

Article

Applying the Circular Economy Framework to Blockchain Agricultural Production

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Abstract: Agriculture is one of the most economically important practices in the world; it is essential for food security and socioeconomic development in several countries. However, the use of pesticides, which are essential for fighting pests and weeds and guaranteeing agricultural yields, has brought about an environmental issue pertaining to the management of empty pesticide packaging. The improper disposal of pesticide packaging can put both environmental and human health at risk. Therefore, the implementation of reverse logistics systems will be essential if we are to ensure that packages are collected, recycled, and disposed of safely. Blockchain technology is an innovative solution that offers transparent and immutable recording of data, thereby facilitating traceability. In this study, we present the application of a circular economy-based framework to agricultural production via blockchain (and involving all actors within production and consumption) to enable the more responsible disposal of empty pesticide packaging for eventual reuse, recovery, or recycling. Bibliographical research was carried out through Scopus and Web of Science from 2018 to 2023; we principally aimed to provide an overview of this pertinent area of research using the following keywords: “blockchain”, “circular economy”, “pesticide packaging”, and “reverse logistics”. Bibliometrics using graphs and tables made it possible to refine the information collected from the databases. We analyzed how blockchain can be integrated alongside reverse logistics, highlighting how it can promote the principles of the circular economy through various methods of sustainable and responsible agriculture.

Keywords: circular economy; blockchain; pesticide packaging; reverse logistics



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1. Introduction

Agriculture and livestock represent fundamental pillars of society, playing essential roles in ensuring food security, economic development, and environmental preservation. These sectors encompass both food production and the supply of vital raw materials for various industries [1]. However, conventional agriculture has caused soil degradation, accelerating the loss of organic matter and affecting its physical and biological activity. To mitigate this degradation, technologies such as zero-tillage, ridging, and laser land leveling have been adopted, resulting in water savings, cost savings, timely sowing, the efficient use of resources, and the counteracting of adverse climatic effects [2].

Papers by researchers such as Singh et al. [3] and Mohankumar et al. [4] have highlighted the significant impact of agriculture on a given country’s economic development. For instance, in India, agriculture supports around 58% of rural families and generates two-thirds of the country’s jobs. On the other hand, in Brazil, one of the world’s largest food manufacturers, vast territorial extension alongside favorable climatic conditions have created a diverse agriculture sector, forming the basis of the Brazilian national economy. Also noteworthy are Brazilian achievements in sugar cane farming, soybean farming, and orange juice production, which have led to its prominent economic position on the world stage [5].

However, the escalation in agricultural production in order to meet the growing global demand for food has generated various challenges, among which pest and weed control are key. Pesticides are a widely adopted means of ensuring food security and greater agricultural productivity. However, the excessive use of these products and the inadequate disposal of empty packaging have had adverse environmental effects and threatened human health [6–8]. By contrast, ecological agriculture represents a new model of agricultural production, in line with the concept of green development; it involves the safe use of synthetic fertilizers and pesticides or their complete omission thanks to resource recycling. This method integrates the traditional agriculture approach with modern management practices, science, and technology, ensuring the safe production of high-quality agricultural products and promoting an ethically sound cycle between production and its ecology [9].

It should be noted that pesticide issues exist everywhere. Europe, China, and the United States are the largest consumers of these products; there are worldwide concerns about pesticide residues left in the environment and their adverse effects on health [10].

In light of such issues, China, Brazil, the United States, and the European Union (EU) have implemented regulations for the responsible use of pesticides, aiming to protect both public health and the environment [11].

We propose a circular economy-based framework to be applied to agricultural production using blockchain technology, with the aim of enabling the responsible disposal of empty pesticide packaging. This approach seeks to involve all actors involved in the process, from production to consumption, with the aim of reusing, recovering, or recycling such materials.

In the next section, we present the theoretical framework that underlies the research, followed by a description of our methodology. We present the study's results, including a bibliometric review and the proposed framework, in the subsequent section. Finally, we discuss the conclusions and further potential of this work.

2. Theoretical Framework

2.1. Pesticide Packaging

Empty containers of pesticides, once used to combat pests and weeds, quite often retain residual product, which can cause several health problems for rural workers and other humans while also damaging the environment. The residues left on pesticide packaging can result in poisoning and other health problems, making their correct disposal of paramount importance; reverse logistics is one way we might manage this [12].

According to Meng et al. [13], the improper disposal of agricultural waste degrades soil and water, generating carbon dioxide, methane, and nitrous oxide. To combat these problems, China has implemented the “Zero Waste City” action plan, a system that controls and supervises the safe use and disposal of hazardous waste. This plan aims to reduce the generation of waste and increase solid waste recycling, thereby minimizing the environmental impact.

There is global concern about the fate of empty pesticide packaging because, in addition to the health and environmental damage, it takes a long time to decompose. Some developing countries, such as Brazil and Chile, have already begun to regulate the disposal of such packaging through reverse logistics [14].

According to Rodrigues et al. [15], empty pesticide packaging puts biodiversity at risk because it has the same properties as pesticides. Therefore, such packaging requires special attention and must be given back to its producers to ensure its correct disposal.

In Brazil, one of the measures adopted to reduce environmental damage resulting from human activities was the National Solid Waste Policy, through Law 12.305 of 2 August 2010, which involved several actions to reintegrate waste into the production cycle and return packaging to producers through reverse logistics [16]. This law also established collection centers from which empty packaging may be collected and returned to producers, thereby contributing to environmentally safe disposal.

The proper disposal of pesticide packaging is of paramount importance in protecting both the environment and human health. The effective implementation of reverse logistics plays a crucial role in the responsible management of waste. By establishing appropriate systems for collecting, transporting, and recycling used packaging, reverse logistics allows these materials to be handled in a safe and environmentally conscious way, thus reducing the risk of soil, water, and food contamination.

2.2. Reverse Logistics

According to Panghal et al. [17], reverse logistics involves the flow of products, materials, and waste back to their origin, either for proper disposal, recycling, reuse, or remanufacturing. This process begins when the customer returns the product, reversing the flow in the supply chain, and the product returns to the manufacturer or distributor. Robles and La Fluente [18] have stated that reverse flows, which reincorporate materials into production processes or dispose of them for resale, are a part of closed-loop supply chains. This means that these supply chains include both direct flows (from products leaving the manufacturer and going to the consumer) and reverse flows (from products returning from the consumer to the manufacturer or another point in the chain), which promote sustainability.

According to Shih et al. [19], reverse logistics contributes by directly reducing the cost of disposal, reducing the use of raw materials, eliminating waste, and promoting recycling; products may be transformed into raw materials, enabling proper disposal, thus protecting the environment and promoting sustainability.

According to Yan et al. [14], the waste from empty pesticide packaging can cause damage to the environment, and it takes a long time to decompose; for these reasons, this subject has attracted global attention. Several countries have taken measures to control the proper disposal of such containers. In Brazil, the National Solid Waste Policy (PNRS) regulates reverse logistics through shared responsibility throughout the life of products, with the aim of reducing irregular disposal.

As stated by Li et al. [20], more than 62 percent of Chinese farmers dispose of pesticide packaging in water or on farmland. In China, administrative measures—such as the soil pollution prevention and control laws of the People's Republic of China—have been implemented to promote the recycling and treatment of empty pesticide packaging, and these are essential to address public health issues, environmental challenges, and improper waste management.

According to Zikankuba et al. [10], pesticide regulations are stricter in developed countries than in developing countries. In the United States, each governmental department deals with the regulations related to its sector; for example, the Environmental Protection Agency has set limits on the maximum permissible food and feed residues and also enforces the registration and regulation of pesticides.

One study carried out by Phan et al. [21] shows that the European Union has the strictest pesticide-related regulations in the world. Several committees are involved in the authorization of pesticide use. The European Union, created in 1993, has the wellbeing and safety of its citizens as its main objective.

The effective implementation of reverse logistics plays a fundamental role in reducing the improper disposal of empty pesticide packaging in the environment. By establishing systems for collecting, recycling, and properly disposing of such waste, reverse logistics not only prevents soil and water contamination, but also promotes the sustainable management of natural resources, thus furthering our progress towards a truly circular economy.

2.3. Circular Economy

Reverse logistics is directly linked to the circular economy because by reintegrating used products or waste into the supply chain, it allows us to reduce our exploitation of raw materials and the environmental consequences of production. According to Santhi and Muthuswamy [22], the purpose of the circular economy is to reduce damage to the

environment by recycling and recovering resources, which differentiates it from the linear economy (produce–consume–discard).

According to Reis et al. [23], population growth and increasing consumption have contributed to the accumulation of waste, which has adverse effects on both environmental and human health [13,24].

The increased presence of waste in modern society is the result of a system known as the linear economy (based on the following pattern: produce–use–discard) [24–27]. A new system is emerging to overcome this linearity, and it is referred to as the circular economy (based on the following pattern: restore–reuse–recycling) [28]. Its purpose is to combat environmental damage and provide social and economic benefits by allowing products to remain in circulation for longer. Figure 1 shows the main principles of the circular economy.



Figure 1. Circular economy.

Catherine Weetman defines the circular economy as a new business model that is essential if we are to overcome the environmental and resource-related challenges of the future. It is implemented by reducing waste and maximizing the efficient use of resources through encouraging recycling and reuse and extending the life cycle of products. The author also points out that the circular economy can create new business and innovation opportunities and promote environmental sustainability [29].

The circular economy helps sustainable development because it has the capacity to reduce waste through recycling and reuse, and it can change business models and also contribute to extending products' life cycles. Blockchain can make a significant contribution to the circular economy, facilitating new business models by promoting transparency and generating economies of trust, thereby transforming economic and institutional systems. It supports the reduce, reuse, and recycle pattern, enabling traceability in supply chains and increasing responsible purchasing behavior. In waste management, blockchain facilitates waste exchange platforms and recycling schemes through smart contracts [30].

As stated by Chidepatil et al. [31], the use of blockchain technology has provided security and immutability to the exchanges of information between manufacturers, collectors, and recyclers; smart contracts enable clear specifications regarding the quality of recycled plastics, pricing, supply and demand, and other factors. This technology has made the circular economy-based treatment of solid waste a profitable enterprise.

The adoption of blockchain technology in pesticide packaging can contribute to the integration of reverse logistics and the principles of the circular economy in agriculture. Such technology makes it possible to transparently and immutably record all stages of a piece of packaging's life, from production to disposal, enabling the complete traceability of products and promoting reuse, recycling, and remanufacturing. As a result, the use of blockchain technology within pesticide packaging not only maximizes the value of

resources, reducing waste and its adverse impact on the environment, but also drives our collective transition to a more circular and resilient agricultural model.

2.4. Blockchain

Blockchain acquired worldwide prominence in 2008 with the cryptocurrency Bitcoin, a digital currency based on this technology [28,32,33]. Blockchain technology operates on a peer-to-peer network, eliminating the need for intermediaries in transactions, and employs a distributed and decentralized database in which records are stored in an encrypted and immutable way [34,35].

As claimed by Castiglione et al. [36], blockchain's security and reliability derive from its decentralized architecture, which guarantees the immutability and visibility of information to all participants in the network.

The blockchain structure consists of a chain of interconnected blocks, each of them containing transaction information, a unique identification (hash), and a reference to the previous block (previous hash). Each new transaction is recorded in a new block, subject to validation by all nodes in the network, before being added to the chain [34]. Figure 2 shows an example of a blockchain transaction.

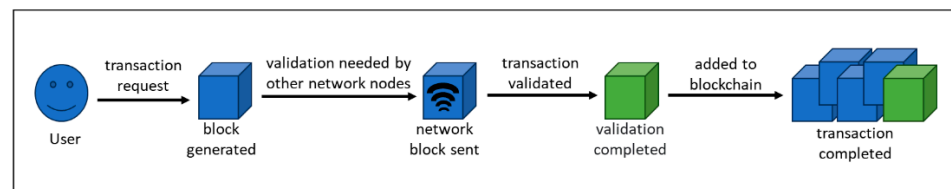


Figure 2. The flow of a blockchain transaction.

The fundamental characteristics of blockchain, as noted by Santhi and Muthuswamy [22], include immutability, decentralization, distributed ledgers, and a consensus mechanism. Immutability ensures that the transactions recorded on the blockchain are permanent and unalterable. Decentralization means that there is no central authority controlling the network; instead, there is a consensus among the participating nodes. The distributed ledger ensures that data are shared and synchronized among the network members. Finally, the consensus mechanism ensures that all transactions are validated by the majority of nodes before being confirmed on the network.

Blockchain technology, as a decentralized data storage system in the form of a distributed ledger, promotes the security and reliability of transactions. Each node in the network keeps a ledger copy and contributes to validating and updating the information, guaranteeing a majority consensus [30,37]. The application of blockchain in commercial transactions allows confidential information to be exchanged securely and efficiently, without the need for intermediaries.

Blockchain technology surpasses traditional databases by offering greater security, transparency, and efficiency in data management. It reduces the need for intermediaries, as its tamper-proof nature and use of cryptographic hash functions make it difficult to alter recorded information. The distributed design facilitates communication and data sharing between business networks, allowing authorized blockchains to establish access rules. Smart contracts automate agreements, eliminating the need for third parties, and digital signatures ensure data integrity. These capabilities make blockchain an immutable and more reliable ledger for managing data in supply chains and reverse logistics [38].

Traceability is one of the most significant advantages offered by blockchain. This technology allows network participants to access reliable information about a product's origin and history, ensuring transparency and authenticity throughout the supply chain [22,39]. Smart contracts, another important element of blockchain, facilitate the automation and execution of agreements among members; examples of these agreements are return programs and discounts enabled through the smart contracts [40].

The adoption of blockchain in the supply chain, as highlighted by Bekrar et al. [41], can contribute to the development of efficient tracking systems. Ethereum, one of the main blockchain platforms, supports the creation and execution of smart contracts, making it possible to implement methods of tracking and managing the supply chain.

After blockchain technology gained prominence with Bitcoin, platforms such as NXT, Ethereum, and Hyperledger Fabric were also developed to manage smart contracts. Ethereum stands out as the most robust and widespread; thanks to its versatility, it is used to develop smart contracts and decentralized applications (dApps) [42]. Launched in 2015, Ethereum has its own cryptocurrency, Ether (ETH), and a decentralized Turing-complete machine (EVM) for running scripts. It supports languages such as Solidity and Vyper and is the main choice for building dApps [43]. In order to build an application on any platform, a development environment is required. The process of deploying smart contracts on Hyperledger Fabric involves building the development environment, downloading Fabric components and Docker images for the chaincodes (which define the business's logic), and using the Go or Java programming languages. Hyperledger Fabric's SDK makes it easy to write applications, using the invocation method to call chaincodes and execute transactions [44].

In recent years, several studies have explored blockchain's potential to improve the efficiency and sustainability of supply chains, in line with the principles of the circular economy [34,45]. By promoting the traceability and transparency of transactions, blockchain can reduce waste, reduce logistics costs, and strengthen the integrity of the supply chain [46].

Blockchain technology, with its ability to provide security, reliability, and transparency in transactions, has the potential to transform reverse logistics management, and in doing so, promoting a more sustainable circular economy. Its application to the tracing and management of pesticide packaging may make a significant contribution to mitigating the environmental risks, while promoting a more efficient and responsible approach to the disposal of such materials.

3. Methodology

Our research was conducted using a methodology that integrates a literature review into applied research. To ensure comprehensive understanding, the literature review was carried out using Scopus and Web of Science, which are recognized for their quality and volume of available publications [47]. Bibliometrics, as a quantitative tool, was used for statistical analysis, providing a detailed view of the data collected [32].

As noted by Snyder [48], a literature review is essential for furthering one's knowledge and ensuring theoretical development; it provides a comprehensive overview of the relevant research area. Gil [49] adds that applied research aims to generate new knowledge applicable to specific situations. The combination of a literature review and a bibliometric study allowed for a detailed analysis of the relationship between the circular economy and blockchain technology, further contributing to the applied research in the development of a model for tracing pesticide packaging.

Figure 3 shows the methodology of our bibliometric study.

As seen in Figure 3, Scopus and Web of Science were initially chosen for our literature searches. According to Kumpulainen and Seppänen, Scopus and Web of Science are the most prominent databases and citation indexes for broad-purpose scientific literature, including books, journal articles, and conference proceedings. These platforms are widely recognized for the quality and comprehensiveness of their scientific publications, thus providing a solid basis for a literature review [50].

Next, keywords were defined to search for and select the scientific articles that would serve as the basis for the study, ensuring a close association with the topic addressed. The following keywords were chosen: "circular economy", "blockchain", "reverse logistics", and "pesticide packaging". These keywords enabled a focused and relevant search of the literature, facilitating the identification of the works most relevant to the topic of the study.

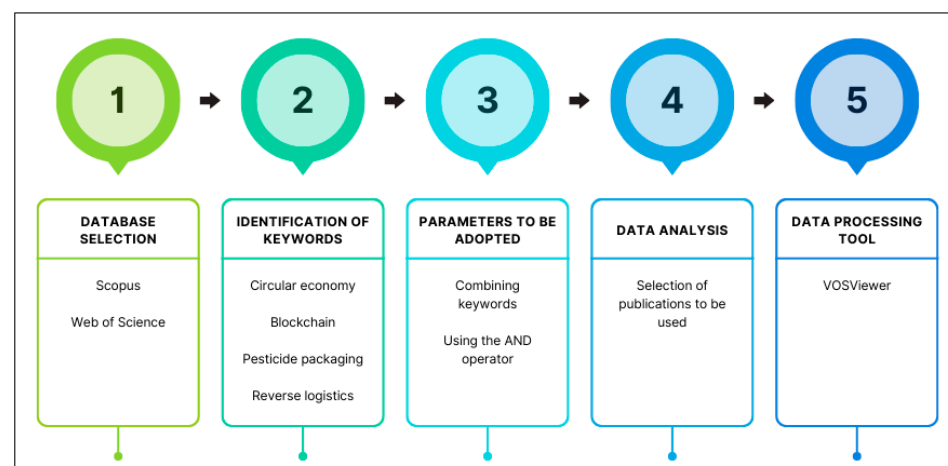


Figure 3. Methodological path.

The search terms were carefully selected to ensure the relevance of the results. We used the AND operator in combination with specific keywords to select essential documents for the search. The combinations used were as follows: “circular economy” AND “blockchain”, “circular economy” AND “blockchain” AND “reverse logistics”, “circular economy” AND “blockchain” AND “pesticide packaging”, and “circular economy” AND “blockchain” AND “reverse logistics” AND “pesticide packaging”. In addition to the AND operator, the selection criterion was limited to publications from 2018 to 2023, ensuring the timeliness and relevance of the studies analyzed; this is because no relevant publications referring to the keywords “circular economy” and “blockchain” were found before 2018.

Subsequently, a search for results was carried out, and exclusion criteria were applied to the returned documents that were not relevant to the theme of this study. The application of these criteria began with the reading of publication titles and abstracts. Whenever this reading was not enough to determine the relevance of the publication for the review, the methods were analyzed. If the association with our research was still unclear, the document was read in full. The data collected were analyzed using graphs and tables created in spreadsheet software.

After selecting the publications and analyzing the graphs and tables, VOSviewer software (Version 1.6.20) was used to create and visualize bibliometric maps. This software facilitates bibliometric data analysis and interpretation, representing networks of co-authorship, co-citation, and recurring terms. The maps generated by VOSviewer allow for the identification of patterns, trends and structures in large sets of bibliographic data, contributing significantly to the understanding and advancement of scientific knowledge.

Scopus and Web of Science were explored to identify articles published from 2018 to 2023, using keywords such as “circular economy”, “blockchain”, “pesticide packaging”, and “reverse logistics” combined with the AND operator, in order to select only the most relevant publications. This approach enabled a comprehensive and up-to-date analysis of the state of the art in this field.

Through our literature review and bibliometric study, we acquired an in-depth understanding of the issues related to the circular economy, blockchain, and reverse logistics as they pertain to pesticide packaging. These insights informed the development of a traceability model created to improve the management and safe return of those materials, thus contributing to the promotion of more sustainable and responsible practices in the agricultural supply chain.

4. Results and Discussion

After searching the literature, the data from Scopus and Web of Science were analyzed. Our search covered documents published from 2018 to 2023 and used the following keywords: “blockchain”, “circular economy”, “pesticide packaging”, and “reverse logis-

tics". However, a search performed with all keywords did not identify any corresponding documents.

Table 1 shows the number of publications found in the Scopus and Web of Science databases from 2018 to 2023, classified according to the keywords used. This analysis provides a comprehensive view of the research in question.

Table 1. Grouping of keywords.

Keywords	Scopus	Web of Science
"blockchain" AND "circular economy"	292	271
"blockchain" AND "circular economy" AND "reverse logistics"	8	1
"blockchain" AND "circular economy" AND "pesticide packaging"	0	0
"blockchain" AND "circular economy" AND "pesticide packaging" AND "reverse logistics"	0	0

Table 1 shows that the number of publications resulting from the keywords "blockchain", "circular economy", and "reverse logistics" is still small, while there has been a progressive increase in publications related to the keywords "blockchain" and "circular economy".

We next sought to find the frequency of publications per year for the keywords "blockchain" and "circular economy". As shown in Table 2, the analysis of the documents obtained from Scopus revealed a steady increase in the number of publications in recent years.

Table 2. Keywords: "circular economy" and "blockchain" (documents per year).

Scopus	
2018	7
2019	10
2020	24
2021	50
2022	90
2023	111

Figure 4 shows the evolution of publications per year using Scopus.

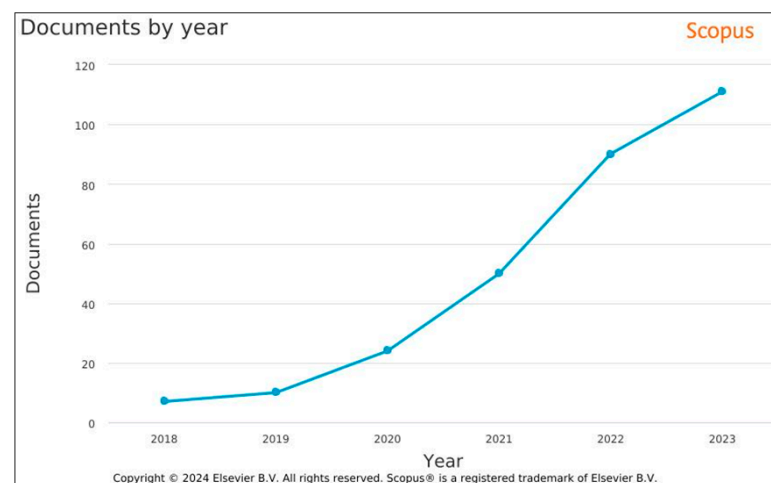


Figure 4. Number of publications per year within Scopus.

We performed the same searches on Web of Science, which also indicated an increase in the number of publications related to "blockchain" and "circular economy" in recent years. However, in 2022, there were slightly more publications than in 2023. Our results are shown in Figure 5.

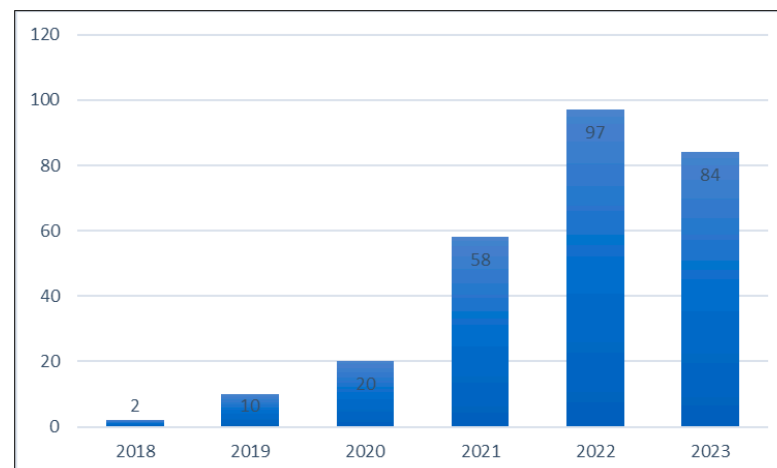


Figure 5. Documents per year within Web of Science.

The research carried out through Scopus and Web of Science indicated a significant increase in researchers' interest in the keywords "blockchain" and "circular economy", as reflected in the growing number of publications each year.

Figure 6 shows a pie chart reflecting the searches of the Scopus database, covering the period from 2018 to 2023 and using the keywords "blockchain" and "circular economy". Each graph sector corresponds to a specific subsection of the publications examined.

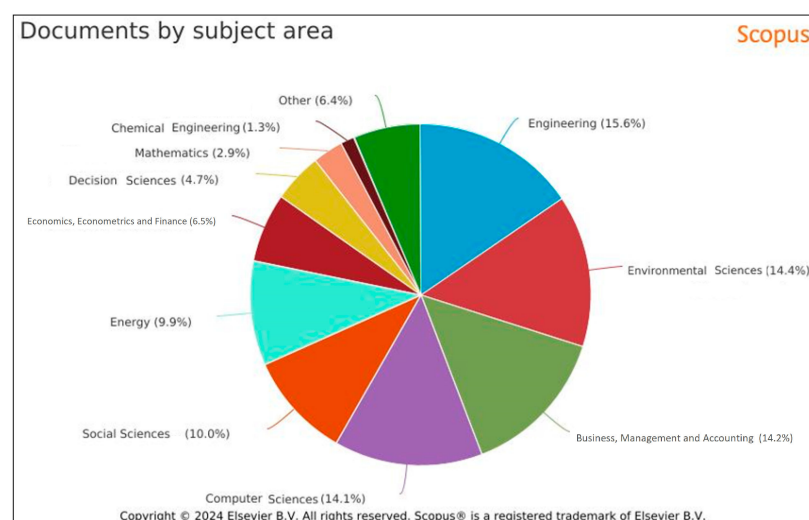


Figure 6. Main publication topics, according to Scopus.

This graph shows that the topic of engineering was featured in the highest volume of publications during the research period, while mathematics and chemical engineering were among those that featured in the lowest number of publications during the same period.

Bibliometrics enabled us to visually represent our literature review. Figure 7 shows our survey and analysis of the keywords "circular economy" and "blockchain", identified through Scopus and visualized with VOSviewer software.

This visual representation highlights the keywords' interconnection through nodes and color groupings, with the larger bubbles associated with the most frequent keywords in the returned publications. The lines represent the connections between those words, highlighting their recurrence in many publications. When a word is selected, the lines connected to it become more evident, as exemplified in the following figure with the choice of the word "traceability".

Figure 8 shows the links between the word "traceability" and the keywords "circular economy", "blockchain", and others that appeared in the researched articles.

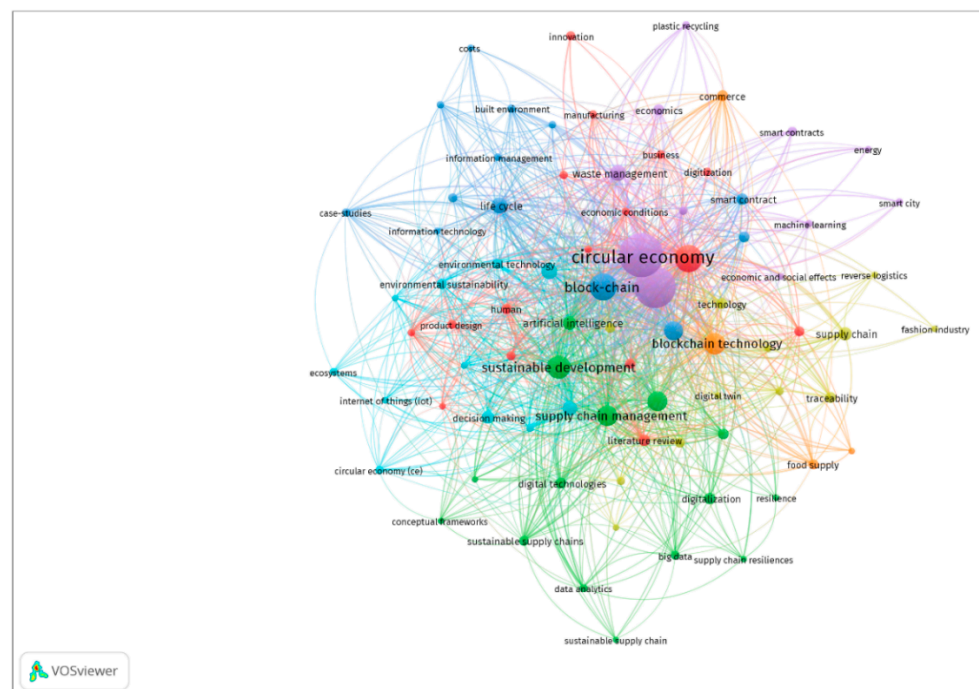


Figure 7. Keywords of analyzed articles identified through Scopus database.

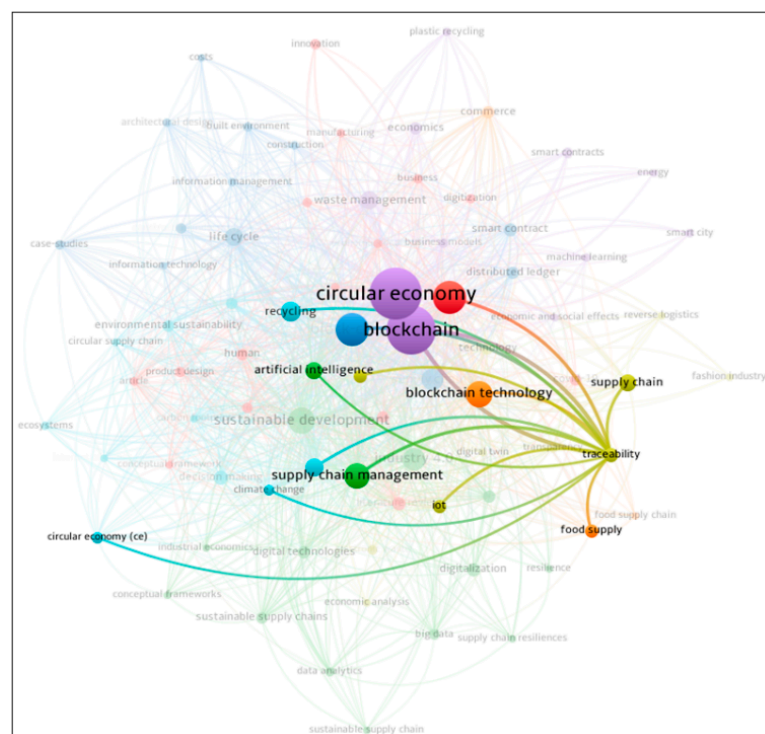


Figure 8. Example of links between keywords.

The bibliometric analysis, represented by the graphs, made it possible to refine the analysis of the information from these databases and also produced a useful overview of the areas under study. This analysis made it possible to verify the high number of publications released in recent years and the number of articles published with the keywords defined in this article.

Our literature review provided an understanding of the state of the art on the subject, highlighting the importance of the circular economy and blockchain technology in

achieving sustainability. The purpose of this article is to make the reverse logistics-based management of pesticide packaging viable, thereby contributing to a well-preserved environment and greater sustainability.

4.1. Model

The reverse logistics model for managing the return of pesticide packaging is a system whose primary aims are packaging collection and proper disposal; ideally, it will minimize environmental damage and ensure compliance with current legislation. This process involves several stages and the participation of different stakeholders, including manufacturers, traders, farmers, collection companies, and governments.

Public authorities play a crucial role in regulating and supervising all stages of reverse logistics, ensuring compliance with the rules. Specific legislation establishes guidelines and shared responsibilities among manufacturers, traders, consumers, and the government. Figure 9, below, shows the flow of pesticide packaging.

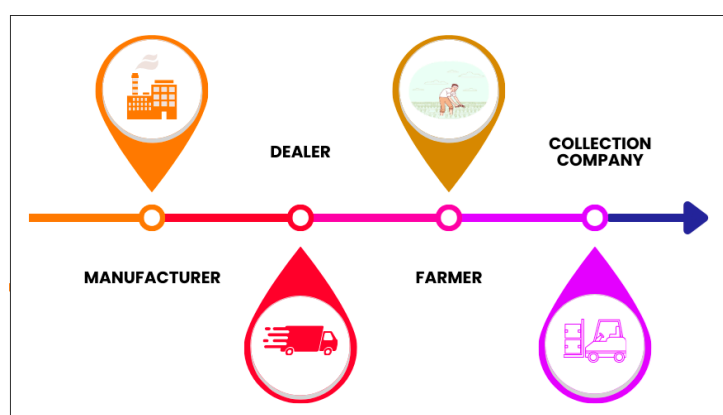


Figure 9. Flow of pesticide packaging.

Joseph Sarkis, an expert in the circular economy and blockchain technology with more than 10 articles published in the Scopus and Web of Science databases, alongside Mahtab Kouhizadeh and Qingyun Serena Zhu, also experts in the field, points out in the article “Digitalisation and the Greening of Supply Chains” that blockchain technology significantly improves environmental performance. Blockchain enables waste to be traced throughout the supply chain, facilitating the collection of information from consumers to manufacturers and potentially rewarding the consumers with cryptocurrencies. Smart contracts store the terms and conditions of the waste programs and trigger recovery actions, thus improving the exchange of waste between companies. In addition, blockchain offers the transparency and traceability needed for recycling and recovery activities throughout a given product’s life cycle, making it especially pertinent in reverse logistics networks and the efficient and sustainable management of waste [51].

Implementing reverse logistics alongside blockchain technology and the principles of the circular economy results in the efficient and transparent management of resources. Reverse logistics allows post-consumer products and packaging to be returned for recycling and reuse, which is essential for the circular economy, which itself aims to minimize waste and maximize the use of resources. Blockchain technology, with its immutable and decentralized registry, helps this process by guaranteeing the authenticity and traceability of the returned materials. The combination of reverse logistics, blockchain, and the circular economy facilitates a sustainable and transparent supply chain in which all participants can verify each stage of a product’s life cycle.

4.2. Blockchain-Based Proposal

This paper presents the development of a framework that utilizes blockchain technology to assist the safe return of empty pesticide containers, which will allow them to be reused, recovered, or recycled.

Blockchain technology can be effectively used in logistics for the return of pesticide packaging; it enables the integration of tracking and transparent registration processes to ensure the more efficient and secure management of the packaging. With the inclusion of blockchain, the entire process is decentralized, and all transactions are recorded in the blockchain. Each participant in the process carries out their transactions in the blockchain.

Figure 10 illustrates the flow of pesticide packaging. The flow begins with the manufacturer, at which point each package receives a QR code for identification. The QR code may include information about the product, such as a unique identifier, manufacturer data, product name, and production date. The QR code is used as a unique identifier in the smart contract and can be scanned to obtain information about the product directly from the blockchain.

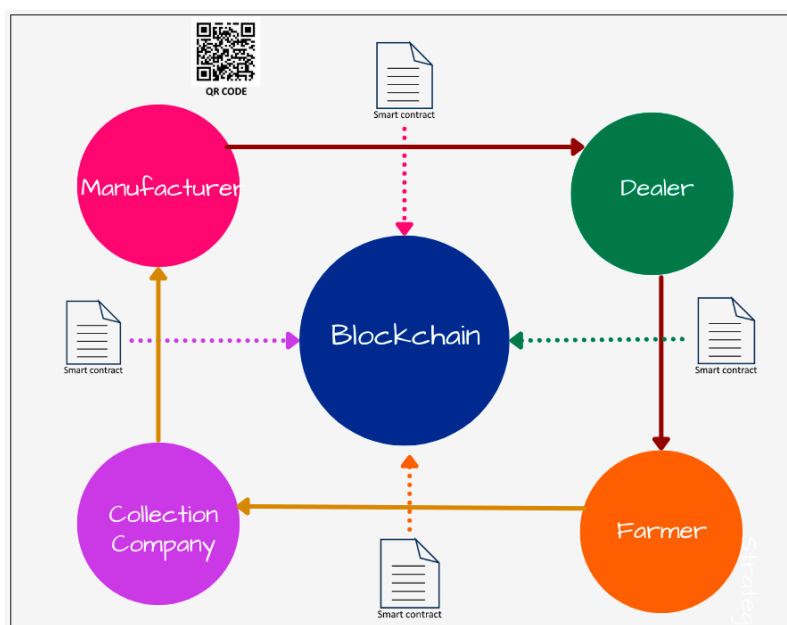


Figure 10. Flow of pesticide packaging using blockchain.

The nodes (manufacturer, retailer, farmer, and collection company) are connected through the transactions in the blockchain, and each stage of the supply chain—from production to sale and eventual recycling—is immutably and transparently recorded. This guarantees data integrity and the products' traceability throughout their useful lives.

To develop this system, we chose the Ethereum blockchain platform, which allows smart contracts to be created and executed. These contracts, which automate and guarantee agreements, are programmed in the language Solidity (version 0.8.13), which is exclusive to Ethereum. We implemented these contracts at all points in the network—including the manufacturer, retailer, farmer, and collection company—to ensure that all transactions are secure and transparent.

The reverse logistics model for pesticide packaging, integrated with blockchain and circular economy technologies, offers an innovative and efficient solution for sustainable waste management. The decentralization and transparency provided by blockchain ensure the traceability and authenticity of information throughout the supply chain. In addition, the reuse and recycling promoted by the circular economy act to significantly reduce the damage caused to the environment. With the active participation of all stakeholders and the support of strict regulations, this model has the potential to transform the management

of agrochemical packaging, incorporating best practices relating to sustainability and environmental preservation.

Figure 11 shows an example of how a smart contract in Solidity can be configured to use QR codes as identifiers. In this example, each product is registered with a QR code, which is used as a unique identifier. RegisterProduct stores the product information in the product's mapping, and getProduct makes it possible to retrieve that information using the QR code. By integrating the QR codes with the smart contracts, it is possible to significantly improve traceability, authenticity, and efficiency in product management throughout the supply chain.

```
pragma solidity ^0.8.13;

contract ProductRegistry {
    struct Product {
        string qrCode; // QR code as a unique identifier
        string name;
        string manufacturer;
        uint256 manufactureDate;
    }

    mapping(string => Product) public products;

    function registerProduct(string memory _qrCode, string memory _name, string memory _manufacturer,
        uint256 _manufactureDate) public {
        products[_qrCode] = Product(_qrCode, _name, _manufacturer, _manufactureDate);
    }

    function getProduct(string memory _qrCode) public view returns (string memory, string memory, uint256) {
        Product memory product = products[_qrCode];
        return (product.name, product.manufacturer, product.manufactureDate);
    }
}
```

Figure 11. An example of a smart contract used in Solidity to register products.

The tracking system for agrochemical packaging may be implemented as follows.

- Each participant must register in the system with accompanying information and a QR code to identify it. The system will score the farmer and the collection company through digital coins (credits). The digital coins will be credited to the system as the empty packaging is collected. These blockchain-based reward systems can be implemented to encourage the farmers and other stakeholders to return the packaging correctly.
- The retailer makes the sale to the farmer via an Ethereum blockchain smart contract. The farmer automatically receives a “debt” until the package is returned. This debt is the product’s QR code, which is registered in his name. When the empty packaging is returned, he receives the “released” title for that QR code, and then receives the digital coins related to the returned empty packaging.
- Using the Ethereum blockchain smart contract, the collection company registers the packaging that is ready to be returned to the manufacturer or to the public authorities in the system. The return of the empty packaging is also carried out using an Ethereum blockchain smart contract and the collection company will also receive digital coins.

To finish the disposal of empty pesticide packaging, public authorities must become involved, and inspections must be carried out at every stage of the chain. For countries with less active governments, it is essential that a mixed approach—including training local agents and empowering the community, involving civil rights groups and carrying out awareness-raising campaigns, seeking legal support, and developing specific regulations—is adopted. These combined strategies can reduce the risks and increase the chance of successful implementation by promoting greater transparency, co-operation, and the active participation of local authorities and the community. Partnerships with local businesses must also be established. Such partnerships will be crucial because they will allow the digital coins received by the farmers and collection companies upon returning the empty pesticide containers to be exchanged at registered local businesses, such as markets, bakeries, pharmacies, and more.

Our proposal of a blockchain-based framework for the reverse logistics-based management of pesticide packaging presents a robust and innovative solution for sustainable waste management. Using QR codes as unique identifiers and smart contracts to record transactions in an immutable and transparent way, the system guarantees traceability and authenticity throughout the supply chain. The integration of digital rewards will encourage farmers' and collection companies' participation, and in doing so, encourage proper packaging return. In addition, public authorities' active participation and collaboration with local businesses are essential to the model's success, as these will ensure that the digital coins received can be practically and efficiently used. By combining advanced technology with the principles of the circular economy, this model has the potential to transform pesticide waste management, bringing it into line with best sustainability and environmental preservation practices.

5. Conclusions

Given the complexity of the topic at hand, we adopted a methodological approach, marrying a literature review and applied research. The literature review was carried out through Scopus and Web of Science, both of which are recognized for their breadth and quality of publications, while bibliometrics was employed for the statistical analyses, allowing for a comprehensive understanding of the state of the art in the circular economy, blockchain, and the reverse logistics-based management of pesticide packaging.

An analysis of the documents obtained from Scopus and Web of Science using the keywords "blockchain" and "circular economy" revealed a steady increase in the number of publications in recent years, indicating authors' interest in these topics.

In addition, this research provided fundamental insights into the development of a traceability and reverse logistics model for pesticide packaging. This model, integrated with blockchain technology, aims not only to guarantee compliance with environmental legislation, but also to promote the more efficient and sustainable management of these materials.

The aforementioned blockchain-based framework represents an innovative solution to the challenges faced in the management of pesticide waste. Using QR codes as unique identifiers and smart contracts to record transactions in a transparent and immutable way, the model ensures the traceability of packaging and the authenticity of data throughout the supply chain.

When comparing this project with the "Medical-Waste Chain" project in the article "Medical-Waste Chain: Medical Waste Collection, Classification and Treatment Management by Blockchain Technology" [52], it can be seen that both use blockchain technology to improve the efficiency, transparency, and security of reverse logistics processes in their respective fields. While the medical waste chain focuses on the health sector and the safe disposal of medical waste, the current project seeks to create a sustainable circular economy-based method of managing pesticide packaging in agriculture. Each project addresses the unique challenges and opportunities within their specific areas, demonstrating the versatility of blockchain and its potential to promote sustainable practices and improve supply chain management.

The active participation of stakeholders—including manufacturers, traders, farmers, collection companies, and public authorities—is essential to the success of this model. Collaboration among those actors, together with strict regulation and incentives such as digital rewards, will boost the adoption of this reverse logistics-based model for managing pesticide packaging.

This project, initiated to develop a circular economy-based framework for agricultural production using blockchain and then continued to ensure the responsible disposal of pesticide packaging, has strengths and weaknesses. Its strengths include promoting sustainability, reducing the presence of toxic waste, and encouraging the reuse and recycling of packaging. The blockchain guarantees transparency and traceability in the supply chain, increasing trust, preventing fraud, and promoting responsibility-sharing among

all stakeholders in the production chain. That said, the project's weaknesses include its technical complexity and the cost of its implementation; the adoption of new technologies and difficulties in coordination between the actors involved are other challenges that we anticipate.

In short, the integration of emerging technologies such as blockchain into the principles of the circular economy represents a great opportunity within sustainable waste management, and it will serve to promote more responsible and transparent practices within the agricultural supply chain. The proposed model constitutes a significant step toward a more sustainable and resilient future, in which innovation and collaboration are crucial to tackle global environmental challenges.

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