helps in improving tracking, simulating and optimizing waste management. For instance, the use of blockchain enabled digital twins in the construction sector has demonstrated an increase in transparency and improved operational efficiency (Teisserenc & Sepasgozar, 2021).
5. Artificial Intelligence (AI):
   Artificial intelligence (AI) technologies are used in data-based decision-making, optimization of waste management operations, and predicting waste generation trends. For example: AI has been applied in the supply chain to improve performance and reduce the environmental impact (Hong Z & Xiao K, 2024).
6. Digital Product Passports:
   Digital product passports combine the physical with the digital by pairing unique identifiers on products with virtual systems that track products from cradle to grave. For instance, in plastic waste management, their application increases transparency and accountability along the value chain (Qian et al. 2023)

With the integration of smart technologies like blockchain, IoT, AI, and digital twins into the recycling paper sector, plastic waste management has become notably improved in aspects of traceability, transparency, and sustainability. These technology innovations support the principles of the circular economy by enhancing resource efficiency, streamlining waste collection systems, and fostering coordinated engagement among stakeholders. The circular economy aims to reduce waste generation and maximize resource utilization through the establishment of closed-loop systems that prioritize the reuse and recycling of products, materials, and resources.

Table 1 Application of Smart Technology to Ensured Traceability and Sustainability

Technology	Application	Example	Author
Blockchain Technology	Enhance transparency and traceability by recording transactions in the lifecycle of plastic products.	Blockchain-based refurbishment certification system ensures data integrity and enhances consumer trust in recycled products.	Regueiro et al. (2024); Abbas & Myeong (2024); Ma et al. (2024); and Borandag (2023)
Internet of Things (IoT)	Real-time monitoring of waste levels, optimizing collection routes, and improving sorting processes.	IoT-enabled smart waste management systems improve sorting processes and increase recycling efficiency.	Barnabas et al. (2021)
LoRaWAN and Smart Bottles	Tracks the movement of plastic waste using wireless sensor networks for real-time monitoring and visualization.	TRACKPLAST smart bottle demonstrated effective monitoring of plastic waste movement patterns.	Ponis et al. (2023)
Digital Twins	Creates virtual models of physical assets for better tracking, simulation, and optimization of waste management processes.	Adoption of blockchain technology through digital twins improves transparency and efficiency in the construction industry.	Teisserenc & Sepasgozar (2021)
Artificial Intelligence (AI)	Enhances decision-making, optimizes waste management operations, and predicts waste generation patterns.	Integration of AI with blockchain for improving supply chain efficiency and reducing environmental impacts.	Hong & Xiao (2024)
Digital Product Passports	Combines physical and digital solutions to track the lifecycle of plastic products, ensuring traceability from production to disposal.	Use of digital product passports in tracking and managing plastic waste enhances transparency and accountability.	Qian et al. (2023)

Source: Scopus and ProQuest

Blockchain technology, often integrated with IoT, QR codes, and image processing, is the best choice for ensuring traceability and sustainability in the plastic waste management sector of the recycling paper industry. Blockchain technology stands out as the most recommended technology for ensuring traceability and sustainability in plastic waste management within the recycling paper industry. Among its key advantages are increased transparency, greater operational efficiency, facilitation of circular economy practices, secure data exchange, and robust fraud mitigation—positioning blockchain as a compelling solution to the prevailing challenges in this sector.

Results indicated that, according to the content analysis conducted on the studies summarized in Table 1, blockchain technology is the most promising approach with regards to traceability and sustainability when utilizing the paper industry for plastic waste management. Below you will find the key drivers and their respective benefits, alongside selected academic references that confirm these statements:

1. Enhanced Transparency and Traceability
   A decentralized, immutable ledger that records every transaction and stage in the life of plastic goods safely is provided by blockchain. It greatly improves transparency and traceability across the entire supply chain (Regueiro et al. 2024).
2. Improved Efficiency and Accountability
   The use of blockchain technology enables better tracking and verification throughout the plastic waste stream, resulting in more effective recycling and greater accountability among participants (Kolade et al. 2024).

3. Support for Circular Economy Practices
   Blockchain technology plays a significant role in supporting circular economy practices by optimizing the reuse and recycling of paper, thereby driving sustainability objectives while reducing waste generation in the paper recycling industry (Qian et al. 2023).
4. Secure Data Sharing and Collaboration
   Blockchain technology reduces cost and time to enable collaboration between many stakeholders while providing a single source of truth for all stakeholders and allowing them to trust the data (Ribeiro da Silva et al. 2023)
5. Fraud Detection and Prevention
   By utilizing scramble to log trade transactions and transaction files, blockchain offers the foundation for identifying fraudulent recycling processes and secure transactional data storage (Ponis et al., 2023).

Drivers and Barriers in the Adoption of Smart Technology for Waste Management

The adoption of smart technologies (blockchain, IoT, QR codes, and image processing) in waste management and, more specifically, in recycling pulp and paper is determined by various barriers and drivers. The following overview synthesizes insights from various authors:

1. Drivers

Table 2 presents key drivers that facilitate the adoption of blockchain, categorized into five thematic dimensions: transparency, accountability, operational efficiency, circular economy support, and stakeholder collaboration.

Table 2 Drivers to the implementation of Blockchain Technology

Driver	Description	Author
Improved Transparency and Traceability	Enhances supply chain transparency and traceability, ensuring compliance with sustainability standards.	Hong Z & Xiao K (2024) and Borandag (2023)
Enhanced Accountability and Trust	Ensures data integrity and trustworthiness, enhancing consumer trust in refurbished products.	Regueiro et al. (2024)
Efficient Supply Chain Management	Improves operational efficiency by providing real-time data and reducing redundancies.	Hau et al. (2023)
Facilitation of Circular Economy Practices	Supports transition to circular economy by enabling better resource management and minimizing waste.	Qian et al. (2023)
Support for Data Sharing and Collaboration	Facilitates secure data sharing and collaboration among stakeholders, essential for supply chain circularity.	Ribeiro da Silva et al. (2023) and Khadke et al. (2021)

Source: Scopus and ProQuest

The drivers of the implementation of blockchain technology are as follows:

a. Improved Transparency and Traceability
   Immutable Records: Blockchain provides an immutable ledger, ensuring transparency and traceability throughout the waste management process. Hong Z & Xiao K (2024) noted that blockchain technology significantly enhances supply chain transparency and traceability, making it easier to track the origins and lifecycle of materials, thereby ensuring compliance with sustainability standards. Borandag (2023) emphasized how blockchain ensures accurate tracking of recyclable materials, promoting transparency and sustainability.

b. Enhanced Accountability and Trust
Regueiro et al. (2024) mentioned the use of blockchain for refurbishment certification ensures data integrity and trustworthiness, enhancing consumer trust in refurbished products.

c. Efficient Supply Chain Management
Blockchain technology helps in optimizing resource utilization through transparency and real-time data availability, which reduces redundancy in circular supply chain management while improving operational efficiency (Hau et al. 2023).

d. Facilitation of Circular Economy Practices
The integration of blockchain technology and IoT facilitates the shift towards a circular economy by better management and minimizing the waste of resources (Qian et al. 2023). These technologies contribute to a circular economy by enabling more effective recycling, better resource management, reducing waste generation, and further sustainable initiatives. Wong et al. (2023) suggested that hybrid approaches that combine blockchain with machine learning can have positive environmental consequences by supporting sustainability in supply chain management.

e. Support for Data Sharing and Collaboration
Blockchain facilitates faster and more transparent data sharing among all stakeholders, enabling closer collaboration and coordination. As noted by Ribeiro da Silva et al. (2023) such secure data-sharing mechanisms are essential for supply chain circularity. Khadke et al. (2021) added that Blockchain is a strong factor to reinforce stakeholder engagement and cooperative interaction. By using blockchain, stakeholders can trust the data provided about the recycling process, being transparent and secure, thus motivating them to participate more in several recycling initiatives.

2. Barriers

While the potential benefits of blockchain technology in promoting transparency, accountability, and efficiency in plastic waste management are promising, there are several critical barriers that impede large-scale adoption of blockchain within the recycling paper industry. It is important to recognize these restrictions and find solutions in order to allow the successful adoption of blockchain-based traceability systems. The major challenges defined in literature can be grouped into six thematic areas — economic, technical, regulatory, behavioral, environmental, and data security concerns — which are summarized in Table 3.
The Barriers of the implementation of blockchain technology are as follows:

a. High Implementation Costs
Initial Investment: Implementing blockchain technology requires significant initial investment, along with IoT devices and autonomous sorting systems, which can be a barrier for low-scale ventures. Bułkowska et al. (2023) and Subekti (2023) also mentioned that these technologies required high initial investment costs and ongoing maintenance costs.

b. Technical Complexity and Scalability Issues
Integration Challenges: The integration of advanced technologies entails high complexity, necessitating substantial technical expertise and a strong infrastructure. Borandag (2023) and Ponis et al. (2023) highlighted the difficulties of the integration of blockchain, IoT, QR codes, and image processing systems, scalability issues.

c. Regulatory and Legal Challenges
Regulatory Uncertainties: The emerging and rapidly changing regulatory landscape related to blockchain and other smart technologies may pose material compliance risks. Kolade et al. (2024) acknowledged that

regulatory uncertainties and legal challenges related to blockchain technology may hinder its adoption in plastic waste management. The lack of regulatory clarity and the requirement for standardised protocols and practices (Bułkowska et al. 2023).

d. Energy Consumption Concerns
The operational or environmental footprint of these technologies, such as the energy consumption of blockchain networks, should be taken into consideration. Almadhi et al. (2023) comprehensive review published by the United Nations emphasized how the high energy consumption of blockchain technology — in particular when using proof-of-work consensus algorithms — is a major concern for its long-term environmental viability. However, the energy needed for transaction validation and network security is also increasing in tandem, which leads to a significant carbon footprint. Concerns surrounding environmental impact have triggered scrutiny on the overall feasibility of blockchain in long-term contexts because its operational impact may often be at odds with other sustainability goals.

e. Resistance to Change
Stakeholders might not embrace new technologies because they are not intuitive or complex (Prabawati et al. 2023). Bułkowska et al. (2023) emphasized that resistance to change could be a major a barrier, thus effective stakeholder through training and education is essential.

f. Data Privacy and Security Concerns
Protecting sensitive business and personal data is crucial, and the transparency of blockchain can often clash with privacy needs. Khadke et al. (2021) emphasized the role of secure and transparent systems, highlighting the critical need for appropriate frameworks for data privacy and security.

Table 3 Barriers of the implementation of Blockchain Technology

Barrier	Description	Author
High Implementation Costs	The considerable initial investment and implementation costs of blockchain technology are often expensive for many parties	Bułkowska et al. (2023) and Subekti (2023)
Technical Complexity and Scalability Issues	Technological limitations such as scaling and integration capabilities with existing systems can prevent its adoption	Ponis et al. (2023)
Regulatory and Legal Challenges	Regulatory and legal hurdles and ambiguity have hampered the mainstream adoption of blockchain technology	Kolade et al. (2024) and Bułkowska et al. (2023)
Energy Consumption Concerns	Energy consumption, particularly in blockchain systems that rely on proof-of-work consensus mechanisms, is highly expensive, and the resulting energy consumption has major environmental ramifications	Almadhi et al. (2023)
Resistance to Change	As a result of the operational tension associated with adopting new technologies and the reluctance of numerous parties, certain hurdles may prohibit the implementation in their organizations.	Bułkowska et al. (2023) and Prabawati et al. (2023)
Data Privacy and Security Concerns	Due to the importance of the establishment of secure and transparent systems, there has been an onset of robust data privacy and security concerns.	Khadke et al. (2021)

Source: Scopus and ProQuest

Traceability Technology for ESG Reporting and Sustainability Accounting Enablers

The nature of blockchain made it a natural choice as a core traceability technology, owing to its ability to provide immutable records of data as well as decentralized verification. These characteristics improve the transparency and integrity of plastic waste streams and let organizations measure relevant indicators responsive to Global Reporting Initiative/GRI 306 (Waste) and the Sustainability Accounting Standards Board/SASB's Material Sustainability Topics, including waste management efficiency and material traceability (Jones et al., 2017; Hong & Xiao, 2024). These frameworks require full disclosure of waste generation, treatment, and recovery processes, which can leverage a lot from digital technologies. As an example of this, blockchain has been implemented into waste management systems where organizations could record the lifecycle of plastic as it moves from materials input through to post-consumer processing. "This approach not only facilitates the collection of ESG-related data but also reduces the potential for errors often seen in manual reporting methods." The subsequent analysis either accounts for the established observations (Regueiro et al. 2024) or highlights discrepancies (Zamil & Hassan 2019).

Traceability technologies, from a managerial lens, are not limited to improvements in operational management; rather, they become an integral aspect of sustainability governance at a strategic level. This real-time visibility supports organizations to react appropriately towards the expectations of stakeholders and evolving regulations (Lestari et al., 2019; Attazahri et al., 2021). Furthermore, the data produced by these systems can easily fit codes into sustainability reports to guide managers to better respond to investor expectations, especially for industries where (ESG) performance matters a lot.

There is also literature reporting the strategic advantage for organizations that first adopt traceability technologies. Proactive businesses active in ESG initiatives and their transparent disclosures aligned with established frameworks such as GRI and SASB, would earn a greater trust of stakeholders, improve their corporate reputation and attract investments with ESG-focus (Semuel et al., 2019; Wong et al., 2023). Relatedly, legitimacy theory asserts that companies can attain public sanction and approval through improvements in transparency in their sustainable development efforts, specifically within environmentally sensitive industries (Zamil & Hassan, 2019).

The integration of smart technologies including blockchain, IoT, QR codes, image processing, and smart contracts into plastic waste management in India's recycled paper industry, leads to numerous managerial implications. In general these innovations offer the opportunity for companies to improve their operational management by increasing efficiency, transparency and sustainability, it also poses a set of challenges that will need to be met with a strategically aligned managerial perspective.

1. Enhanced Operational Efficiency
   Implications:
   a. Streamlined Processes: By reducing dependence on manual process through automation with IoT devices and image processing technologies, tracking, sorting, and management of plastic waste can be greatly facilitated helping to ensure more streamlined workflows. According to Borandag (2023), the combination of the Internet of Things (IoT), image processing, and QR codes has made major improvements in the productivity of recycling activities.
   b. Cost Reduction: Managers face high initial investment in smart technologies such as blockchain and IoT as there are barriers to entry, so they need to devise cost-effective strategies and financial models. To alleviate the estimated cost burden of implementation in the short run, developing long-term financial considerations as well as dealing with external funding opportunities or strategic partnerships (Subekti, 2023).

2. Improved Transparency and Traceability
   Implications:
   a. The findings of this review highlight the critical role of traceability technologies in the alignment of industrial practices with international sustainability reporting frameworks, e.g. the Global Reporting Initiative (GRI) and the Sustainability Accounting Standards Board (SASB). These frameworks stress transparency, accountability, and validity of environmental data with the wider use of blockchain and IoT technological deployments considerably enhancing these aspects (Khadke et al., 2021; Regueiro et al., 2024).
   b. Real-Time Monitoring: The blockchain-based system significantly improves transparency and traceability in the recycling process. Blockchain's immutable ledger and IoT's real-time monitoring capabilities can automate and authenticate such disclosures, thereby supporting consistent and auditable ESG Reporting (Hong & Xiao, 2024)
   c. Bułkowska et al. (2023): Highlighted the role of blockchain in enhancing transparency and traceability in waste management.
3. Regulatory Compliance and Risk Management
   Implications:
   a. Management must stay abreast of emerging regulatory environments and actively work with policy makers to encourage regulatory frameworks that support uptake of smart technologies in waste. This includes promoting clear and enabling legal frameworks. Particularly regulation uncertainties and unresolved legal issues with blockchain technology are potential substantial roadblocks to implementation into plastic waste management systems (Kolade et al. 2024)
   b. Risk Mitigation: The transparency and accuracy of data provided by blockchain and IoT can help in identifying and mitigating risks in waste management processes.
   c. Khadke et al. (2021): Discussed the regulatory benefits of implementing blockchain technology in plastic recycling.
4. Stakeholder Engagement and Collaboration
   Implications:
   a. Building Trust: The transparency provided crucial in building trust with key stakeholders such as suppliers, customers, and regulatory bodies.
   b. Enhanced Collaboration: By allowing the secure and transparent exchange of data, blockchain encourages deeper collaboration from all stakeholders involved within the recycling supply chain.
   c. Wong et al. (2023) have shown the way the convergence of blockchain and machine learning at Maersk made improved stakeholder collaboration and trust possible.
   d. According to Prabawati et al. (2023), effective adoption of these smart technologies requires active collaboration among diverse stakeholders, including manufacturers, waste management agencies, policymakers, and consumers. It is expected by managers that they will encourage this kind of engagement as it can lead to the consistent adoption of technology and running of operations.
5. Strategic Planning and Decision-Making
   Implications:
   a. Managers must focus on pilot projects to assess whether and how smart technologies will work in the real world. As noted by Ponis et al. (2023) The lessons learned from these pilot initiatives can help to improve and shape wider implementation strategies.

   b. Smart technologies facilitate the transition to circular economy models that allow reuse and recycling of materials. This has led managers to include these technologies in their operations to promote sustainability and resource efficiency (Qian et al., 2023).

6. Challenges and Change Management

   Implications:

   a. Overcoming Resistance: Managers must address resistance to change by effectively communicating the benefits of new technologies and providing adequate training and support to employees.
   b. Investment in Skills: There is a need for continuous investment in skills development to ensure that employees can effectively use and manage new technologies.
   c. Bułkowska et al. (2023): Noted the challenges of stakeholder acceptance and the importance of training and education in implementing new technologies.

CONCLUSION

In conclusion, by joining the upset environment community, Indonesia introduced can optimize its recycling, minimize its waste and encourage sustainable practicing, helping to promote a cleaner and more sustainable environment. These ground-breaking techniques foster transparency, improved operational efficiency, adherence with regulations, and use of resources in a responsible manner. Concerning the plastic waste management processes of the recycling paper industry, the literature review showed that blockchain has been highlighted as a technology of promise for improving traceability and sustainability. There are major hurdles to the integration of smart technologies in waste management, however the adoption drivers are equally strong. By actively targeting these barriers, stakeholders can optimize their uptake on smart technologies, and realize the potential benefits of traceability, operational effectiveness, data reliability and environmental performance. From a management perspective, the adoption of these technologies brings several strategic benefits, including improved operational transparency, better regulatory compliance, and increased stakeholder engagement. But managers also face challenges, including technology complexity, high implementation costs, data privacy apprehension, and resistance to change. It is only with effective change management and ongoing investment in skills development that the challenges can be addressed — and the potential of these technologies delivered. This study offers a new perspective on existing discussions of traceability in sustainability management and accounting, which have mainly focused on technology and engineering, that consider traceability tools as a way for ESG compliance and a means for improving the quality of sustainability reports. As noted by Khadke et al. (2021) and Hong & Xiao (2024), traceability technologies enhance not only operational efficiency but also produce robust, auditable data that contribute to GRI and SASB frameworks. Doing so not only promotes data transparency and integrity but also allows for easy ESG compliance with sustainability reporting frameworks (Zamil & Hassan, 2019).

Consistent with the legitimacy and stakeholder theories, firms with incorporated traceability in their ESG strategy are well placed to justify their actions to external stakeholders while optimizing internal decision-making. Representatively, these technologies enable us to do real-time monitoring, risk management, and a collaborative approach to resource governance, which are best practices for integrated waste management (Attazahri et al., 2021).

ORCID

Rr. Citra Rapati https://orcid.org/0009-0000-0037-5521
Marimin Marimin https://orcid.org/0000-0002-9415-5008
Yandra Arkeman https://orcid.org/0000-0002-6183-6069
Popong Nurhayati https://orcid.org/0009-0003-5665-5671

REFERENCES

Attazahri, A. K., Putro, U. S., & Nita, A. (2021). Designing scenarios for integrated and sustainable e-waste management: Case of Indonesia. *Indonesian Journal of Sustainability Accounting and Management, 5*(2), 209–221. https://doi.org/10.28992/ijsam.v5i2.387

Almadhi, A., Abdelhadi, A., & Alyamani, R. (2023). Moving from Linear to Circular Economy in Saudi Arabia: Life-Cycle Assessment on Plastic Waste Management. *Sustainability, 15*(13), 10450. https://doi.org/10.3390/su151310450

Abbas, Z., & Myeong, S. (2024). A Comprehensive Study of Blockchain Technology and Its Role in Promoting Sustainability and Circularity across Large-Scale Industry. *Sustainability, 16*(10), 4232. https://doi.org/10.3390/su16104232

Barnabas, S. G., Geethan, K. A. V., Ganesh, S. V., Rajakarunakaran, S., & Kumar, P. S. (2021). Role of Modern Technologies and Internet of Things in the Field of Solid Waste Management. *International Journal of Computers, Communications and Control, 16*(5), 1–12. Available at: https://univagora.ro/jour/index.php/ijccc/article/view/4239/1694

Borandag E. 2023. A Blockchain-Based Recycling Platform Using Image Processing, QR Codes, and IoT System. *Sustainability, 15*(7), 6116. https://doi.org/10.3390/su15076116

Bułkowska, K., Zielińska, M., & Bułkowski, M. (2023). Implementation of Blockchain Technology in Waste Management. *Energies. 16*(23), 7742. https://doi.org/10.3390/en16237742

Geissdoerfer, M., Morioka, S. N., de Carvalho, M. M., & Evans, S. (2018). Business models and supply chains for the circular economy. *Journal of Cleaner Production, 190*, 712–721. http://dx.doi.org/10.1016/j.jclepro.2018.04.159

Hau, B. M., You, S. S., Cho, G. S., Yeon, J. H., Kim, H. S. (2023). Circular supply chain management with blockchain integration. *Logforum, 19*(4), 515–533. https://doi.org/10.17270/J.LOG.2023.930

Hong, Z., & Xiao, K. (2024). Digital economy structuring for sustainable development: the role of blockchain and artificial intelligence in improving supply chain and reducing negative environmental impacts. *Scientific Reports, 14*(1). http://dx.doi.org/10.1038/s41598-024-53760-3

Jones, P., Wynn, M., Hillier, D., & Comfort, D. (2017). The Sustainable Development Goals and Information and Communication Technologies. *Indonesian Journal of Sustainability Accounting and Management, 1*(1), 1–15. https://doi.org/10.28992/ijsam.v1i1.22

Khadke, S., Gupta, P., Rachakunta, S., Mahata, C., Dawn, S., Sharma, M., Verma, D., Pradhan, A., Krishna, A. M. S., Ramakrishna, S., ... & Dalapati, G. K. (2021). Efficient plastic recycling and remolding circular economy using the technology of trust–blockchain. *Sustainability, 13*(16), 9142. https://doi.org/10.3390/su13169142

Kolade, O., Oyinlola, M., Ogunde, O., Ilo, C., & Ajala, O. (2024). Digitally enabled business models for a circular plastic economy in Africa. *Environmental Technology & Innovation, 35*, 103657. https://doi.org/10.1016/j.eti.2024.103657

Lestari, I. B., Hamzah, N., & Maelah, R. (2019). Corporate Social and Environmental Strategy and Reporting in Indonesian Plantation Industry. *Indonesian Journal of Sustainability Accounting and Management, 3*(1), 84–94. https://doi.org/10.28992/ijsam.v3i1.80

Lindholm-Lehto, P. C., Knuutinen, J. S., Ahkola, H., & Herve, S. H. (2015). Refractory organic pollutants and toxicity in pulp and paper mill wastewater. *Environmental Science and Pollution Research, 22*(9), 6473–6499. http://dx.doi.org/10.1007/s11356-015-4163-x

Liu, Z., Wu, T., Wang, F., Osmani, M., Demian, P. (2022). Blockchain Enhanced Construction Waste Information Management: A Conceptual Framework. *Sustainability, 14*(19), 12145. https://doi.org/10.3390/su141912145

Ma, D., Ma, P., & Hu, J. (2024). The Impact of Blockchain Technology Adoption on an E-Commerce Closed-Loop Supply Chain Considering Consumer Trust. *Sustainability, 16*(4), 1535. https://doi.org/10.3390/su16041535

Martínez-Peláez, R., Ochoa-Brust, A., Rivera, S., Félix, V. G., Ostos, R., Brito, H., Félix, R. A., Mena, L. J. (2023). Role of Digital Transformation for Achieving Sustainability: Mediated Role of Stakeholders, Key Capabilities, and Technology. *Sustainability, 15*(14), 11221. https://doi.org/10.3390/su151411221

Ministry of Industry. (2021). *Pulp and Paper Industry Performance Analysis Book*.

Ponis, S., Plakas, G., Aretoulaki, E., Tzanetou, D., & Maroutas, T. N. (2023). LoRaWAN for tracking inland routes of plastic waste: Introducing the smart TRACKPLAST bottle. *Cleaner Waste Systems, 4*(021), 100068. http://dx.doi.org/10.1016/j.clwas.2022.100068

Prabawati, A., Frimawaty, E., & Haryanto, J. T. (2023). Strengthening Stakeholder Partnership in Plastics Waste Management Based on Circular Economy Paradigm. *Sustainability, 15*(5), 4278. https://doi.org/10.3390/su15054278

Qian, C., Gao, Y., & Chen, L. (2023). Green Supply Chain Circular Economy Evaluation System Based on Industrial Internet of Things and Blockchain Technology under ESG Concept. *Processes, 11*(7), 1999. https://doi.org/10.3390/pr11071999

Regueiro, C., Gómez-Goiri, A., Pedrosa, N., Semertzidis, C., Iturbe, E., & Mansell, J. (2024). Blockchain-based refurbishment certification system for enhancing the circular economy. *Blockchain: Research and Applications, 5*(6), 100172. http://dx.doi.org/10.1016/j.bcra.2023.100172

Ribeiro da Silva, E., Lohmer, J., Rohla, M., & Angelis, J. (2023). Unleashing the circular economy in the electric vehicle battery supply chain: A case study on data sharing and blockchain potential. *Resources, Conservation and Recycling, 193*, 106969. https://doi.org/10.1016/j.resconrec.2023.106969

Rumetshofer, T., & Fischer, J. (2023). Information-Based Plastic Material Tracking for Circular Economy—A Review. *Polymers, 15*(7), 1623. https://doi.org/10.3390/polym15071623

Rapati, R. C., Victor, A., Raharjo, A. R., & Nuraisyah, A. (2023). Plastic Waste Management to Support The Circular Economy in The Pulp and Paper Industry. *Business Review and Case Studies, 4*(1), 1–11. http://dx.doi.org/10.17358/brcs.4.1.1

Semuel, H., Hatane, S. E., Fransisca, C., Tarigan, J., & Dautrey, J. -M. (2019). A Comparative Study on Financial Performance of the Participants in Indonesia Sustainability Reporting Awards. *Indonesian Journal of Sustainability Accounting and Management, 3*(1), 95–108. https://doi.org/10.28992/ijsam.v3i1.84

Subekti, R. (2023). A Circular Economy-Based Plastic Waste Management Policy in Indonesia (Compared to China and EU). *Yustisia, 12*(2), 168–184. https://doi.org/10.20961/yustisia.v12i2.72177

Teisserenc, B., & Sepasgozar, S. (2021). Adoption of blockchain technology through digital twins in the construction industry 4.0: A PESTELS approach. *Buildings. 11*(12), 670. https://doi.org/10.3390/buildings11120670

Varriale, V., Cammarano, A., Michelino, F., Caputo, M. (2023). Industry 5.0 and Triple Bottom Line Approach in Supply Chain Management: The State-of-the-Art. *Sustainability, 15*(7), 5712. https://doi.org/10.3390/su15075712

Wong, S., Yeung, J. K. W., Lau, Y. Y., Kawasaki, T. (2023). A Case Study of How Maersk Adopts Cloud-Based Blockchain Integrated with Machine Learning for Sustainable Practices. *Sustainability, 15*(9), 7305. https://doi.org/10.3390/su15097305

Zamil, G. M. S., & Hassan, Z. (2019). Impact of Environmental Reporting on Financial Performance: Study of Global Fortune 500 Companies. *Indonesian Journal of Sustainability Accounting and Management, 3*(2), 109–118. https://doi.org/10.28992/ijsam.v3i2.78