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The Future is Traceable: Integrating Blockchain, Waste Management, and the Circular Economy for Sustainability

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Abstract

Blockchain technology's emergence in waste management (WM) offers a fresh approach to addressing problems, including efficiency, transparency, and traceability. However, the lack of transparency in tracking trash from its production to its disposal makes traditional waste management frameworks vulnerable to fraud, poor management, and inefficiency. Blockchain provides a safe and immutable platform that records every stage of the waste lifecycle, enabling real-time verification and monitoring. This study sheds light on how blockchain technology, in conjunction with smart contracts, might improve recycling and promote waste operations' transparency. The idea of a digital product passport is also reinterpreted in the larger framework of trash recycling and the circular economy (CE). The study demonstrates the need to develop indicators for SWM efficacy assessment using data from Scopus and WoS (Web of Science) and R and Bibliometrics tools.

Keywords: *Blockchain Technology's, Waste Management, Circular Economy, Sustainable Approach.*

Introduction

Due to urbanization and population development, waste management has become one of the world's most complicated issues (Srivastava, V., Ismail, S. A., Singh, P., & Singh, R. P. 2015). Cities worldwide have been producing more waste over the last ten years, negatively impacting the environment and human health. 2025 over 2.2 billion tons of solid garbage will be produced worldwide. Excessive garbage generation and inappropriate disposal methods significantly affect the ecology. The most concerning statistic is that 33% of the waste produced in cities is not disposed of in a way that is safe for the environment. These growing trash quantities are too much for conventional waste management technologies (Demirbas, A. 2011). These systems have several difficulties, including antiquated data protection regulations, a dearth of recycling facilities, and lousy customer behavior around garbage sorting (Lakhouit, A. 2025). Such difficulties necessitate an innovative strategy and prompt action to guarantee that their concerns are sufficiently handled.

Countries all across the world have implemented various waste management strategies (Zorpas, A. A. 2020). Japan has a particular system where people must separate their garbage into recyclables, non-recyclables, and burnable. Through legislation and a pay-as-you-throw system, where residents pay for the quantity of rubbish they dispose of, Germany likewise prioritizes

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recycling and waste reduction. South Korea has embraced this idea as a national waste management policy. Due to its limited territory, Singapore has significantly invested in waste-to-energy facilities that convert solid waste into electrical power. Germany has a two-pronged approach to packaging waste, with manufacturers handling the collection and recycling of their packaging. Sweden has significantly reduced its reliance on fossil fuels by using waste incineration for waste management and electricity production. Customers who purchase drinking bottles in Norway pay a modest deposit and receive rewards for returning them to reverse vending machines as part of an efficient bottle recycling program. The container deposit program in South Australia has also reduced littering and increased recycling rates (O'Dwyer, C., Zaman, A., & Breadsell, J. K. 2022).

One of the most ambitious of these initiatives is Saudi Arabia's NEOM project, which envisions a progressive metropolis built on the ideas of the circular economy where its citizens can prosper in a technologically sophisticated and sustainable setting (Sumra, K. B., Siddique, H., Afzal, S., & Qazi, A. 2025). Through the use of blockchain technology to create an integrated waste management system, such integrated diagnostics of the circular economy (CE) and its relationship to new material flows have the potential to revolutionize the industry by bringing efficiency and transparency to the task of tracking waste from production to recycling within the same CE framework.

Blockchain technology has emerged as a potent instrument in the waste management industry (Baralla, G., Pinna, A., Tonelli, R., & Marchesi, M. 2023). The decentralized system can securely store data, guaranteeing high-quality services. It has clear advantages, such as confirming data accuracy, confirming how environmentally friendly products are, and increasing recycling effectiveness (Liu, J., Liu, Z., Yang, Q., Osmani, M., & Demian, P. 2022). Blockchain can provide a tamper-proof ledger of trash transactions by tracking and validating waste material from initial manufacture to the final recycling step (Bułkowska, K., Zielińska, M., & Bułkowski, M. 2023). Blockchain technology can also optimize garbage collection and disposal, increasing system transparency and making the process more effective and less vulnerable to fraud (Gopalakrishnan, P. K., Hall, J., & Behdad, S. 2021).

The objective of a circular economy is to minimize waste by extending the useful life of resources, materials, and products (Morseletto, P. 2020). Blockchain technology can enhance data interchange across different waste management ecosystem players, which can support the goal of an effective waste management system (Ahmad, R. W., Salah, K., Jayaraman, R., Yaqoob, I., & Omar, M. 2021). These players include customers, businesses, governments, garbage collection agencies, recycling facilities, and product manufacturers. Blockchain facilitates efficient recycling, extends recyclable resources, and minimizes landfill usage by reducing the smooth interchange of data and tracking waste items.

Furthermore, the blockchain can facilitate the creation of digital product passports that record crucial details about a product over its lifecycle, such as the extraction of raw materials and linked recycling procedures at the end of its useful life (Koppelaar, Rembrandt HEM, et al.,2023). In actuality, it is increasing waste management transparency and encouraging companies and consumers to embrace sustainable practices since they can see their products' environmental impact.

Since solid waste (SW) is still a significant issue worldwide, there has never been a greater expectation to move toward a circular economy (CE) (Hoang, Anh Tuan, et al.,2022). The "take-make-dispose" paradigm of the current linear economic model seriously depletes our natural resource base and pollutes the environment. Goal 12.5 of the UN's Sustainable Development Goals (SDGs) emphasizes the significance of tackling waste generation through recycling, reuse, and reduction initiatives.

Recycling: Products in a circular economy are made to last, be reused, and eventually be recycled. Highlighting the need to extend product life cycles, reduce waste production, and use resources as efficiently as possible (Morseletto, P. 2020). By putting circular economy principles into practice, real benefits like innovation, job creation, and a reduction in solid waste production can result in economic gains at a rate of 10–30%. In this context, optimizing material recovery and reuse through effective solid waste management (SWM) is crucial to advancing the circular economy. They promote environmental sustainability and lessen the demand for natural resources (Afshari, H., Gurtu, A., & Jaber, M. Y. 2024). Several global projects were effectively executed, including CE principles in SWM planning. Some areas have seen a rise in the utilization of waste as an industrial resource, selective waste collection, and industrial waste reuse. Additionally, resource recovery, bioenergy, and value-added products will be promoted by applying CE principles to the management of solid waste management's (SWM) biodegradable and non-biodegradable fractions (Duan, Y., Tarafdar, A., Kumar, V., Ganeshan, P., Rajendran, K., Giri, B. S., ... & Awasthi, M. K. 2022).

One of the biggest obstacles to advancing the circular economy in SWM is encouraging cooperation between various social actors (Salmenperä, H., Pitkänen, K., Kautto, P., & Saikku, L. 2021). These actors are conventionally characterized as those entities (governments, corporations, institutions, etc.) that function in the social sphere of law, order, economy, environment, etc. Institutions must support the transition from a linear to a circular economy to address joint difficulties and create shared advantages. When these actors work well together, it can be possible to implement sustainable practices and integrate the circular economy's tenets into waste management systems (Salmenperä, H., Pitkänen, K., Kautto, P., & Saikku, L. 2021). Among these is the significant contribution that environmental education makes to encouraging public involvement in rubbish collection (Behzad, M., Shooshtarian, S., & Maqsood, T. 2025). This technique can also enhance living circumstances and promote social and economic sustainability, particularly in underdeveloped nations where waste pickers depend on sorting waste for a living.

Through laws encouraging waste reduction, reuse, recycling, and ethical product manufacture, they maximize the application of the circular economy's tenets (Espuny, Maximilian, et al.,2025). Research on how governments may Study shows that research stimulating the transition to a circular trash economy is still needed, according to studies (Sohail, M. T., Ullah, S., & Sohail, S. 2025). It involves. This identifies the gap between industrial sectors and other players in this transition and creates an atmosphere favorable to the use of circular economy techniques. Several case studies demonstrate how the circular economy can help with solid waste management issues. However, there are still unanswered questions regarding integrating CE into every industry (Grieco, C., & Morgante, A. 2025). Such work further demonstrates that the current body of research does not fully understand the role of government in promoting a circular economy, and more policy-driven studies of the circular economy are necessary (Yu, L., Jia, N., & Li, M. 2025).

A transition to a circular economy presents a chance to stop trash production and pave the way for a sustainable future, given the rise in waste output worldwide (Rittl, L. G. F., Zaman, A., & de Oliveira, F. H. 2025). Blockchain Technology in Waste Management: A Revolution in

Reducing Waste and Enhancing Transparency, Effectiveness, and Data Precision However, we can build a more circular and sustainable waste economy that may generously benefit society and the environment if we have the proper institutional backing, public awareness, and technological innovations like blockchain.

Theoretical Basis

Utilize Sustainable and Circular Operations to Reduce Waste

The current global economic model, which was primarily based on the Industrial Revolution, is based on a linear economy paradigm that assumes that nature has a limitless capacity for regeneration and that our planet's resources are unlimited. This "take, make, dispose" strategy encourages resource extraction to meet human needs, profit-driven manufacturing, and the disposal of useless items. Numerous environmental issues have resulted from this approach, including excessive trash generation, high greenhouse gas (GHG) emissions, a shortage of landfill space, and irreparable ecological damage (Bajpai, A., & Koul, M. 2025). For public managers and legislators, these consequences have become significant roadblocks to achieving sustainable development.

Solid waste management (SWM) is one of the most challenging parts of these problems. In addition to polluting and destroying the urban environment, improper waste management risks human health, lowers productivity and impedes economic growth. In underdeveloped nations, where over 90% of garbage is disposed of in open-air landfills or dumps that do not collect recyclables, inadequate waste management also deteriorates soil and groundwater. On the other hand, industrialized countries pollute the air by burning garbage for electricity in power plants (Abbas, Qamar, et al.,2025).

Modern Solid Waste Management (SWM) techniques, such as effective waste collection, waste-picker cooperatives, well-built landfills, and waste-to-energy technology, can help achieve this. Increasing the value of known garbage, encouraging recycling, and decreasing the amount of waste flow help create urban-rich soil(Meyer, O. 2025). Despite these developments, the interaction of institutional, legal, environmental, social, and economic factors that fall under the SWM category adds to the complexity of this issue. Inappropriate usage of technologies like incineration, which reduces garbage size and generates electricity, can also pose health problems and exacerbate global warming. We must adopt a more sustainable mindset to benefit from the Circular Economy (CE) model (Saravanan, K., & Chandrasekar, T. 2025).

Embraced its potential for sustainable development.

A new paradigm called the Circular Economy (CE) aims to address the shortcomings of the linear economy. Additionally, CE aims to keep materials and products in use for as long as feasible, in contrast to the linear "take, make, dispose" paradigm. The phrase "reduce, reuse, recycle" is commonly used to mean limiting waste production, making the most use of materials and resources, and permitting items to be recycled or reused when their useful lives are ending, if applicable. In addition to increasing economic growth, innovation, and employment, this conserves natural resources (Guan, X., Hassan, A., & A. Nassani, A. 2025). Since the Earth is viewed as a finite, closed system with little capacity for regeneration, CE promotes closed-loop systems. It emphasizes the importance of striking a balance between environmental protection and economic prosperity. By recycling, reusing, and reducing, you may maximize the use of materials and keep them in use, unlike the linear model, where trash frequently ends up in landfills or is burned (Tighnavard Balasbaneh, A., Sher, W., & Ashour, A. 2025). Because of the circular economy created by this new system of production and consumption, fewer raw materials are extracted, less energy is used, and less waste is produced. Based on the 3Rs (reduce, reuse, and recycle) as the result of the recycling process, the circular economy (CE) concept entails the reuse of resources through sustainability and the reduction of environmental consequences.

Barriers to Vouchers or a Circular Economy

Though the CE model has many merits and advantages, making the switch from the linear economy is difficult for many reasons. These include high levels of complexity, uncertainty, stakeholder conflict, and incompatibilities on spatial, temporal, and institutional scales (Kuran, U., Krause, T., & Ünal, V. 2025). These barriers prevent us from efficiently converting waste management systems to a circular model.For example, moving to circular systems from linear ones will be a complex switch across sectors, behaviors, and policies. Stakeholders need to work together to encourage the reusing and recycling of materials while implementing systems that allow them to do so. However, divergent interests, institutional constraints, and reluctance toward change can make such collaboration challenging (Bandauko, E., & Arku, G. 2025). Second, shifting towards a circular economy may involve significant infrastructure, technical and capital costs, especially for waste management practices in the developing regions. However, the CE's ability to synchronize economic and environmental goals inspires its promise to tackle these issues (Aivazidou, E., Tsolakis, N., & Mollona, E. 2025). This approach has helped establish some more sustainable production and consumption patterns, which can help reduce waste generation, conserve resource usage, and generate economic growth.

Making Circular the Future: The Journey Begins

A bunch of disruptive innovations and technology have appeared to enable the transition of the Circular Economy straight away to waste management. One such promising technology is blockchain, which provides a decentralized, secure, and transparent system to record transactions and trace material movement (Niu, G. 2025). From the production stage to the recycling stage, technical solutions are working on making waste management technology as efficient as possible, allowing blockchain to establish transparency and accountability in the new era of waste management. This technology enables the tracking of materials through the recycling stream, which reduces the potential for fraud and increases efficiency (Kim, M. J., Han, C. H., Park, K. J., Moon, J. S., & Um, J. 2025).

For example, four of our clients are re-designing plastics using molecular tagging and blockchain technology so that these plastics actually remain in a closed loop and can be recycled indefinitely. The development provides a solution for plastic waste, which has proven tricky to recycle and typically winds up in landfills or the ocean (Haba, B., Djellali, S., Abdelouahed, Y., Boudjelida, S., Faleschini, F., & Carraro, M. 2025). How it works: Inputs tagged plastics allow them to follow their lifecycle and ensure they are correctly recycled into new products. Other technologies explored in circular business models include technologies that can track the flow of inputs and outputs in operation, such as blockchain, 3D printing, and (Radio Frequency Identification) RFID tags, as well as Industry 4.0 and IoT technologies. The most excellent waste tracking, automation of sorting methods, and strengthening of knowledge change among the stakeholders' technologies make waste management processes more innovative and more effective (Lakhouit, A. 2025). Another notable method is keeping the waste-to-energy technologies in line, so they generate energy from waste materials and reduce the amount of waste they will develop and their alternative energy sources. This method is aligned with the larger goals of the circular economy by significantly reducing waste and generating energy.

Circular Economy and Waste Management Integration

Applying CE principles to waste management systems can result in more effective and sustainable solutions. Changes in company behavior and public legislation will be necessary to switch to CE (Walpole, G., Bacon, E., Malik, T., & Rich, N. 2025). Governments must actively support circularity by enacting laws promoting recycling, reuse, and waste reduction to put such activities into effect. Additionally, companies must implement circular business models, which limit waste and continuously repurpose resources (Psarommatis, F., May, G., & Azamfirei, V. 2025). Circular business models can explicitly address pollution, resource depletion, and waste creation, among other issues. For instance, businesses might employ sustainable materials, adapt their products to make recycling easier, and implement take-back initiatives to encourage the recycling of unwanted goods. In addition to removing trash, this develops a sustainable business plan that supports the ideas of the circular economy (Barbosa, M. W., Bronzo, M., Júnior, N. T., & de Sousa, P. R. 2025). Supporting a circular economy also heavily relies on awareness and education. By educating customers on waste reduction, recycling, and reuse, we can promote actions that make the switch to circular waste management systems easier.

This kind of economy is a novel approach to waste management that seeks to address most of the problems brought on by the linear model. This shift to circular systems, which encourage resource reuse, waste reduction, and sustainability, can result in a more robust and effective waste management system (Fatorachian, H., Kazemi, H., & Pawar, K. 2025). Circular waste management can become more productive and efficient with the help of new business models and technology like waste-to-energy systems and blockchain. A more sustainable future with less waste, more resources, and less of an influence on the environment may be achieved by putting the proper regulations into place, encouraging innovation, and working together (Dou, J., Dou, J., Qin, M., & Su, C. W. 2025).

Methodology

This study utilized an exploratory mixed-method design using both qualitative and quantitative approaches. To begin the data collection process, a literature review identified relevant and key academic and industry documents on sustainable and circular operations in waste management. Bibliometric analysis was used to evaluate the connections between sustainable waste management and circular economy principles. This enabled a comprehensive overview of several important issues, namely (a) emergent trends and topics, (b) interaction between researchers and institutions, (c) metrics (to assess research quality), (d) gaps in the current literature; (e) generating input to assist the creation of public policy; and (f) generating innovative research agendas. Bibliometric literature analysis of publications (2014–2024) reveals a decade of continual rise in worldwide environmental destabilization and commitment to global waste management policies, especially in Europe, where social and ecological aspects remain vital to policies.

Methodological Approach

The following key methodological steps were followed: (a) selection of appropriate academic databases, (b) identification of key points/terms for data retrieval, (c) selection of data processing tools, (d) definition of relevant inclusion and exclusion criteria, (e) identification of relevant publications, (f) removal of duplicates, and (g) qualitative and quantitative assessment of findings. The WoS and Scopus databases were selected for this study because they cover a wide range of high-impact academic journals. The study was carried out between January and February 2025 using the keywords "Sustainable Operations" and "Circular Economy" in association with "Waste Management."

Data Collection and Processing

Inclusion and exclusion criteria were utilized to ensure that selected studies were directly related to sustainable operations, circular economy, and waste management. The screening was conducted by rewriting all non-duplicate articles' titles, abstracts, and keywords. We only kept those that explicitly discussed the relationship between these themes. Duplicate records between the two databases were erased to maintain robustness and minimize bias. This bibliometric analysis used the R programming language and the Bibliometrics and Shiny packages, which provide a high-end analytic framework for bibliometric evaluations. In the second part of our analysis, we used the Bibliometric package (within R Studio) to process metadata and the Shiny package to present bibliometric results (Barbara, Marco, & Andrea, 2020), making our analysis accessible and intuitive.

After downloading the data from Scopus and WoS, the exported files differed. BibTeX . The search used in WoS was as listed below: TS = ("Sustainable Operations") AND TS = ("Circular Economy") AND TS = ("Waste Management")

The Boolean operator "AND" guaranteed that the search algorithm considered all three terms simultaneously. Here, TS (Topic Search) means that these keywords were used for the titles, abstracts, and keywords of the selected studies.

For Scopus, the search strategy was modified as follows: (Title-Abs-Key ("Sustainable Operations") And Title-Abs-Key ("Circular Economy") And Title-Abs-Key ("Waste Management")) And Pub year > 2014 And Pub year < 2024

In Scopus, the syntax used the TITLE-ABS-KEY command to restrict results to those that featured the search terms in their title, abstract, or keywords. The date filter only included articles published from 2014-2024. The search yielded 253 publications in Wo S and 341 in Scopus, respectively.

Data Cleaning and Analysis

This process started with integrating the datasets and identifying multiple records. After removing duplicative entries, the final dataset included 421 unique publications. Next, we performed bibliometrics on those data to draw relevant conclusions.

The data were analyzed by applying the three core bibliometric laws:

Bradford's Law — To find the most prolific journals contributing to the literature on sustainable and circular operations in waste management. This helped identify the key sources of literature.

Zipf's Law – Used to evaluate the frequency of keywords, revealing the main themes and trends in the literature

Lotka's Law – Analyzed author productivity and impact, identifying key contributors and leading research institutions.

The cleaned data was then visualized using the Shiny package to create interactive dashboards that comprehensively explore bibliometric trends.

Key Findings

The analysis provided several key insights about sustainable and circular waste management approaches:

• Starting in 2016, the number of publications regarding the use of biological agents in waste management has increased steadily, indicating the increasing importance and urgency of solving the globally common waste problem.

• Europe became a frontrunner in policy-driven research, led by institutions in the United Kingdom, Germany, and the Netherlands.

• An analysis of keywords indicated that more articles referred to recycling in terms of "resource efficiency," "closed-loop systems," and "zero-waste strategies."

• University/research institution collaboration networks emphasized the critical role of international collaborative action in making circular economy concepts work.

• Research gaps include limited empirical studies on practical implementations of circular economy frameworks in waste management and a lack of studies on developing economies.

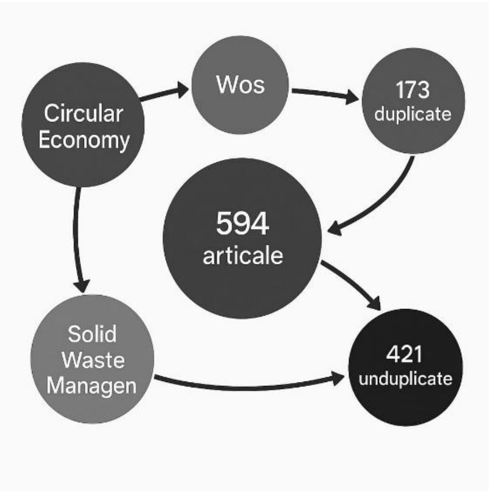

Figure 1.

Data collection and sample definition step.

General Statement on Solid Waste Management and the Circular Economy

They suggested improvements in line with CE that would reduce the need for landfills by 11.5% and raise waste-to-energy conversion capabilities by 4.6%. Discussed waste recycling and recovery in Bolivia and identified several challenges, including the effects of political instability and lack of financial resources (Kempston, S., Coles, S. R., Dahlmann, F., & Kirwan, K. 2025). They conclude that multidisciplinary and inter-sectoral collaboration and funding are key to implementing waste management strategies based on the CE in developing countries. The transition above also heavily relies on tech innovation. Rena et al. Automated waste separation, route optimization, and digital applications can improve efficiency. Further integration of blockchain technology into SWM systems is recommended to enhance transparency and accountability while achieving CE objectives (Amer, L., Thneibat, M., Sammour, F., & Lepkova, N. 2025). Other studies have examined urban mining for resource recovery. Observed that recycling incentivizes waste collectors while the economic potential of using urban waste material for the production process reduces dependent spots over landfills.

Blockchain Technology Facilitates Sustainable and Circular Operations to Help Fight Waste

Usually, organizational units and cloud platforms serve as the focal point for this collection of data processing systems (Mohr, M., Pebesma, E., Dries, J., Lippens, S., Janssen, B., Thiex, D., ... & Griffiths, P. 2025). Their systems serve as intermediaries, facilitating communication between different entities. However, they also have drawbacks, such as the points of failure they create, the susceptibility to cyberattacks, and the frequently occurring inconsistency of information. Because participants need to trust intermediaries to validate transactions and data veracity, these pain points can drive up prices and render system management unmanageable.

The application of blockchain technology is in decentralization. Without a central authority, this decentralized database system allows users to capture, distribute, and store information transparently and cooperatively across a network (Nguyen, T. L., Nguyen, L., Hoang, T., Bandara, D., Wang, Q., Lu, Q., ... & Chen, S. 2025). Because data stamped on a "Blockchain" cannot be altered, these systems have high credibility and security. Transparency: The same reliable information source is available to all network users.

A chain of data blocks is called a blockchain. Blocks contain crucial information such as data, a link to the preceding block, and a unique identifier (hash) (Quispe, M. A. C., & Pacheco, A. 2025). Because doing so would destroy the entire chain, any attempt to alter data in a block would be instantly identifiable. This framework continuously verifies the data that each network participant uses.

Blockchain technology can facilitate a transparent and safe system for tracking waste products from generation to recycling in the smart waste management industry. By having efficient recycling and resource management procedures, this technology can maximize accountability, minimize fraud, and improve operations supporting the principles of a circular economy (Pattanayak, S., Ramkumar, M., Goswami, M., Narayanamurthy, G., & Rana, N. P. 2025).

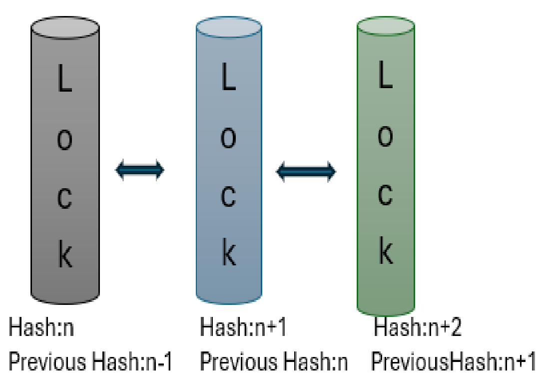

Figure2: Sequence of Data blocks in Technology

A blockchain is a publicly accessible, distributed database with multiple users run by a network of computers using a specific blockchain protocol (Muzammal, M., Qu, Q., & Nasrulin, B. 2019). Each participant, or node, maintains its databases and has equal authority to execute and verify modifications (Abdulla, H. S., & Aladdin, A. M. 2025). To sum up, the decentralized system silo-proof guarantees that no one party controls the database and that the members approve all modifications. The two main benefits of blockchain in waste management are immutability and transparency. The network instantly recognizes and rejects changes to previously recorded data (Shan, P., Meng, Z., Xu, H., Li, C., Zhang, L., & Xi, B. 2025). Therefore, this networked ecosystem allows all parties involved in trash management, such as waste generators, recyclers, and municipalities, to exchange waste-related data that anybody can verify and rely on. Because each member possesses a complete copy of the blockchain, this structure makes it extremely difficult for the system to fail and impossible for a person or entity to take control. Using a consensus process, the blockchain ensures it is a reliable and verified source of truth by only making changes when all network participants concur (Yousef, N., Sata, A., Shukla, M., Jarboui, S., & Mobarsa, D. 2025). This technology tracks garbage across its whole life cycle, which benefits the circular economy by ensuring comprehensive waste accountability for each cycle through efficiency.

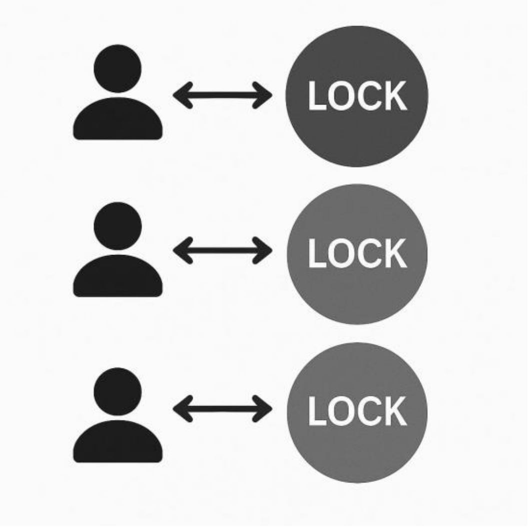

Figure3: The Environment of Blockchain Technology

Blockchain has the potential to significantly increase waste management's openness and traceability by utilizing publicly accessible registries that are subject to verification (Niu, G. 2025). While encryption techniques conceal private information, the source of the records can still be identified. This makes it possible to utilize blockchain explorers or independent analytical software to track and examine the data used in the waste management process. Choosing the kind of blockchain that the application needs: Public Blockchains are accessible to anyone and encourage participation (Mahula, S., Tan, E., Crompvoets, J., & Timmers, P. 2025). Private Blockchains are inaccessible to anyone other than organizations or consortiums. With both private management and the use of public infrastructure for specific activities, hybrid blockchains combine the finest features of both worlds (Bhumichai, D., Smiliotopoulos, C., Benton, R., Kambourakis, G., & Damopoulos, D. 2024). With its openness and data immutability, blockchain technology can track waste materials throughout their lifecycle, support recycling initiatives, and verify product sustainability. To improve resource management and facilitate the transition to a sustainable circular economy, blockchain technology can offer precise data regarding garbage disposal and recycling procedures (Singh, A. K., & Kumar, V. P. 2024). Through material reuse and recycling, this technology enhances waste management processes and lessens environmental impact.

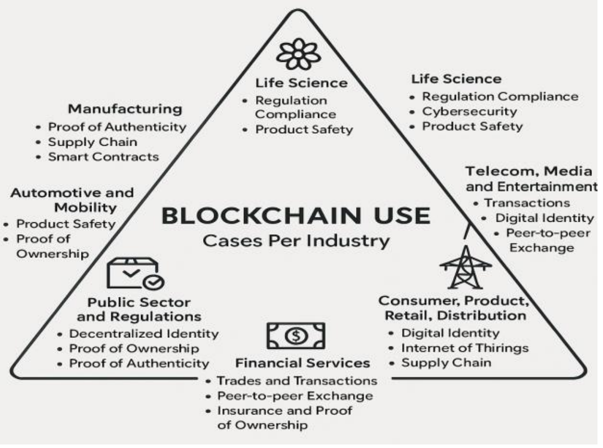

Figure 4.

The use of blockchain in different sectors.

Implementation of Blockchain Technology in Waste Management

The Role of IoT and Blockchain

When merging with the Internet of Things (IoT), blockchain technology can provide meaningful benefits in managing waste efficiently and sustainably. IoT governs diverse physical devices, from straightforward sensors to hierarchical machines connected by the Internet (Almutairi, R., Bergami, G., & Morgan, G. 2024). It would allow for real-time data collection, analysis, and exchange, optimizing processes, lowering costs, and enhancing the quality of life. IoT applications include but are not limited to smart homes, health monitoring, and sophisticated industrial production systems can automate several processes with blockchain, providing security and immutability of the data gathered, especially for waste management, where traceability, transparency, and data integrity are key. Blockchain can serve as a communication bus for developing digital services and products, while real-time data on waste collection, processing, and transportation is gathered through IoT devices (Bułkowska, K., Zielińska, M., & Bułkowski, M. 2024). This guarantees that all data is securely recorded and tampered with, adding to the overall transparency and accountability in waste management.

Smart Cities: Stay Smart with Blockchain for Traceability

Waste management is one of the essential components of a smart city, including household, commercial, medical, and industrial waste. The materials are typically categorized into types: liquid waste, solid waste, hazardous waste, recyclables, and e-waste. Blockchain technology has the potential to help in the effective management of such waste streams (Kumar, Rahul, et al.,2025). With blockchain, waste can be tracked and monitored in real-time from the point of collection to sorting, transportation, treatment, and disposal or recycling techniques. Rather than using a centralized waste management system susceptible to data manipulation, blockchain helps maintain the system's integrity by ensuring that all waste disposal activity is transparent and immutably logged.

Waste Management and Digital Asset Tokens on Blockchain

Digital assets, such as security tokens, associated with waste materials will be in one area of waste management that blockchain will enhance. The tokens are a dependable and faster way to trace recycled waste materials and optimize waste management processes (Sundqvist, A. 2025). Digital tokens assist in streamlining business operations, cutting costs, and helping ensure that waste is handled correctly according to company policies. Traceability, for example, ensures that waste is separated, processed, and recycled appropriately, safeguarding the environment. Blockchain can similarly help keep track of the type of waste (e.g., healthcare waste) processed in recycling plants. Blockchain also minimizes the cost of waste collection, sorting, transportation, and processing by enhancing the transparency of waste traceability. Additionally, a few industries can utilize this technology to trace and monitor the source and transport route of food scraps, waste to produce fertilizers, and other resources that can be recycled into new resources (Gupta, N., Wijenayake, W. P. T., Roy, D., Kumar, R., Rangot, M., Chugh, P., ... & Mitra, D. 2025).

Smart Waste Solutions

One practical example of integrating blockchain in waste management is the Waste24 system, implemented in selected Polish cities. Waste24 is a waste collection company that uses blockchain technology to track the levels and collection of trash containers. It records waste management data live on the system, which makes it more transparent. Waste24 serves clients by integrating blockchain with proprietary software solutions to help achieve higher recycling rates and improve waste management efficiency (Li, W., Ng, T. F., Ibrahim, H., & Wang, S. L. 2025). Waste24 leverages blockchain technology to automate waste disposal for large producers with several operating branches. Waste collection is a costly component of overall expenses, and the blockchain utilizes optimized collection timetables to enable more control over costs. IoT sensors are integrated into the system and provide real-time updates on the fill levels of containers, allowing for more efficient garbage collection and minimizing unnecessary stops. Furthermore, blockchain technology supports a "Digital Key" app, opening gates and garbage shelters, which minimizes the dirty pace of garbage trucks lying idly on the street, streamlining many processes.

Blockchain across the Circular Economy

Blockchain's role in waste management is essential for the circular economy, where resources are reused and recycled rather than thrown away. For example, old mobile phones contain valuable materials, such as lithium and cobalt, which can be recovered and reused to make new products. The lifecycles of these materials can be tracked using blockchain, which ensures that they are recycled or sent for disposal in certified centers (Jayarathna, H. S. N. M., Perera, B. A. K. S., Atapattu, D., & Rodrigo, N. 2025). "Blockchain can provide the required trust, to ensure that waste flows to designated waste treatment centers," explains Bansi. Blockchain's traceability improves accountability, ensuring materials are recycled or reused according to sustainability protocols.

The Rise of Digital Product Passports and Blockchain

Using blockchain as DPPs is a valid step in the move towards a circular economy, enhancing the waste management process. Dapp is a blockchain solution that maintains the transparency of products from their lifecycle to the end (Kim, M. J., Han, C. H., Park, K. J., Moon, J. S., & Um, J. 2025). It lets businesses digitally document and exchange information about products, delivering evidence of origin and sustainability. QR codes, NFC, and RFID tags can link the DPP to physical products and make this information readily available to consumers and supply chain participants. The DPP aims to enable circularity through increased product visibility and traceability. It contains key information regarding its manufacturing, usage, end-of-life stages, and lifecycle, including material composition, manufacturing and assembly processes, repair and replacement history, collection and recycling information, sales volumes, and more. This complete information allows stakeholders to make more informed decisions, resulting in more in-depth recycling, less wastage of raw materials, and ultimately, helping transition from a linear economy to a circular economy (Baldassarre, B. 2025).

Digital Product Passports Benefits

- **Transparency**: DPPs make all information about raw material origin, production, usage and recycling processes available. This transparency gives consumers and businesses the data necessary to make sustainable choices.
- Improved Recycling: By offering information on a product's composition, DPPs result in more precise recycling processes and enable the choice of suitable recycling techniques for specific materials.
- **Waste Reduction**: DPPs help maximize the utilization of raw materials by providing accurate details about materials and quantities, minimizing material wastage over the product's life cycle.
- **Circular economy support:** Traditionally, product use follows a linear pattern with a "make-use-dispose" paradigm.
- **Confidence of the Consumer:** People can check information about the source, environmental impact of the product, and recycling methods with the DPP, and these values can affect their decision to buy more sustainable products.
- **Manufacturer Incentives:** Benefiting from lifecycle data, manufacturers could be incentivized to design longer-lasting, recyclable products, supporting sustainability initiatives.

Blockchain's Role in Circular Economy and Waste Management

Yet blockchain technology is an essential enabler in transitioning to a circular economy, specifically in managing waste. Blockchain provides an immutable, decentralized ledger that can act as a mechanism for the transparency and accountability of waste materials control. Technology is now increasingly used to track the lifecycle of different waste categories, including plastic, e-waste, textiles, medical waste, and hazardous materials (Skrzetuska, E., & Rzeźniczak, P. 2025).

For plastic waste specifically, it aids in sorting by polymer type through its network, enhances waste tracking, and automates financial transactions via cryptocurrency rewards. Logistics and waste utilization are powered by smart contracts on the blockchain, making transparency and individual accountability for all digital recycling players possible. This creates a more efficient and permanent ecosystem for plastic recycling. As an essential use case in e-waste management, blockchain would utilize innovative contract applications to automate transactions and enhance stakeholder interaction (Chen, Z., Sarkis, J., & Yildizbasi, A. 2025). It enables accurate tracking of waste for responsible disposal to avoid illegal recycling. Likewise, in the textile and medical waste management domain, the blockchain ensures that it handles material securely and transparently while tracking the movement of the waste and preventing it from reaching non-medical savvy people. Hazardous waste transfer and treatment processes can be improved through blockchain technology by allowing enhanced control and real-time monitoring. These measures ensure environmental regulation compliance and provide a transparent trail of information while averting illegal dumping and encouraging better management practices (Asare, S. O., Fobiri, G., & Bondinuba, F. K. 2025).

Challenges in Implementing a Circular Economy for Plastics

Blockchain and DPPs hold powerful potential, yet implementing a circular economy model of plastics is not challenging (Carvalho, C., Silva, C. J., & Abreu, M. J. 2025). Challenges include effective sorting of plastics by type of polymer, in-depth tracking of waste, and traceability of past use, especially for food and non-food plastics. Economic, regulatory, and collaborative bottlenecks also hold back progress, especially around the redesigning of plastic products and investments in new technologies (Dewasiri, N. J. 2025). To combat these issues, simple solutions exist, such as rethinking plastic products, adding key information to support downstream recycling and building the technological backbone of waste management. In this process, blockchain plays a crucial role, allowing product lifecycle data to be shared securely, providing transparency on product footprints, and facilitating more efficient recycling.

Type of Waste	**Applications of Blockchain Technology in Waste Management**
Plastic waste	A Different Payment System: Blockchain enables direct, transparent financial transactions for waste management services, incentivizing stakeholders to embrace sustainability. Rewards for Recycling and Reusing: Blockchain provides real-time rewards (cryptocurrency) to companies and individuals who recycle or reuse plastic, creating a form of immediate incentive for sustainable action. Tracking and Monitoring Waste: The transparent and unalterable ledger system of blockchain enables accurate tracking of plastic waste from its source to the recycling stage, ensuring accountability and reducing contamination. Waste Management through Smart Contracts: The logistics of managing waste are automated through Blockchain, release of payments posts recycling milestones using self-executing contracts with predefined conditions.
Type of Waste	**Applications of Blockchain Technology in Waste Management**

E-waste	Smart Contract Modules for Stakeholder Interaction: Blockchain technology can provide a set of rules to track stakeholder interactions across the e-waste supply chain. Different modules look after portions of the process, for example, collection, processing, or resale. Transaction Validation: Blockchain facilitates correct transactions through smart contract modules automation and checks, avoiding illegal practices like improper e-waste disposals or exports. Electronics Lifecycle Tracking: With blockchain technology, every phase of the lifecycle of an electronic device can be recorded to provide transparency and a secure, immutable record that helps with proper disposal, reuse, and recycling.
Textile waste	No Central Perception for Transaction Confirmation: The technology of blockchain negates the need for an authoritative person to cross-check block transactions, allowing parties involved in the recycling of textile waste to directly recognize each other and finalize trades of materials. Immutable Ledger: The unchangeable ledger of blockchain records textile waste data permanently and allows every stage of a textile product's journey, from production to disposal, to be traceable and verifiable. Transparency in Transactions: Blockchain records all transactions and make it visible to the permitted people hence building trust among all stakeholders across the textile recycling ecosystem; this fosters responsible sourcing and disposal practices.
Medical waste	Immediate Documentation & Sharing: Hospitals and waste treatment facilities can utilize blockchain to document that waste is being treated with immediacy for efficient information-sharing on where and how medical waste is being treated. Healthcare Waste Management: Blockchain increases accountability by enabling visibility of all entities involved in the cycle, such as hospitals, transporters, and treatment facilities. Tracking Medical Waste Back to Its Source: Through its metadata features, blockchain can easily track medical waste to its source to ensure regulation compliance and proper handling at each step of the way. Prevention of Forgery & Tampering: Secured by design, blockchain offers an immutable ledger, ensuring no recorded data can be modified, which preserves the integrity of records in high-control environments like medical waste management within the healthcare industry. Simplified Transactions: Blockchain streamlines and automates the transactions among medical centers, waste treatment and recycling plants, reducing admin block and ensuring adherence of laws and environmental standards.
Type of Waste	**Applications of Blockchain Technology in Waste Management**

Hazardous waste	By allowing secure and selective access to relevant data for various participants such as producers, transporters, and treatment companies, blockchain system ensures confidentiality and integrity of data while preserving transparency in the waste management process. Immutable Hash Impacts on Structure: All important details, such as times of the transaction, companies involved, people being part of the process, are saved as an immutable hash, giving what is called traceability, making it easy and simple to verify and audit the data. Real-Time Transactions Audit: Blockchain enables the real-time audit of hazardous waste transactions through smart contracts that track the application, payment (settlement), and invoicing of the entire transaction process. This will help ensure full compliance with the regulations and contribute to improved protection of the environment by enabling regulatory bodies to monitor the process in real time.

Table1: Application of Blockchain Technology in (WM)

By applying blockchain for these diverse types of waste, we can usher in improved transparency, efficiency, and accountability in waste management processes, leading to a more sustainable and circular economy.

Conclusions

Blockchain Technology in Waste Management Blockchain technology emerges as a revolutionary solution to the challenges of visibility, traceability, and efficiency in waste management. Blockchain adds transparency, preventing fraud and raising compliance for recycling practices by providing a safe, indestructible record of waste products tracked from cradle to grave. On top of that, DPPs support circularity by providing information on sustainability and traceability of products, thus supporting a more sustainable economy. The transparent nature of the blockchain also speaks to the needs of a circular economy, extending product lifecycle, maximizing resource utility, and minimizing waste generated, as it provides real-time data, automates many workflows via smart contracts, and better tracks waste generated during production, including packaging. Although the transition from a linear economy to a circular economy is fraught with difficulties, we believe that stakeholder collaboration and technological innovations such as blockchain can help enable sustainable waste management practices. The potential of blockchain and DPPs to revolutionize waste management systems, reinforce the circular economy, and promote a sustainable future for industries and societies alike can be evidenced by the case studies and technological implementations presented.

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