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Review

Blockchain-Based Management of Recyclable Plastic Waste

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Abstract: Effective management of recyclable plastic waste is critical for environmental sustainability and economic viability. Blockchain technology has transformative potential in addressing the challenges of plastic waste management. Currently, the inefficiency of plastic recycling systems results in low recycling rates and significant environmental impacts due to poor sorting, contamination, and limited technology application. However, innovations such as chemical recycling, solvent-based techniques, and biotechnology offer promising advances in the management of plastic waste. Blockchain technology provides a transparent, decentralized ledger that enhances traceability and incentives through smart contracts, decentralized applications (DApps), and digital watermarks. These blockchain solutions can improve waste tracking, automate payments, and reward participants who recycle responsibly. Although significant investment in technology and education is required, integrating blockchain with the Internet of Things (IoT) and artificial intelligence (AI)-driven analytics could revolutionize plastic waste management by creating transparent, efficient, and collaborative recycling ecosystems. Blockchain technology has immense potential to redefine the management of plastic waste and promote a sustainable, circular economy.

Keywords: blockchain technology; recyclable plastic waste management; circular economy; smart contracts; decentralized applications; Internet of Things; digital watermarking; traceability and transparency; waste sorting and contamination

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1. Introduction

Blockchain technology is increasingly recognized as an effective tool for improving waste management practices and is known for its significant contribution to transparency, efficiency, and sustainability. In a decentralized network, blockchain provides greater transparency and traceability in waste management [1]. It maintains a secure and immutable ledger that records every transaction or activity throughout the waste management lifecycle, from waste generation, collection, and transportation to recycling or disposal. This level of transparency is critical to reducing fraud, mismanagement, and inefficiencies common in traditional waste management systems [2].

Blockchain technology also harnesses smart contracts that automatically execute agreements based on predefined rules and conditions [3]. Within waste management, smart contracts can automate payments, enforce regulatory compliance, and ensure the smooth execution of waste processing tasks without intermediaries. This automation leads to more efficient operations and significantly reduced administrative costs [4].

In addition, blockchain improves accountability between waste management stakeholders—including collectors, recyclers, and disposal facilities—by providing a verifiable record of all actions. This real-time monitoring of every transaction and every waste movement strengthens the reliability of the entire waste management system [5].

Additionally, blockchain supports the development of incentive schemes such as tokenization [6] or digital rewards [7] for participants who engage in sustainable waste management practices. These incentives can drive greater participation in recycling programs and proper waste disposal methods, fostering a more circular economy [8].

Lastly, blockchain can be integrated with the Internet of Things (IoT) and Artificial Intelligence (AI) technologies to create a more dynamic waste management system [9]. IoT devices can efficiently track the amount of waste, optimize collection routes, and monitor recycling processes. The data collected are stored securely on the blockchain, enabling more informed decision-making and resource management [10]. This integration highlights the transformative potential of blockchain in reshaping waste management into a more effective and sustainable system.

Managing recyclable plastic waste poses significant challenges that impact both environmental sustainability and economic viability. One of the main problems is the inefficiency of current waste management systems, which leads to significant environmental degradation. The global system for managing plastics and polymeric materials is often insufficient for minimizing the amount of waste released into the environment [11]. Effective recycling, reuse, and efficient conversion of these waste materials into alternative applications are important but underutilized solutions due to technological and infrastructural limitations [12,13].

Another major concern is the low recycling rates, particularly in regions like Europe, where only about 10% of plastic waste is recycled [14]. The quality of recycled materials often does not meet the standards required for high-quality applications, which makes the recycling process even more difficult. This inadequacy is largely due to the unavailability of raw materials, inconsistent quality, costly sorting processes, and unclear regulations for the disposal of plastic waste [14].

The system's fragmentation and the complexity of traceability in waste streams significantly hinder effective recycling efforts [15]. These challenges are exacerbated by the lack of coherent integration between the public and private sectors involved in waste management. In addition, recycling targets and calculation methods put forth by entities like the European Commission are putting pressure on current waste management systems, which are already struggling with fragmentation of responsibilities and inadequate cost–benefit ratios [16].

Environmental concerns also loom large, particularly with the slow biodegradation rate of conventional plastics [17]. These materials accumulate in the environment and pose a major threat to all life forms. Effective environmental techniques are urgently needed to reduce the hazardous effects of conventional disposal methods. Research continues into the role of microbes, particularly algae, in enhancing the biodegradation processes of various synthetic plastics [18].

Finally, the economic challenges of managing plastic waste, such as the high collection costs and the low profitability of recycling certain plastics, are significant. Extended Producer Responsibility (EPR) schemes are possible solutions to these problems [19]. However, the effective implementation of EPR requires overcoming significant economic and logistical barriers to increase collection rates, minimize contamination, and optimize recycling processes [20].

Addressing these challenges requires a multifaceted approach encompassing technological, regulatory, and economic areas. The approach aims to improve recycling rates and reduce the environmental impact of plastic waste.

The current review provides significant contributions and innovations in the field of plastic waste management through the use of blockchain technology. It shows how blockchain improves transparency, traceability, and efficiency in mechanical, chemical, and biological recycling processes. By integrating blockchain with IoT and AI, this review demonstrates the potential for real-time data collection, optimized recycling processes, and improved decision-making. It also presents pilot programs and case studies that provide practical evidence of blockchain's effectiveness in improving recycling rates, reducing costs, and fostering stakeholder collaboration. This comprehensive approach provides a valuable roadmap for developing more sustainable and efficient plastic waste management systems.

2. Circular Economy Marketplace for Recycled Plastics

The concept of a circular economy represents a shift from traditional linear economic models, which typically follow a "take–make–dispose" pattern, towards a more sustainable framework that emphasizes "reduce, reuse, and recycle" [21]. In a circular economy, resources are used for as long as possible to extract the maximum value from them and recover and regenerate products and materials at the end of their life (Figure 1). This model starkly contrasts the linear approach, in which products are manufactured from raw materials and disposed of as waste after use.

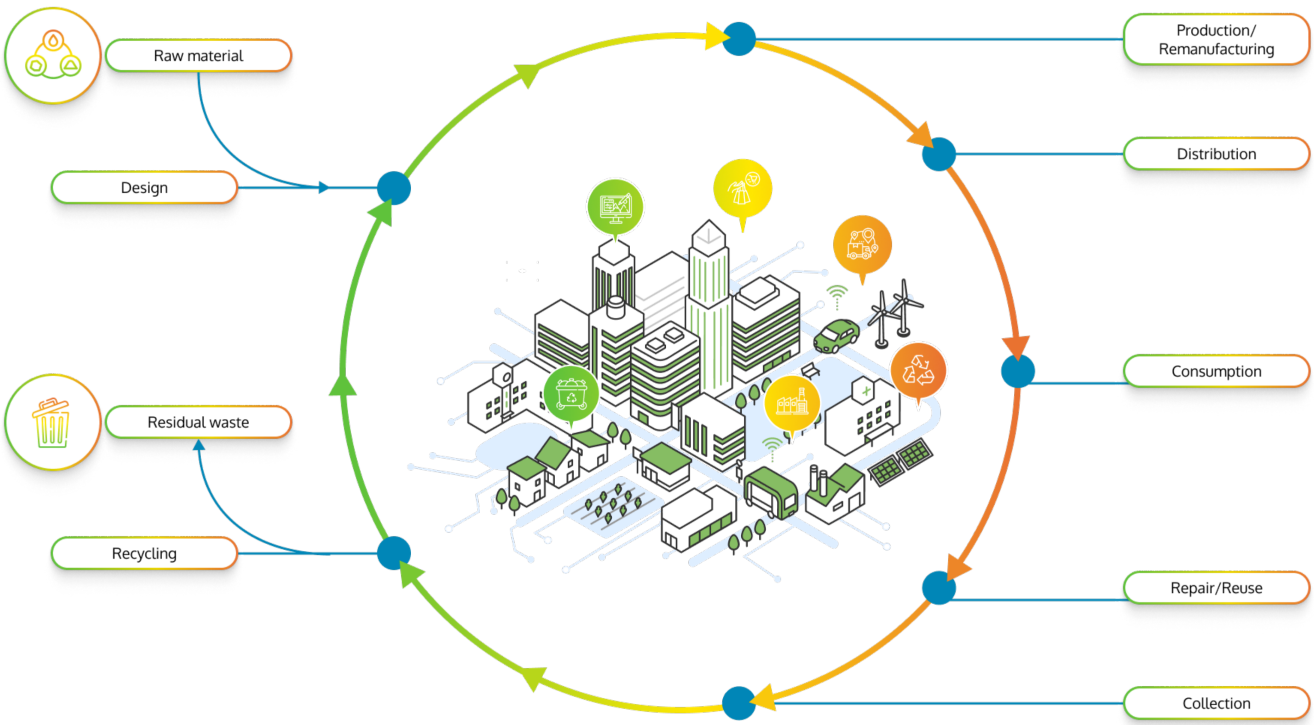

Figure 1. Circular economy model for waste management.

The circular economy is crucial in plastic recycling, as plastics' durability [22] and degradation time [23] pose environmental problems. The application of circular economy principles aims to minimize waste, reduce pollution, and decrease the need for new plastic production [22], often associated with fossil fuels and greenhouse gas emissions.

A circular economy for plastics involves designing products for recycling from the outset [23], using mono-materials, designing them for dismantling, and avoiding additives that make recycling difficult. Efficient recycling systems are essential for processing plastic waste into new products, such as recycling PET bottles into new PET products [24].

The circular economy also encourages the use of renewable resources and innovative recycling technologies, such as chemical recycling [25], which can convert plastics into monomers or useful chemicals. These processes can handle a wider range of plastics with fewer quality issues than traditional mechanical recycling [26].

Adopting a circular economy model in plastic recycling reduces environmental impacts, conserves resources, and promotes innovation in materials science [27]. It supports sustainable development by balancing economic activity with environmental and social benefits, minimizing waste, and promoting resource efficiency. This model creates economic opportunities in sustainable materials management and supports environmental sustainability.

3. Plastic Waste Recycling

The production of plastics has grown exponentially in recent decades and contributes significantly to modern comfort and environmental pollution. If the world's major economies are included, it is estimated that more than 300 million tons of plastic are produced annually worldwide. The world's largest producer of plastics is China (Figure 2). Despite the versatility and usefulness of plastics in various sectors—including packaging, construction, and healthcare—their longevity and resistance to degradation make plastic waste a major environmental threat.

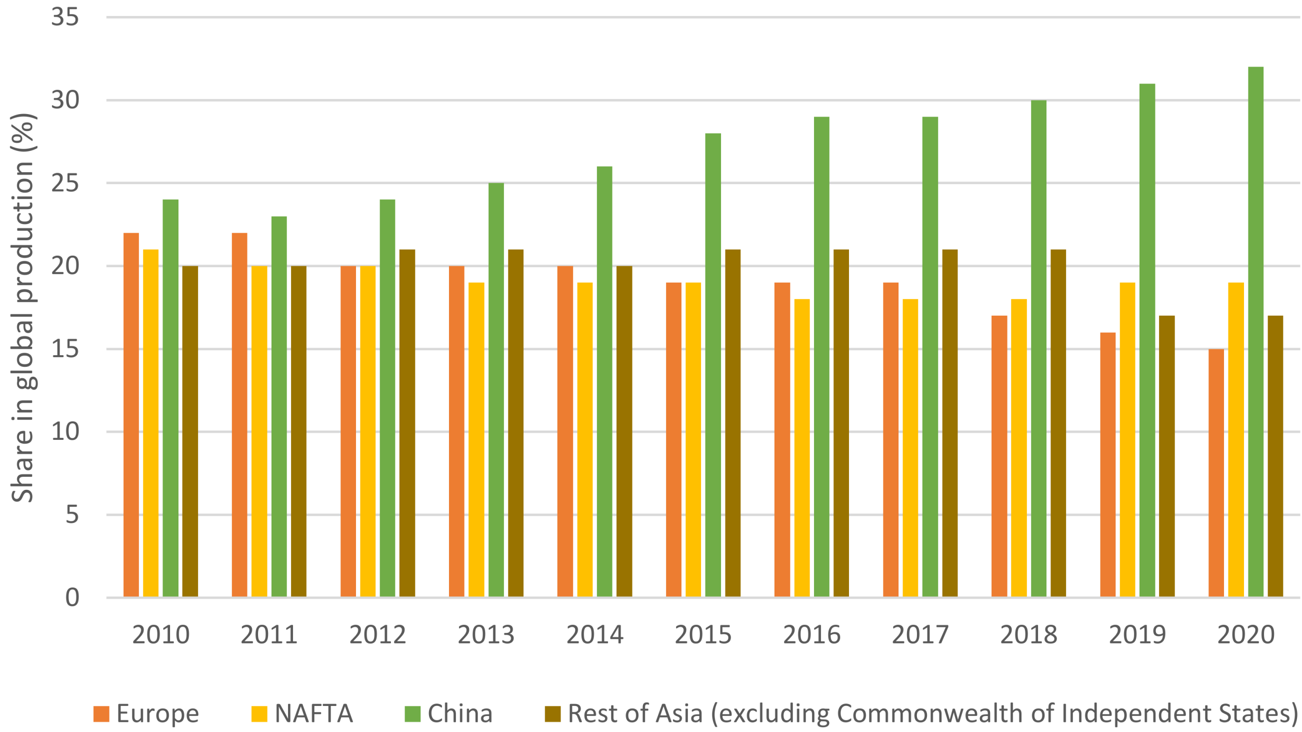

Figure 2. Regional share of global plastic production, 2010 to 2020 [28].

A significant proportion of the plastic produced quickly becomes waste due to its widespread use in single-use products and packaging. Statistics show that much of this plastic waste is not recycled, causing it to accumulate in landfills, waterways, and natural habitats, where it lasts hundreds to thousands of years. The life cycle of plastics, from production to disposal, illustrates a linear economic model—produce, use, and dispose —which is unsustainable given current production and consumption rates.

This increasing plastic waste generation requires urgent action to improve recycling rates and implement more sustainable waste management strategies. The environmental impact of poorly managed plastic waste is profound, affecting terrestrial and marine ecosystems and human health [29]. Moving from this linear approach to a more circular approach, where plastics are reused, recycled, and repurposed, is essential to mitigate these environmental problems.

Plastics are categorized into many types based on their chemical structure and properties. The most common way to classify plastics is by their Resin Identification Code (RIC), which usually assigns a number from 1 to 7 to facilitate sorting for recycling purposes. Here are the main types of plastics that are commonly used (Table 1):

Table 1. Plastic resin identification and usage codes.

Plastic Resin Identification Codes						
1	2	3	4	5	6	7
PET	HDPE	PVC	LDPE	PP	PS	OTHERS
Polyethylene Terephthalate	High-Density Polyethylene	Polyvinyl Chloride	Low-Density Polyethylene	Polypropylene	Polystyrene	
Common products: soda and water bottles, cups, jars, trays, clamshells	Common products: milk jugs, detergent and cosmetics bottles, flowerpots, grocery bags	Common products: cleaning supplies, jugs, pool liners, twine, sheeting, automotive product bottles,	Common products: bread bags, paper towels, tissue overwrap, squeeze bottles, trash bags	Common products: yogurt tubes, cups, juice bottles, straws, hangers, sand, shipping bags	Common products: to-go containers, hot cups, razors, shipping cushions, cartons, trays	Common products: polycarbonate, nylon, acrylonitrile butadiene styrene, acrylic, polylactic acid
Recycled products: clothing, carpets, clamshells, soda and water bottles	Recycled products: detergent bottles, flowerpots, crates, pipes, decking	Recycled products: pipe, wall siding, binders, carpet backing, flooring	Recycled products: trash bags, plastic lumber, furniture shipping envelopes, compost bins	Recycled products: paint cans, auto parts, food containers, hangers, plant pots, razor handles	Recycled products: picture frames, crown molding, rulers, flowerpots, hangers, toys	Recycled products: electronic housings, auto parts

3.1. Plastic Recycling Processes

Plastic waste management has become a critical environmental challenge due to the increasing production and consumption of plastics globally. Effective recycling methods are essential to mitigate the impact of plastic waste on ecosystems and human health. Mechanical recycling, the most prevalent form of recycling, involves physically processing plastic waste without altering its chemical structure. Despite its widespread use, this method has significant limitations, including the degradation of polymer quality with each cycle and the necessity for precise sorting to avoid contamination. More advanced recycling methods, such as chemical and biological recycling, have been developed to address these issues.

Mechanical recycling is the most widespread form of plastic recycling, accounting for around 20% of the plastic waste disposed of worldwide. In this method, the plastic waste is physically processed without changing its chemical structure. The typical process involves collecting, sorting, cleaning, shredding, melting, and reshaping the plastic to make new products. Mechanical recycling is the most effective for certain types of plastic, such as PET, used in beverage bottles, and HDPE, used in silk jugs [30]. Despite its widespread use, mechanical recycling has limitations, most notably the degradation of polymer quality with each recycling cycle, which limits the range of products made from recycled material. In addition, the immiscibility of the different polymers often requires precise sorting to avoid contamination and preserve the material's properties [31].

Chemical recycling methods like pyrolysis account for about 10% of plastic waste recycling in Europe [14]. This method converts the plastic waste into monomers or other chemicals through chemical reactions. Chemical recycling is particularly valuable for dealing with mixed plastic waste and applications requiring high-purity recycled materials. It offers the potential to recycle plastics continuously without significant loss in quality. One of the most important methods of chemical recycling is pyrolysis. In pyrolysis, plastic waste is heated to high temperatures in the absence of oxygen, which breaks down long polymer chains into smaller hydrocarbons. These hydrocarbons can then be converted into fuels, monomers, or other chemicals. Pyrolysis is particularly valuable for processing mixed or contaminated plastic waste, which presents a major challenge for mechanical recycling.

Pyrolysis can achieve an energy efficiency of up to 89.6%, making the process almost self-sufficient in terms of energy requirements [32]. Despite its promising possibilities, pyrolysis faces hurdles such as high energy requirements and the need for advanced technical infrastructure to ensure efficient and environmentally friendly operation [33].

Gasification is another well-known chemical recycling method in which plastic waste is converted into synthesis gas—a mixture of hydrogen, carbon monoxide, and carbon dioxide—by exposing it to high temperatures and a controlled amount of oxygen or steam. The syngas can be further processed to produce a variety of chemicals and fuels, including methanol and hydrogen, which are valuable in numerous industrial applications. Gasification offers a cleaner alternative to incineration as it produces less harmful emissions and can process various plastic types, including those unsuitable for mechanical recycling [34]. Gasification has shown up to 80% efficiency in converting plastic waste into useful products [35].

In solvolysis, a solvent-based recycling process, plastic waste is dissolved in a suitable solvent to extract and purify polymers. This method is particularly suitable for plastics that contain additives or colorants that are difficult to remove by mechanical means. Solvolysis can obtain high-purity polymers comparable to virgin material, allowing them to be reused in high-quality applications. However, the economic feasibility of solvolysis is still being investigated, as the cost of solvents and the need for extensive purification steps can make the process expensive. Despite these challenges, solvolysis has been shown to achieve up to 70% purity of recovered monomers when treated with activated carbon [36].

Chemical recycling faces several challenges that must be overcome to achieve widespread acceptance. These processes' economic and energy costs are significant, often making them less competitive than conventional recycling methods. In addition, many chemical recycling technologies are still in development and require significant investment in research and infrastructure to be viable on an industrial scale. Regulatory frameworks and market incentives are also needed to support the uptake of chemical recycling and ensure that recycled materials can compete with virgin materials in terms of quality and cost.

Biological recycling of plastic waste is an innovative and promising approach that uses natural processes to break down and recycle plastics [37]. This method uses microorganisms and enzymes to break down plastic polymers into their monomeric components, providing a potentially sustainable solution to the growing plastic waste problem. If the field progresses, it has the potential to complement existing mechanical and chemical recycling methods, overcome some of their limitations, and improve overall waste management strategies.

Microbial degradation uses bacteria and fungi that can naturally degrade plastic polymers. Certain microorganisms have developed specific enzymes that can degrade plastics, such as polyethylene terephthalate (PET) and polyurethane. One notable example is the bacterium *Ideonella sakaiensis*, which produces an enzyme called PETase. PETase can break down PET into its monomeric units, terephthalic acid, and ethylene glycol, which can then be repolymerized to produce new PET products [38]. Research has focused on improving the efficiency of PETase through genetic modification to increase its activity and stability under different environmental conditions. Modified variants of PETase have shown improved capabilities by degrading PET faster and more efficiently, even at lower temperatures. The efficiency of microbial degradation of PET using modified PETase can reach up to 90% under optimized conditions [39].

In addition to PETase, other microorganisms that can degrade various types of plastics have also been identified. Strains of *Pseudomonas* and *Bacillus* can degrade polyurethane and polyethylene, respectively. These bacteria are found in various environments, including soil and marine ecosystems, contributing to the natural degradation of plastic waste. The diversity of microbial communities provides a rich resource for discovering new species with plastic-degrading capabilities. It paves the way for the development of more effective biological recycling methods. For example, the efficiency of *Pseudomonas* in degrading polyurethane can be up to 60% after 18 days of incubation [40].

Enzymatic recycling uses enzymes that catalyze the breakdown of plastic polymers into their monomeric components. This method operates under mild conditions compared to conventional chemical recycling processes, which often require high temperatures and aggressive chemicals. Advances in protein engineering and synthetic biology have enabled the development of enzymes with improved performance. Techniques such as directed evolution and computational modeling are used to develop enzymes that break down plastics more effectively. For example, genetically engineered variants of PETase have been developed to improve their catalytic efficiency and thermal stability, making them more suitable for industrial applications [41]. The efficiency of these genetically modified enzymes can reach degradation rates of up to 98% for PET under optimized conditions [42].

Researchers are also investigating enzyme cocktails, in which several enzymes work together synergistically to break down complex plastic mixtures [41]. This approach can increase the overall efficiency of biological recycling as it simultaneously targets different components of the plastic waste. Combining enzymes with complementary activities makes it possible to achieve more complete and efficient degradation of plastics and reduce the need for extensive pre-sorting and cleaning of waste materials. Studies have shown that enzyme cocktails can increase degradation efficiency by up to 40% compared to single-enzyme systems [18].

Biotechnology is crucial in scaling biological recycling processes from laboratory research to industrial application. One of the main areas of focus is the development of bioreactor systems tailored to the degradation of plastics. These systems provide controlled environments for microorganisms and enzymes to degrade plastics efficiently. Parameters such as temperature, pH, and nutrient supply are optimized to maximize the degradation rate. Bioreactors can be designed to process large volumes of plastic waste, making biological recycling more feasible on an industrial scale [41]. The efficiency of bioreactor systems for the microbial degradation of plastics can reach up to 85%, making them competitive with other recycling methods [43].

Another important aspect is integrating biological recycling methods into existing waste management infrastructures. This integration includes pre-treatment plastic waste to make it more accessible for biodegradation and combining biological methods with mechanical and chemical recycling for a hybrid approach. Such hybrid systems can improve the overall efficiency of plastic waste management by utilizing the strengths of each method. For example, mechanical recycling can process high-value plastics, while biological methods can process mixed and contaminated plastics that are difficult to recycle mechanically. Combined systems have shown up to 70% efficiencies in pilot studies [18].

3.2. Improvement in Recycling Plastic Waste Systems by Blockchain Technology

Blockchain technology can significantly improve plastic waste recycling through mechanical, chemical, and biological processes by providing transparency, traceability, and efficiency. Here is how it can improve each method:

(1) Mechanical recycling

Blockchain can streamline mechanical recycling by creating a transparent and immutable record of plastic waste from collection to recycling. Blockchain ensures that all participants in the recycling chain—waste collectors, sorting facilities, and recyclers—are accurately tracked and incentivized. This transparency helps to reduce contamination and ensure that high-quality recycled materials are produced. Blockchain can also automate payments for recycling services and provide digital rewards to encourage better sorting and recycling practices, improving the overall efficiency and profitability of mechanical recycling [44].

(2) Chemical recycling

Chemical recycling processes such as pyrolysis, gasification, and solvolysis can benefit from blockchain by improving traceability and quality control. Blockchain can track the origin and composition of plastic waste and ensure it is suitable for chemical recycling. This technology can help manage and verify the complex supply chains involved in chemical recycling to ensure that waste is processed efficiently and that the resulting products meet quality standards. By integrating blockchain with IoT sensors, real-time data on the waste composition and processing conditions can be securely recorded, optimizing the recycling process and reducing operational costs. In addition, smart contracts can automate regulatory compliance and safety checks, ensuring that chemical recycling processes adhere to environmental standards [45].

(3) Biological recycling

In biological recycling, blockchain can facilitate the monitoring and optimization of microbial and enzymatic degradation processes. By recording data on the type and quantity of plastics degraded, blockchain ensures accurate tracking and reporting of recycling results. This technology can also help manage bioreactor systems by providing real-time data on environmental conditions such as temperature, pH, and nutrient levels, which are crucial for optimizing microbial activity. Blockchain-enabled traceability can certify the quality and purity of monomers produced through biological recycling, increasing their market value. Furthermore, blockchain can be integrated with AI and IoT to predict and optimize the efficiency of biological recycling processes, leading to more effective and scalable operations [8].

Blockchain technology can potentially improve plastic waste management in mechanical, chemical, and biological recycling processes. By creating transparency, traceability, and automation, blockchain can improve recycling processes' efficiency, quality, and sustainability. This integration can help overcome many of the current challenges in plastic waste management and progress towards a circular and sustainable economy.

3.3. Challenges and Solutions in Plastic Recycling

The recycling of plastics faces several challenges that hinder its efficiency and effectiveness. These mainly include problems related to sorting and contamination and the deterioration of plastic quality during the recycling process.

One of the primary challenges in recycling plastics is the need for precise sorting to avoid contamination [11]. Plastics must be sorted by type because different polymers have different melting points and properties [46], and mixing them can lead to poor-quality recycled products. Current sorting technologies, such as near-infrared spectroscopy (NIR) and other advanced sensing and sorting systems, have significantly improved the efficiency of the sorting process [47]. However, these technologies are expensive and require significant investment, which can be an obstacle for many recycling facilities. In addition, contamination from food scraps, labels, and other non-plastic materials can further complicate recycling and require extensive and often costly cleaning processes [48].

Recycled plastics often suffer from polymer degradation [49], which limits their reuse, particularly for applications that require high material performance. Each cycle of mechanical recycling can weaken the polymer chains, leading to inferior mechanical properties such as reduced strength and flexibility [50]. This degradation is exacerbated by heat, mechanical stress, and environmental influences during the use phase and the recycling process. To counteract this, additives can be used to improve the properties of recycled plastic, and mixing recycled plastic with virgin material can also help to maintain the quality of the end product [51].

The economic factors associated with the circular economy for plastics also pose a major challenge. The production of new plastics is often cheaper than recycling, mainly due to the lower cost of petroleum feedstock and the established infrastructure for production [52]. This economic reality discourages investment in recycling technologies and infrastructure. In addition, the market for recycled plastics can be volatile as oil prices, supply chain disruptions, and changes in consumer demand heavily influence prices.

Technological limitations also play a crucial role. Current recycling technologies cannot efficiently process all types of plastic waste [53]. For example, certain plastics, such as flexible packaging films or composites made from different plastics, are particularly difficult to recycle using conventional mechanical processes [54]. Advances in chemical recycling technologies offer some promise [55]. However, these methods are still at an early stage of development and are not yet widely implemented at scale due to high operational costs and technological complexities.

Regulatory challenges further complicate the picture. While some regions have introduced strict regulations and policies to promote recycling and waste management, there is a lack of global standardization. Different countries have different standards and guidelines for using and recycling plastics, which can lead to inconsistencies and inefficiencies in the global market for recycled plastics [56]. This lack of uniform regulation can make international cooperation more difficult and hinder the development of a globally integrated circular economy for plastics.

Finally, consumer behavior and awareness are key factors. Despite growing public awareness of plastic pollution, many consumers do not know how to properly dispose of and recycle plastics [57]. There is a significant need for educational initiatives and incentive programs to encourage consumer participation in recycling programs [58]. Without widespread public engagement and behavior change, achieving a truly circular economy for plastics remains a daunting challenge.

Overcoming these challenges requires a multifaceted approach that includes technological innovation, economic incentives, regulatory frameworks, and extensive public education. Collaboration between governments, industry representatives, and consumers is essential to creating an effective and sustainable circular economy for plastics [59].

3.4. Environmental Benefits of Improved Recycling Practices

Managing recyclable plastic waste poses significant challenges that impact both environmental sustainability and economic viability. One of the main problems is the inefficiency of current waste management systems, which leads to significant environmental degradation. The global system for managing plastics and polymeric materials is often insufficient to minimize the amount of waste released into the environment (Table 2).

Table 2. Regional environmental benefits of plastic recycling practices in 2019 [60–62].

Region	Plastics Waste Collected for Recycling in 2019 (mln Tons/Year)	CO_2 Emissions (mln Tons CO_2/Ton of Plastic Waste)	Potential Saving Amounts of CO_2 by Recycling (mln Tons CO_2/Ton of Plastic Waste)
Europe	16.67	11.34	24.89
NAFTA	7.29	4.96	10.88
Asia	23.175	15.76	34.60
Latin America	4.51	3.07	6.73
Africa	2.711	1.84	4.05

Table 2 presents an analysis of the environmental benefits derived from improved recycling practices across different regions in 2019. The table includes data on the amount of plastic waste collected for recycling, the CO_2 emissions associated with this plastic waste, and the potential CO_2 savings that can be achieved through recycling. The regions analyzed are Europe, NAFTA, Asia, Latin America, and Africa.

In 2019, 16.67 million tons of plastic waste were collected for recycling in Europe. This region's CO_2 emissions from plastic waste amounted to 11.34 million tons, with potential CO_2 savings from recycling reaching 24.89 million tons. This highlights the significant environmental benefits of recycling in Europe and showcases substantial reductions in CO_2 emissions.

In the NAFTA region, 7.29 million tons of plastic waste were recycled. The CO_2 emissions for this plastic waste were 4.96 million tons. If recycling practices are optimized, NAFTA could achieve potential CO_2 savings of 10.88 million tons. This demonstrates the importance of recycling initiatives to mitigate environmental impact in this region.

Asia recorded the highest amount of plastic waste collected for recycling, with 23.175 million tons. The corresponding CO_2 emissions were 15.76 million tons, and the potential CO_2 savings through enhanced recycling practices could reach 34.60 million tons. This underscores Asia's critical role in global recycling efforts and the significant environmental gains that can be achieved.

Latin America had 4.51 million tons of plastic waste collected for recycling. The CO_2 emissions from this waste were 3.07 million tons, with potential savings of 6.73 million tons if recycling practices are improved. These data indicate considerable opportunities for environmental benefits through recycling in Latin America.

Finally, Africa collected 2.711 million tons of plastic waste for recycling, with CO_2 emissions amounting to 1.84 million tons. The potential CO_2 savings from recycling could be 4.05 million tons. Although Africa has the lowest figures in this table, the data highlight the region's potential to significantly reduce CO_2 emissions through enhanced recycling efforts.

3.5. Innovations in Plastic Waste Recycling

Plastic waste recycling is rapidly advancing, with several innovative technologies promising to revolutionize how we handle plastic waste [63]. These innovations aim to improve the efficiency and effectiveness of recycling processes and create value from waste materials [64].

Recent developments in chemical recycling are at the forefront of innovation in the recycling sector. Technologies such as pyrolysis, where plastic waste is converted into fuel or other chemicals under high temperatures and in the absence of oxygen, are being further developed to increase yields and reduce energy consumption [65]. Similarly, advances in enzymatic recycling, in which technical enzymes break down plastics into their original monomers, are paving the way for the recycling of plastics that were previously considered non-recyclable [66]. These enzymes are specifically designed to break down and degrade polymers such as PET efficiently.

Another promising area is the development of solvent-based recycling technologies that dissolve plastic waste and enable the extraction and purification of polymers [67]. These methods are particularly effective for mixed and contaminated plastic waste, which mechanical recycling cannot process without significant loss in quality [68]. The solvent-based process not only recovers high-quality polymers but also enables the separation of additives and colorants, resulting in pure raw materials suitable for high-quality applications [69].

Biotechnology is playing an increasingly important role in tackling the plastic pollution crisis. Researchers are exploring the use of genetically modified bacteria and fungi that consume and break down plastic waste [70]. These microorganisms are engineered to produce enzymes that can break down different types of plastic more efficiently than natural processes allow. For example, research into PETase, an enzyme that digests PET plastics, has shown the potential for developing scalable biological recycling solutions [41].

As the plastic waste recycling industry embraces innovations in chemical, enzymatic, and solvent-based recycling technologies [52], it becomes increasingly important to integrate digital tools that can enhance these processes and foster collaboration. Advanced technologies like blockchain, IoT, and AI are uniquely positioned to support and accelerate these innovations by providing transparent, data-driven, and automated solutions. By leveraging blockchain's decentralized ledger for tracking [71], IoT's data-gathering devices for monitoring [72], and AI's analytical capabilities for optimizing decision-making [73], the recycling industry can transform plastic waste management into a seamless, efficient, and sustainable process.

It is crucial to integrate these innovative recycling technologies into broader circular economy strategies. The aim is to develop waste management systems in which plastic never becomes waste but is continuously fed back into the production cycle. This approach not only reduces the environmental impact of plastic waste but also reduces dependence on the production of virgin plastics, thereby conserving resources and reducing greenhouse gas emissions.

Collaboration between policymakers, industry leaders, and technologists is essential for these technological innovations to have a significant impact [41]. Setting standards for recycled content in products, incentivizing innovation through subsidies and grants, and creating robust markets for recycled materials are critical steps in driving the adoption of these technologies.

4. Blockchain Digital Watermarking of Plastic Waste

Watermarking plastics using blockchain technology involves sophisticated integration of digital markings or tags into plastic products during manufacturing [74]. These digital watermarks encode important data about each plastic item, including the type of material, production date, manufacturer details, and specific recycling instructions [75]. These data are then embedded in formats such as QR codes or Radio-Frequency Identification (RFID) tags that are physically printed and mounted on the product or its packaging.

Once the digital watermark is created, it is registered in a blockchain, creating a secure, immutable ledger that tracks the lifecycle of the plastic product from manufacture to disposal [76]. This system enables decentralized traceability so that different actors in the supply chain, including manufacturers, consumers, and recyclers, can scan and update the blockchain with new information as the product progresses through its lifecycle [77]. This process increases transparency and traceability and enables all stakeholders to verify and ensure compliance with environmental standards and recycling regulations (Figure 3).

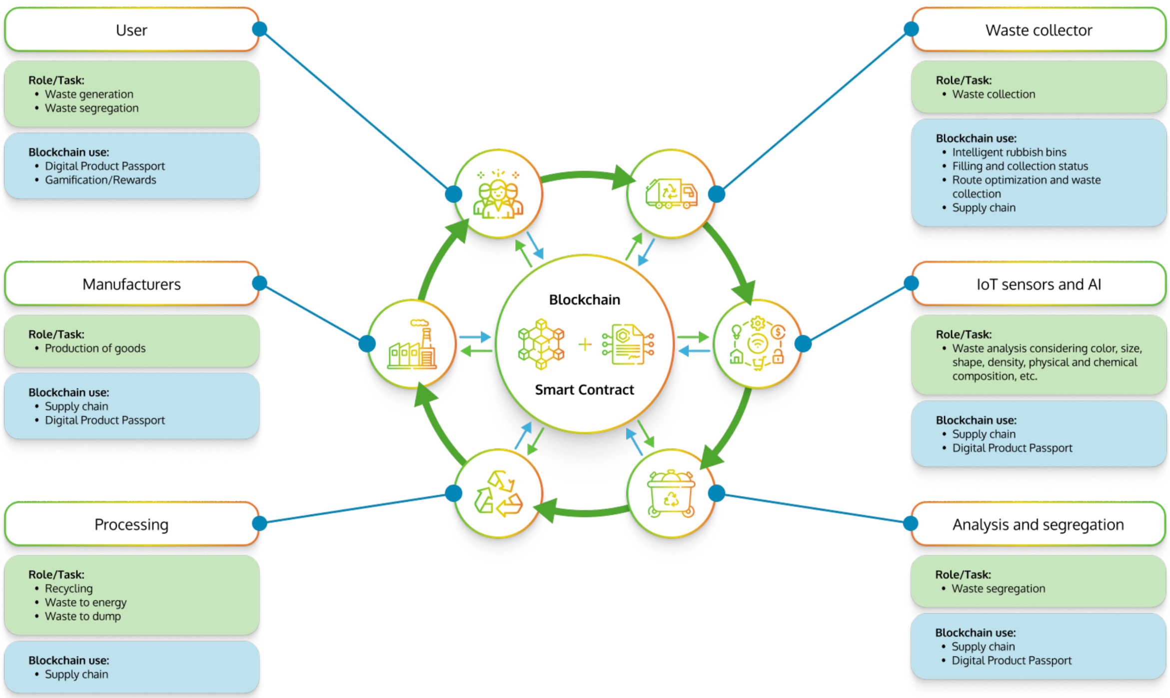

Figure 3. Implementation of blockchain and smart contracts in plastic waste management.

In addition, blockchain-enabled digital watermarks help automate recycling processes and make them more efficient [78]. Recycling centers equipped with the appropriate scanning technology can easily read the digital watermarks to sort plastics accurately according to the embedded recycling instructions, reducing contamination and increasing the quality of recyclable materials [79]. Consumers also scan the watermarks to educate themselves on proper disposal and recycling methods, promoting better recycling habits and greater environmental awareness [80].

The concept of digital watermarking of plastics, as facilitated by blockchain technology, bears a notable resemblance to the idea of Digital Product Passports (DPP). Both approaches aim to embed crucial lifecycle information into products to enhance traceability and accountability throughout their usage and disposal phases [81]. Digital Product Passports are designed to store detailed information about products, such as material composition, origin, usage instructions, and end-of-life disposal recommendations [82]. These passports are accessible via digital platforms and can contribute significantly to the goals of the circular economy by enabling better management of product lifecycles and promoting recycling. Like the digital watermarks of blockchain, DPPs ensure that every stakeholder along the supply chain, from the manufacturer to the end consumer, has access to up-to-date and reliable information. This facilitates informed decisions about product use, maintenance, and recycling, ultimately leading to more sustainable consumption patterns and reduced environmental impact. This synergy between digital watermarking in blockchain and DPPs could set a new standard in product lifecycle management and provide a robust framework for the transition to a more sustainable and circular economy.

However, implementing blockchain for plastic watermarking is not without its challenges. It requires significant investment in technology and infrastructure, as well as the development of industry standards and acceptance by regulators to ensure widespread adoption [78]. In addition, blockchain security and data privacy must be strictly maintained, especially if the system contains sensitive information.

Overall, using blockchain technology for watermarking plastics offers a promising approach to improving the sustainability and efficiency of waste management. This is in line with global efforts towards a circular economy and better environmental protection.

5. Blockchain Applications in Plastic Waste Management

Blockchain technology is fast becoming a key player in improving transparency and traceability in the disposal of plastic waste. Various studies and initiatives show how this technology can revolutionize the sector by enabling immutable and transparent waste tracking from its creation to recycling.

A major advantage of blockchain in waste management is its ability to create a transparent and unalterable ledger of all transactions [83], greatly enhancing plastic waste tracking. For instance, the study by Steenmans et al. [84] describes blockchain as a potential disruptor that can fundamentally change waste management practices by improving the management of plastics. It highlights the role of blockchain in monitoring and tracking waste, which can transform management practices and increase accountability in the recycling process. This systematic review shows the state of blockchain adoption and its impact on plastic waste management, focusing on payment systems, recycling rewards, and monitoring waste activities through smart contracts.

Bułkowska et al. [2]'s work shows an implementation of blockchain technology in an existing waste management company. It is an example of how blockchain improves the transparency, traceability, and efficiency of waste management systems. By incorporating blockchain, every step in the waste management lifecycle, including collection, transportation, recycling, and disposal, is recorded on a secure platform. This facility not only provides transparency but also facilitates real-time monitoring and verification of waste-related data, which is crucial for environmental sustainability and regulatory compliance.

Further exploring the applications of blockchain, Mondal and Kulkarni [85] propose a blockchain-based decentralized application to improve the management of plastic waste. This application aims to bridge the gap between waste generation and recycling opportunities by providing a transparent and timely tracking system. The proposed system not only tracks but also rewards recycling efforts, which could increase participation rates and improve the efficiency of plastic waste management. This approach reflects a growing trend toward integrating technology to solve traditional waste management problems and emphasizes the importance of transparency and accountability in the recycling process.

Blockchain technology introduces innovative incentivization models in waste management [86], particularly for enhancing participation in recycling efforts and sustainable practices. These models leverage blockchain's unique capabilities to track behaviors and transactions accurately and transparently, rewarding participants with digital tokens or credits.

5.1. Smart Contracts

A smart contract is a self-executing digital contract in which the terms of the contract are written directly in lines of code. It is stored and managed in a blockchain network, which is a decentralized and distributed digital ledger [87]. Smart contracts are increasingly being used in various industries, from finance and insurance to supply chain and real estate, due to their efficiency, cost savings, and increased security.

Smart contracts offer several application benefits for waste management (Figure 4). These contracts can automate and streamline various processes, making them more efficient, transparent, and cost-effective. Smart contracts automatically trigger payments when certain predefined conditions are met [88]. For instance, waste collection companies can be instantly paid once they complete their collection routes and log the data into a blockchain system [89]. This speeds up the payment process and minimizes disputes over service completion. Additionally, smart contracts can manage deposit schemes where incentives are provided to residents and businesses for recycling or properly disposing of waste [90]. Dana et al. [91] explore using blockchain and smart contracts to automate and secure transactions when buying and selling waste. This system enables transparent and efficient market operations and facilitates a more fluid exchange of waste materials without the traditional bottlenecks and trust issues associated with multiple parties. In addition, these contracts can include incentive mechanisms that reward sustainable practices, such as issuing digital tokens to individuals or companies that consistently adhere to recycling guidelines [92]. These tokens can be redeemed for various benefits, promoting a recycling culture and supporting the circular economy.

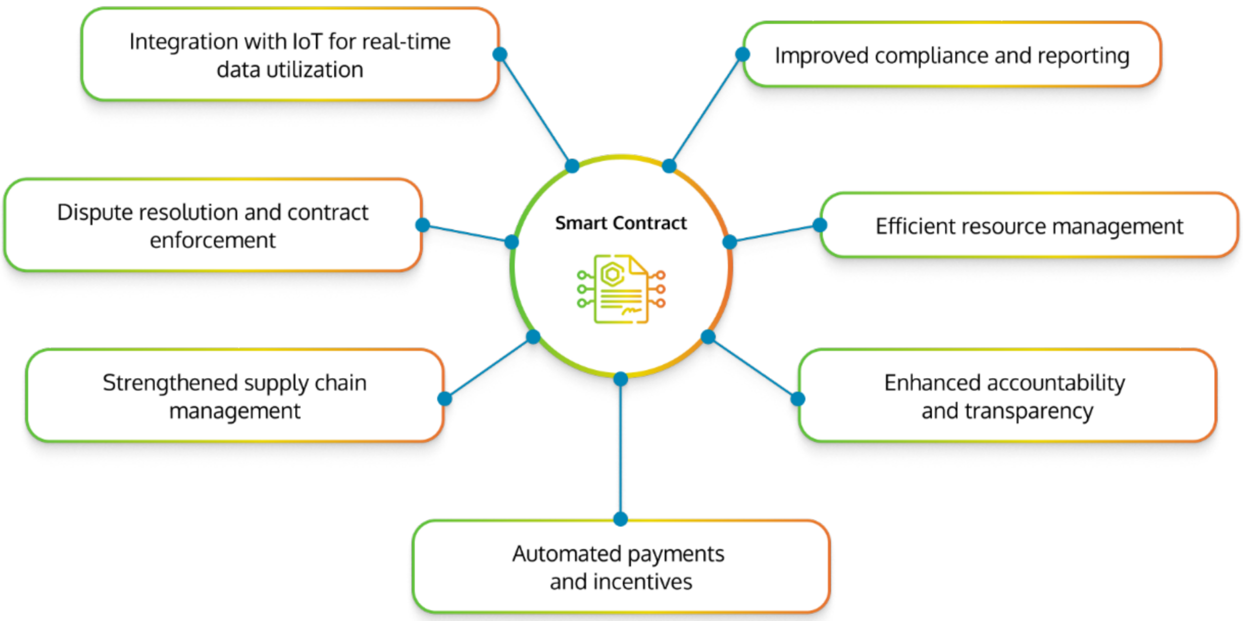

Figure 4. Smart contract development in advanced waste management.

A blockchain-based reward system for recycling aims to promote sustainable practices through digital tokens [93]. Individuals or companies that adhere to recycling guidelines receive a special token that can be redeemed for various benefits. This promotes a culture of recycling and supports the circular economy. A public institution should organize the reward system and bring together waste management and recycling stakeholders to ensure credibility and trust in the system. Users register to receive a unique blockchain identifier, enabling seamless program participation. For environmentally friendly activities, such as material recycling or eco-friendly purchases, users receive a special token. These transactions are recorded in the blockchain, which ensures transparency and fraud prevention.

In addition, these special tokens can be exchanged for product discounts, service vouchers, or donations to environmental protection organizations [94]. The system is integrated into the points of sale and automatically awards points for corresponding purchases. Partnerships with stores and service providers that accept these tokens increase the value of the rewards.

In addition, the special token system increases customers' commitment to recycling and reduces the amount of waste sent to landfills [95]. It promotes conscious shopping, the reduction in carbon footprint, and the sustainable use of resources. The direct benefit of environmentally friendly actions increases user engagement and brand loyalty. Automation through smart contracts ensures fast and efficient distribution of rewards without manual control.

Ultimately, implementing a special token via blockchain technology provides transparency, security, and motivation for environmentally friendly action, which benefits both users and the environment [96].

Furthermore, every transaction recorded on a blockchain is immutable and transparent, meaning that all parties can view the transaction history and cannot change it without consensus. In waste management, this means better accountability for everyone involved, from waste producers to processors and recyclers. Smart contracts can, for example, track the route of recyclable materials to ensure they are actually processed properly and to reduce the risk of fraud [97]. Smart contracts can also automate data collection and reporting to regulators. This automation ensures that reports are generated in real-time and are always based on the most accurate and up-to-date information, simplifying compliance with environmental laws and regulations [98].

Another advantage and application are that a smart contract can optimize logistics and resource allocation by automating scheduling based on real-time data [99]. For example, they can dynamically adapt waste collection schedules to the actual fill level of the bins, which is monitored by IoT sensors. This not only ensures more efficient routes and fuel consumption but also prevents garbage cans from overflowing, keeping cities clean and reducing environmental impact. When integrated with IoT devices that monitor waste volumes, smart contracts can trigger actions (e.g., scheduling additional collections) when certain thresholds are reached [100]. This integration leads to more responsive and adaptable waste management services that proactively respond to problems. In recycling, smart contracts can manage complex supply chains by ensuring that every step—from waste collection to sorting and processing—is carried out as agreed. They can also help to certify recycled products and reassure end users that the materials they are buying meet certain quality and sustainability standards. Sen Gupta et al. [45] describe a blockchain-based system that uses smart contracts to optimize the storage, collection, and disposal of solid waste. This system not only reduces environmental impact but also contributes to a healthier urban environment by ensuring that waste management tasks are carried out more reliably and efficiently. The use of smart contracts ensures that operational standards are met and that the process is carried out in accordance with the legal framework.

Using smart contracts in the plastic waste management industry drastically improves the traceability of recycled materials [101]. Every step—from waste disposal to arrival at recycling facilities—is recorded in a blockchain, creating an immutable ledger that can be accessed by all stakeholders involved. Thanks to this transparency, everyone in the recycling chain, from consumers to regulators, can track and verify plastic waste's proper handling and processing. Such traceability is crucial for compliance with environmental standards and certification of recycling processes that meet sustainability requirements.

Implementing smart contracts can also enhance the security and availability of waste management systems, especially those that rely on networked infrastructures [102]. Holanda Filho et al. [103] propose a secure architecture for a solid waste management application, using smart contracts and permissioned blockchain to enhance security and operational availability. This approach demonstrates the feasibility and benefits of using blockchain and smart contracts to secure data and operations in environmentally critical applications.

5.2. Decentralized Applications (DApps)

Further broadening the scope of blockchain applications, decentralized platforms can engage entire communities in waste management efforts [104]. Decentralized applications (DApps) based on blockchain technology are increasingly recognized for their potential to improve the management of plastic waste, particularly in promoting sustainability and recycling. These applications operate on a decentralized network, often built on platforms such as Ethereum, Solana, SkeyNetwork, and others, and are powered by smart contracts that automate and enforce the execution of agreed protocols without intermediaries.

Decentralized applications that leverage blockchain technology transform plastic waste management by providing a robust and immutable ledger of transactions [105]. This capability is crucial for tracking the life cycle of plastic items from production to recycling. This transparency ensures that all stakeholders—from manufacturers to consumers to recyclers—can verify the origin, handling, and final processing of plastics. For example, DApp could precisely record and verify the path of a plastic bottle [106], ensuring that it has been recycled in compliance with environmental standards and promoting accountability and sustainability in the recycling industry. Moreover, DApp could issue digital tokens to users who deposit plastic waste in designated recycling bins [107]. These tokens could then be exchanged for goods or services, encouraging participation and supporting a community-oriented approach to recycling.

DApps also enable efficient, real-time data management, which is essential for optimizing the recycling process [108]. They can manage the logistics of plastic waste collection and recycling by providing up-to-date information on the status and capacity of recycling facilities [109]. These timely data allow collection routes and schedules to be adjusted as needed, increasing the efficiency of waste disposal and reducing unnecessary resource expenditure.

However, the use of DApps in the plastic waste management industry is not without its challenges. Scalability is a major issue, as blockchain needs to process large volumes of transactions and data efficiently [94]. The technology's need for extensive computing resources can lead to delays and increased costs. For DApps to be effective at scale, there also needs to be widespread adoption and standardization across the industry to ensure that all parties can interact seamlessly within the DApp ecosystem. The initial setup and maintenance of such systems also require significant investment in technology and expertise.

In addition, the integration of blockchain into waste management enables municipalities to actively participate in environmental policies. Blockchain can significantly improve the community's engagement by providing a transparent system where all transactions and actions are recorded in a decentralized ledger. Community members can monitor these activities and participate in the decision-making process, fostering a sense of ownership and collective responsibility for environmental sustainability. This community participation is critical to the long-term success and effectiveness of recycling initiatives, making blockchain an invaluable tool to advance global sustainability efforts.

Blockchain applications can facilitate decentralized waste management systems that are not only efficient but also inclusive [110]. For example, Ahmad et al. [94] discuss the role of blockchain in waste management in smart cities, where decentralized applications can help manage waste more effectively while engaging the community. These applications allow waste to be tracked in real-time, ensure compliance with waste treatment laws, and enable efficient resource management. Through the use of smart contracts, these systems automate key waste management services, reducing the need for centralized oversight and enabling direct community involvement.

Another application of blockchain in community engagement is through incentivization models that reward community members for proper waste disposal and recycling efforts [94]. França et al. [8] propose using blockchain to improve waste management in small communities by replacing traditional waste management cards with digital tokens. These tokens serve as an incentive for community members who contribute to waste management, encouraging active community participation and engagement in sustainable practices.

5.3. Enhancing Plastic Waste Management with IoT, Blockchain, and AI

Creating an integrated ecosystem that combines the Internet of Things (IoT), data analytics, blockchain technology, and artificial intelligence (AI) can significantly improve the efficiency and sustainability of plastic waste management processes.

In the first phase, blockchain technology acts as a communication bus that facilitates the integration of different IoT solutions and serves as a platform for event logging. This role requires the implementation of suitable programming libraries and frameworks that enable smooth integration and communication between IoT devices and the blockchain [111]. In addition, the use of open-source software and open protocols is crucial to ensure the interoperability and flexibility of the system. The open-source nature of blockchain environments allows solutions to be adapted and optimized to the specific requirements of the plastic waste management system and ensures that all its components can work together efficiently.

Once events are recorded by the blockchain, the next step is to analyze the data using AI algorithms. These algorithms provide valuable insights and predict future actions, improving decision-making in plastic waste management. Integrating all these technologies requires collaboration between municipal authorities, technology companies, waste management companies, and local communities [112]. Ensuring the openness of the system, data security, and continuous technological updates in response to changing needs and conditions are critical for maintaining the effectiveness of the system.

Integrating blockchain as a communication bus connecting IoT and AI solutions into the plastic waste management system requires advanced programming libraries, open-source code, robust firmware, and interoperability standards. These technical elements ensure the system's security, scalability, and flexibility, which are essential for effective and sustainable plastic waste management. Such integration enables the creation of an advanced ecosystem that significantly improves the efficiency and sustainability of processes related to plastic waste.

The integration of blockchain technology, IoT, and AI into the plastic waste management system creates a complex ecosystem that is more efficient, transparent, and sustainable [83]. Blockchain provides a secure and transparent platform for logging events, while AI analyzes the data to provide valuable insights and predictions that help optimize plastic waste management processes. This combination leads to improved decision-making, better resource utilization, and a reduction in the environmental impact of plastic waste management.

5.4. Case Studies of Blockchain for Plastic Waste

Blockchain technology is increasingly recognized as a transformative tool for plastic waste management. Several case studies and implementations show that it has the potential to improve transparency, traceability, and efficiency throughout the waste management lifecycle (Table 3).

Table 3. Blockchain applications in plastic waste management.

Key Contributions/Innovations	Benefits	Ref.
Blockchain can revolutionize plastic waste management by enhancing payment systems, recycling rewards, and waste tracking. It emphasizes the use of smart contracts for automating processes and ensuring compliance within the recycling chain.	Improved transparency, traceability, and efficiency. Promotes circular economy.	[84]
Improve the efficiency of plastic waste management by increasing transparency and introducing a rewards system to incentivize community participation, aiming to boost recycling rates and reduce the environmental footprint.	Increased recycling rates and reduced environmental impact.	[85]
Use of blockchain to automate waste separation and collection and to track the lifecycle of plastics, promoting a transparent and collaborative system that benefits all stakeholders and ensures sustainable plastic waste management.	Better coordination among stakeholders, significant environmental and economic benefits.	[113]
Blockchain-based solid waste management (SWM) model enhances transparency and optimizes economic aspects. Community-controlled framework improves accountability and reduces fraud.	Optimized waste management, economic efficiency, transparency, and accountability	[114]
Implementation of blockchain in monitoring garbage can fill levels and waste collection integrates sensors and smart IoT to optimize waste collection, reduce costs, and improve city traffic flow, demonstrating practical benefits in real-world scenarios.	Streamlined waste collection, cost reduction, and improved traffic flow.	[2]

One pivotal study by Steenmans et al. [84] provides a comprehensive overview of how blockchain technology can disrupt traditional waste management practices, particularly in the management of plastics. This study highlights several key areas where blockchain has a role to play, including payment systems, recycling rewards, and monitoring and tracking of waste activities. Smart contracts are particularly characterized by their ability to automate processes and ensure compliance within the recycling chain, promoting a circular economy approach to plastic waste management.

Another significant contribution to the field comes from Mondal and Kulkarni [85], who propose a blockchain-based DApp designed to improve the efficiency of plastic waste management. Their model aims to bridge the gap between waste generation and recycling capabilities by enhancing the transparency of the recycling process and introducing a rewards system to incentivize community participation. This approach promises to increase recycling rates and reduce the environmental footprint of plastic waste.

The application of blockchain in fostering an efficient circular economy for plastic recycling was explored by Khadke et al. [113]. Automating waste separation and collection and using blockchain to track the lifecycle of plastics promotes a transparent and collaborative system. Such a system not only facilitates better coordination between stakeholders—from producers to recyclers—but also ensures a sustainable approach to plastic waste management that brings significant environmental and economic benefits.

The blockchain-based solid waste management (SWM) model proposed by Gopalakrishnan et al. [114] to enhance the transparency of recycling systems and optimize solid waste management presents a promising approach to address many of the inefficiencies and transparency issues associated with traditional waste management systems. It uses a community-controlled blockchain framework where client companies pay to participate in the platform to access services from community-managed providers. This model not only improves waste management but also helps optimize the system's economic aspects. The introduction of blockchain provides a reliable and immutable record of all transactions and interactions within the system, improving transparency and accountability throughout the waste management lifecycle [115].

In this model, an optimization framework is developed to determine the optimal quantity of waste that can be traded between supplier and consumer companies to maximize their profits. This involves considerations such as the number of suppliers, consumer companies, and the processing capacity of these entities. The model addresses several constraints, including maximum storing capacity, storage, and transportation constraints, to ensure that the system operates efficiently [116]. Additionally, the cost aspects associated with blockchain implementation are carefully analyzed, drawing on use cases from companies that provide blockchain solutions. This helps to estimate the financial burden and benefits associated with adopting blockchain technology in SWM systems.

By implementing blockchain, the SWM model significantly increases the transparency of the recycling systems [117]. Every waste management transaction and activity—from collection to recycling—is recorded on the blockchain, ensuring that all the data are easily verifiable and protected from tampering. This level of transparency is crucial in building trust between stakeholders and ensuring compliance with environmental regulations. In addition, the immutability of blockchain records means that all parties can be held accountable for their actions, leading to improved management practices and potentially reducing incidents of fraud and mismanagement.

A remarkable solution that has been implemented in some Polish cities is the monitoring of the fill level of and collection of waste in garbage cans. Waste24, a waste collection company, wants to achieve optimal recycling rates and streamline waste collection. The company achieves this by using blockchain technology in software for municipal services and individual waste producers. This integration increases transparency in waste management and complies with current regulations that require clear documentation, as found in tools such as the waste database. The proprietary software combined with the blockchain ensures that each participant's data in the waste cycle is recorded in real-time, enabling accurate tracking of waste management activities [2].

Waste24 emphasizes waste disposal automation, addressing significant challenges faced by large waste producers and businesses with multiple branches. For these entities, waste collection is a critical cost factor. By using blockchain, Waste24 improves control over expenses for each collection cycle. The Waste24.net platform integrates with container sensors to notify users of any overflows.

Leveraging blockchain as a communication channel eliminates architectural barriers, a crucial aspect given that time is of the essence in waste collection. Waste must be collected swiftly to avoid garbage trucks obstructing traffic. An indirect outcome of the blockchain implementation is the "Digital Key" application, designed to open gates and waste shelters quickly, reducing truck stoppage time and improving city traffic flow. All these solutions are built on the SkeyNetwork blockchain ecosystem. With the integration of smart IoT sensors, the Waste24.net system, and the SkeyNetwork blockchain, it is possible to consistently monitor the available space in a company's garbage bin. This approach not only streamlines waste collection but also reduces costs.

5.5. Comparison of DApp and Their Impact on Recycling Rates and Sustainability

The comparison of decentralized applications and their impact on recycling rates and sustainability reveals significant insights into how blockchain technology can revolutionize waste management practices. Decentralized approaches to waste management, particularly in recycling, leverage the inherent benefits of blockchain technology, such as transparency, traceability, and enhanced stakeholder participation, which are crucial for sustainable practices [94].

A study by Capodaglio [118] explores decentralized wastewater management systems, emphasizing resource recovery in rural and peri-urban areas. The decentralization of waste management systems facilitates local recycling and the reuse of resources, significantly reducing environmental impact compared to centralized systems. This approach aligns with eco-innovation and sustainability, providing practical solutions that adapt to local conditions while promoting environmental, economic, and social benefits.

Kavvada et al. [119] discuss striking a balance between economies of scale in treatment facilities and the size of conveyance infrastructure. The study uses a heuristic modeling approach with geospatial algorithms to evaluate the financial costs, energy use, and greenhouse gas emissions associated with decentralized water reuse systems. The findings suggest that decentralized systems can significantly reduce infrastructure costs and improve the sustainability of urban water systems.

Tsai [120] investigates how social capital influences regional recycling rates, providing evidence that higher levels of social coherence within communities are correlated with better recycling performance. This study demonstrates that decentralized recycling initiatives can benefit significantly from a region's social capital, enhancing community participation and the overall effectiveness of recycling programs.

5.6. Roadmap for Blockchain-Based Plastic Waste Management

Implementing blockchain technology in plastic waste management requires careful planning and strategic alignment. Here is a structured adoption roadmap, which can support stakeholders at different levels, from individual companies to broader governmental programs, ensuring a coordinated approach to sustainable plastic waste management:

(1) Assessment and strategy development:

Begin by assessing your organization's current plastic waste management practices and technology capabilities. Define clear goals such as reducing plastic pollution, enhancing traceability, and improving recycling rates. Develop a blockchain adoption strategy aligning with sustainability and waste management objectives.

(2) Stakeholder engagement and buy-in:

Identify key stakeholders, both internal and external, including waste management staff, IT personnel, and external partners like recyclers and municipalities. Conduct educational workshops or meetings to outline the benefits and challenges of blockchain technology. Secure management buy-in to allocate necessary resources.

(3) Technical planning and feasibility study:

Conduct a feasibility study to identify a suitable blockchain network based on factors like transaction speed, security, and scalability. Plan the technical infrastructure, including servers, blockchain nodes, and network security. Address integration needs with existing legacy systems and software.

(4) Pilot program development:

Design a small-scale pilot program to test blockchain implementation in a specific plastic waste management area. Focus on activities like tracking plastic collection or incentivizing recycling efforts. Develop clear success metrics and collect baseline data for comparison.

(5) Implementation and training:

Implement the pilot program, ensuring accurate integration and secure data migration. Provide comprehensive training to staff on blockchain technology and any new waste management processes. Monitor the pilot program's performance to gather key metrics.

(6) Evaluation and scaling:

Evaluate the pilot program against success metrics, collecting feedback from stakeholders. Plan to scale the blockchain solution across more regions or waste management activities based on pilot results.

(7) Continuous improvement and compliance:

Regularly monitor the blockchain network for security, transaction speed, and data integrity. Stay updated on data privacy regulations and maintain compliance with industry standards. Periodically review technologies and processes to identify new innovations.

This roadmap provides a structured approach to implement blockchain in plastic waste management. It ensures phased adoption while maximizing benefits like improved transparency, traceability, and sustainability.

6. Conclusions and Future Trends

Blockchain technology has the potential to revolutionize the management of recyclable plastic waste by improving transparency, traceability, and incentives, promoting a more sustainable and circular economy. Despite progress, current global plastic recycling systems remain inefficient, leading to significant environmental damage. Problems such as low recycling rates and poor quality of recycled materials, particularly in Europe, are exacerbated by inefficient sorting systems.

Innovations in chemical recycling, solvent-based techniques, and biotechnology are essential to solve the plastic waste crisis. These technologies aim to improve recycling efficiency and increase the value of waste materials. Blockchain applications, including digital watermarks, decentralized applications (DApps), and smart contracts, offer solutions to improve traceability, incentivize participation, and automate recycling tasks. Smart contracts, for example, can streamline supply chain processes, reduce fraud, and automate payments, while DApps can promote transparent peer-to-peer waste management and increase participation through incentives.

However, for blockchain-based solutions to be effective, significant investment in technology, infrastructure, and education is required. Future developments in blockchain technology will likely focus on improving traceability and developing certification schemes for recyclable plastics that provide transparent records of the lifecycle of plastic products. Integrating blockchain with IoT devices will further optimize the disposal of plastic waste by monitoring waste volumes and contamination, securely storing data, and optimizing collection routes. AI integration can also improve recycling processes by predicting waste trends and developing new polymers and recycling methods. Blockchain technology could also facilitate global networks exchanging plastic waste and recycled materials, improving the efficiency of global recycling markets and reducing environmental impact.

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