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Transforming Urban and Municipal Plastic Waste Management through Smart Technologies

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ABSTRACT

Plastic pollution remains a critical environmental challenge, with global plastic production surpassing 430 million tonnes annually and only 9% effectively recycled. Rapid urbanisation and outdated waste infrastructure have intensified inefficiencies in collection, sorting, and recycling, resulting in significant plastic leakage into ecosystems and risks to human health. To address these systemic issues, this study examines how smart technologies can modernise plastic waste management systems to align with circular economy goals. Focusing on the integration of the Internet of Things (IoT), artificial intelligence (AI), robotics, blockchain, and mobile applications, it highlights how sensor-equipped bins enable real-time monitoring, AI-driven robotics enhance sorting precision, and blockchain ensures transparent material traceability. Mobile platforms also support citizen participation and accountability in waste behaviours. Drawing from global case studies, the paper identifies measurable outcomes such as increased recycling rates, reduced contamination, and optimised logistics. The study provides a structured assessment of scalable digital interventions, offering practical insights for municipal authorities, urban planners, and policymakers seeking to achieve SDG 11 and 12 targets by 2030.

Keywords: Plastic Waste, Smart Technologies, IoT, AI, Sustainability, Waste management.

INTRODUCTION

The global plastic waste crisis has reached an unprecedented scale. Annual plastic production now exceeds 400 million metric tonnes. However, only about 10% of this waste is effectively recycled through closed-loop material recovery, where plastics are reprocessed into products of similar quality and function (Singh & Walker, 2024). This form of recycling relies heavily on high-quality waste inputs, with pre-consumer manufacturing waste constituting a vital component in achieving efficient material recovery (Rahimi & García, 2017; Hopewell et al., 2009). The rest is disposed of in landfills, incinerated, or leaked into natural ecosystems, contributing to a growing environmental burden. As a result, the world now faces the urgent challenge of managing this immense and ever-expanding volume of plastic waste more sustainably (Geyer et al., 2017). Scientific research underscores the environmental and human health risks associated with the accumulation of plastic debris. Persistent microplastics and toxic chemicals leach into soil and water systems, threatening biodiversity and contaminating food and water sources (Kibria et al., 2023). Without intervention, the problem is projected to intensify as estimates suggest global plastic production could surpass 650 million metric tonnes by 2050 (Fayshal, 2024). This trajectory highlights the urgent need for systemic change in how plastic waste is managed, moving beyond traditional approaches that are becoming increasingly inadequate. Conventional waste management systems in many parts of Africa, Southeast Asia, and Latin America often lack the infrastructure necessary to effectively process modern plastic waste streams (Joshi et al., 2019a).

A critical bottleneck is the insufficiency of collection and recycling capabilities, which has allowed the global plastic pile to grow steadily (Bhardwaj et al., 2024). Mixed and contaminated plastic waste poses a major recycling challenge due to the presence of food residues, improper sorting, and the mixing of incompatible plastics. These factors lower material quality and hinder efficient closed-loop recycling, especially in complex urban waste streams. In practice, when plastic streams are too heterogeneous or dirty, they are not recycled but diverted to landfills or incineration, nullifying recovery efforts (Hird, 2022). The widespread use of advanced materials, such as multilayer films, thermosets, and composites, further complicates recycling, as these materials resist conventional processing techniques (Cabrera et al., 2022). Manual sorting, still common in many facilities, is labour-intensive, time-consuming, and prone to human error. As a result, a vast portion of plastic waste never reenters the production cycle. The prevailing linear model of waste management, which depends heavily on manual collection and single-stream sorting, continues to suffer from high contamination rates and limited throughput capacity. These systemic inefficiencies illustrate why only a small fraction of plastic is recovered and reused.

In response, recent technological advances have opened new avenues for transforming plastic waste management. Smart technologies, particularly those driven by artificial intelligence, the Internet of Things, robotics, and blockchain, are being actively explored to address the limitations of legacy systems. IoT-enabled smart bins, for example, can collect real-time data on waste weight, composition, and fill level. Waste management systems can use this information to optimise collection schedules, reduce operational costs, and minimise fuel usage by avoiding empty pickups. (Singh & Walker, 2024). At material recovery facilities, AI-driven sorting systsems are increasingly deployed to enhance efficiency. Computer vision technologies powered by deep learning can now identify and classify different types of plastics, such as PET, HDPE, and others, directly on conveyor belts in real-time (Bhattacharjee & Bhave, 2025). This capability not only increases the speed and accuracy of sorting but also reduces the reliance on manual labour. Some advanced systems integrate machine learning with IoT sensors and blockchain technology, creating a closed-loop framework that optimises logistics and ensures traceability of recovered materials (Rodrigues et al., 2025). In recent years, smart city initiatives have increasingly incorporated Internet of Things (IoT) technologies to improve urban waste management, as demonstrated by various case studies and supported by extensive literature. Researchers have proposed a range of intelligent waste systems leveraging sensors, machine learning, and real-time data processing to optimise collection routes, detect hazardous waste, and monitor bin levels (Vishnu et al., 2021; Bano et al., 2020). These systems typically involve smart bins equipped with sensors to track waste volume, humidity, and even odour (Gull et al., 2021).

While recent advancements in digital and automated technologies offer significant benefits, many existing waste management solutions remain limited to isolated functions such as monitoring or prediction. The fragmentation of current approaches reveals a gap in integrating smart technologies into cohesive, real-time systems suited to the complexities of urban plastic waste management. While this review does not propose a new framework, it synthesises existing technologies, analyses their practical use in urban settings, and identifies how they contribute to improved efficiency, traceability, and citizen engagement. By leveraging real-time data, smart waste management systems enable operators to better understand waste flows, anticipate generation trends, and continuously refine their operational strategies. This study examines how such integrated digital solutions can address the shortcomings of traditional plastic waste systems. These innovations have the potential to reduce pollution, conserve resources, and support the transition toward a more resilient global waste management paradigm, in alignment with SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water), both of which emphasise reducing plastic waste and its environmental impacts.

KEY SMART TECHNOLOGIES IN WASTE MANAGEMENT

Smart technologies have played an increasingly influential role in the evolution of waste management. These innovations enable cities to handle waste more efficiently, sustainably, and safely. Below are the key technologies reshaping the modern waste management landscape:

a. Smart Bins and Internet of Things (IoT)
b. Artificial Intelligence (AI) for Automated Sorting
c. Robotics in recycling facilities
d. Mobile Apps and Citizen Engagement Platforms in Waste Management
e. Blockchain for Plastic Waste Tracking

Smart Bins and Internet of Things (IoT)

Smart bins, equipped with an array of interconnected sensors, enable live monitoring of waste conditions and fill levels, enhancing the efficiency and reliability of municipal waste collection processes (Vishnu et al., 2021; Shyam et al., 2017). Municipalities are increasingly acting on this data through sensor-informed routing decisions, mobile applications, and integrated tools that support real-time operational adjustments and long-term planning. One of the core components of these systems is the ultrasonic sensor. By measuring the distance from the bin's lid to the waste surface, it provides accurate fill-level data, which is compared to capacity thresholds to trigger collection alerts (Aguila et al., 2019). Common models, such as the HC-SR04, operate within a range of 2–400 cm with an accuracy of approximately ±3 mm. However, their performance may be affected by extreme humidity, temperature fluctuations, and irregular bin surfaces, which can cause erratic reflections and false readings.

Load cells installed at the base of bins complement this measurement by providing precise weight data, especially critical when bins reach weight thresholds that could impact safe collection operations. These sensors are often strain gauge-based and can provide accuracy within 0.1% of full scale, although they are sensitive to temperature shifts and require regular calibration. In environments where safety and sanitation are paramount, such as industrial zones or hospitals, smart bins incorporate humidity and temperature sensors to detect potentially hazardous conditions. Sensors like the DHT22 or SHT31 typically operate between −40°C to +125°C and 0–100% relative humidity. However, condensation and dust can reduce the lifespan and accuracy of the sensor. A sudden rise in humidity or temperature can signal decomposing organic material or chemical reactions, enabling authorities to intervene promptly (Ali et al., 2020; Hoque et al., 2019). Gas sensors, such as the MQ-135, enhance the capability of smart bins to detect harmful gases, such as methane, ammonia, and CO_2, thereby helping to prevent dangerous emissions and ensure public safety. These real-time readings also support municipalities in complying with emissions control regulations, such as 40 CFR § 60.34f(d), which mandates surface monitoring of landfill methane at concentrations below 500 ppm, and California's Landfill Methane Regulation, which requires continuous monitoring and capture of fugitive emissions.

The Radio Frequency Identification (RFID) technology embedded in smart bins provides additional layers of functionality. These tags, which require no line of sight and operate across multiple frequency bands (LF, HF, UHF), allow for the identification and tracking of individual bins and collection vehicles (Bhardwaj & Gupta, 2024; Hannan et al., 2011). This is essential for verifying service completion, managing routes, and scheduling maintenance operations (Pardini et al., 2018). When paired with GPS systems, RFID-enabled bins can be located and monitored with high precision, thereby improving logistical efficiency (Joshi et al., 2019b; Fadel, 2017). The integration of smart technologies into urban infrastructure has led to more efficient waste-handling systems. As illustrated in Figure 1, the Internet of Things (IoT)-based smart waste management process supports continuous data collection and adaptive route planning for efficient waste collection (Alqahtani et al., 2020).

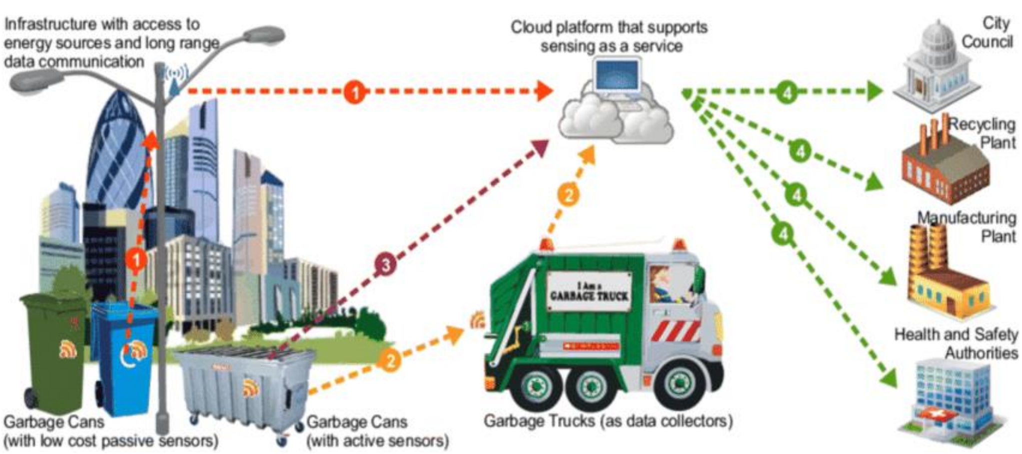

Figure 1: Internet of Things-based smart waste management process (Alqahtani et al., 2020)

Image sensors are also increasingly used in advanced bin models. Installed within protective IP-rated enclosures, these high-resolution cameras capture internal bin visuals to assess not only fill status but also waste type and bin condition (Arthur et al., 2024). This is particularly valuable in scenarios involving bulky, heterogeneous, or potentially hazardous waste. With pan, tilt, and zoom functionalities, these sensors offer granular insight into bin usage patterns and maintenance needs.

The performance of smart bins is driven by an integrated Internet of Things (IoT) infrastructure. Sensor data is transmitted through various communication protocols, including MQTT (Message Queuing Telemetry Transport), LoRaWAN (Long Range Wide Area Network), GSM (Global System for Mobile Communications), and Bluetooth, each suited to different deployment conditions. However, urban settings pose risks such as network congestion, data interception, spoofing, and denial of service, requiring strong encryption and authentication measures (Beretas, 2024). MQTT is lightweight and reliable over TCP/IP (Transmission Control Protocol/Internet Protocol) networks, ideal for low-power environments (Fawwaz et al., 2022). LoRaWAN is effective for long-range, low-energy communication, making it suitable for dispersed deployments (Baldo et al., 2021). GSM remains popular for its broad coverage and ease of integration in urban areas (Wijaya et al., 2017), while Bluetooth, despite its limited range, is useful for local diagnostics and maintenance (Pardini et al., 2018; Ogunwolu et al., 2022).

An onboard controller in each bin manages this data and connects to cloud platforms, such as iSmartWMS. It enables real-time, secure communication and allows for remote diagnostics and command execution. Ensuring secure data transfer is crucial in public systems to maintain integrity and prevent misuse (Wen et al., 2018). IoT is transforming municipal waste management by replacing static collection schedules with dynamic, data-driven systems. Real-time monitoring and predictive analytics help optimise routes, reduce fuel consumption, and minimise emissions. Research shows that these smart systems can significantly reduce the energy use and carbon footprint of waste logistics (Huang, 2020; Kang et al., 2019). These systems are scalable and can integrate with broader smart city infrastructure such as traffic, lighting, and energy systems (Humayun et al., 2022). Innovations like blockchain are also being explored to safeguard data privacy in IoT networks (He et al., 2018), while cloud-based frameworks are being refined to support system-wide deployments (Dizdarević et al., 2019). Emerging optimisation tools, such as the Arithmetic Optimisation Algorithm (AOA) and its multi-objective version (MOAOA), are being applied to enhance energy efficiency in IoT systems, with potential applications in waste management as well (Bahmanyar et al., 2022). Looking forward, technologies like 5G and advanced cloud computing will further enhance smart waste management by enabling faster, more flexible, and energy-efficient operations (Humayun et al., 2022).

Smart bins powered by IoT are a key part of sustainable urban living. Cities like Barcelona, Seoul, and San Francisco utilise sensor-equipped bins to cut costs, reduce emissions, and improve waste collection. These deployments have optimised routes, increased recycling rates, and eliminated overflows (Tomorrow.bio, 2023). With intelligent monitoring and optimised logistics, they represent the intersection of engineering, environmental responsibility, and digital innovation. For example, systems illustrated in Figure 2 utilise real-time data from sensors to track waste levels, improve collection efficiency, and reduce emissions (Haque et al., 2020).

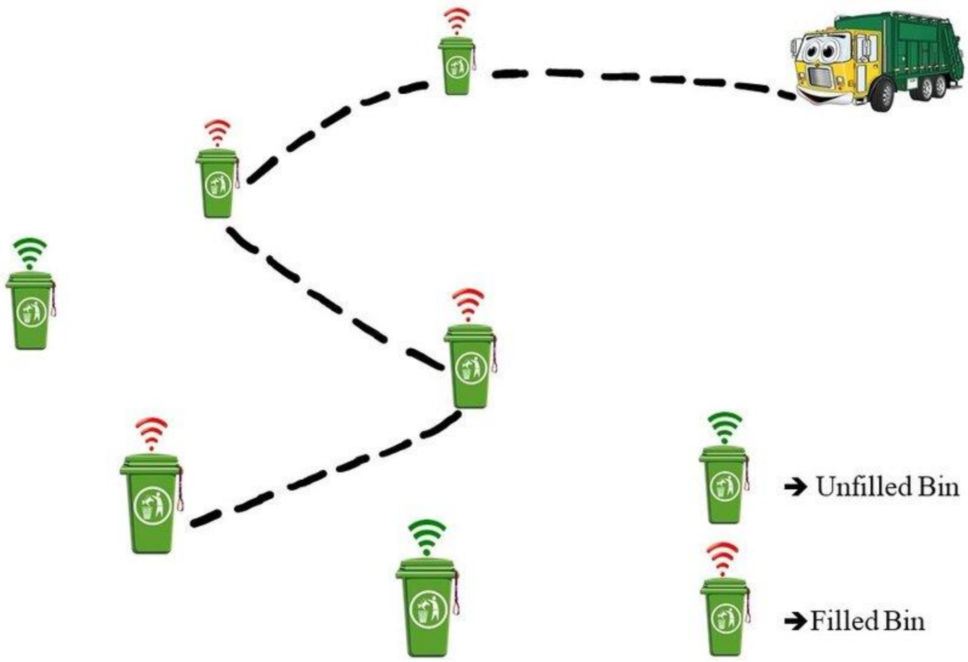

Figure 2: A typical IoT-based waste collection system (Haque et al., 2020)

Cybersecurity and Data Privacy in Smart Waste IoT Systems

As sensor-equipped bins and IoT networks proliferate in urban waste management, cybersecurity and data privacy have emerged as critical considerations. These smart bins transmit sensitive operational data—such as location, waste volume, and routing information that can be exploited through attacks like data spoofing (e.g., falsifying fill-level or location data), interception via eavesdropping on wireless signals, or denial-of-service attacks that disrupt communications (Beretas, 2024; Brighente et al., 2024).

Such vulnerabilities pose serious risks, including operational disruption, billing fraud, and the potential exposure of municipal infrastructure maps. Weak authentication on MQTT gateways, for example, can enable attackers to inject false data, leading to unnecessary dispatches or concealing actual overflows. A study on MQTT-based IIoT systems shows how false data injection attacks can manipulate system perception and trigger actions that serve an attacker's goals (Alsabbagh et al., 2024). Similarly, LoRaWAN networks face threats such as packet forging and jamming, which can compromise data integrity and disrupt transmission (Coman et al., 2019).

Privacy concerns also intensify when the user or household-level waste generation data is collected for billing or planning purposes, making robust data handling policies essential to protect personally identifiable information. To mitigate these risks, municipalities can implement end-to-end encryption, strong authentication protocols, regular software updates, and intrusion detection systems to monitor network traffic for anomalies. Moreover, integrating blockchain or distributed ledger systems is being explored as a way to ensure tamper-proof logging of sensor data and enforce secure access control (Dizdarević et al., 2019).

By proactively addressing these cybersecurity and privacy challenges, cities can help ensure that smart waste systems remain reliable, resilient, and publicly trusted components of broader smart city infrastructure.

Artificial Intelligence (AI) for Automated Sorting

The integration of Artificial Intelligence (AI) into urban smart waste management systems marks a pivotal advancement in transforming traditional waste sorting processes. AI-driven systems enhance the efficiency and precision of automated sorting operations by integrating object recognition sensors, real-time data analytics, and explainable AI (XAI). These technologies are particularly impactful in critical sectors such as medical and hazardous waste management (Sutikno et al., 2024). This shift toward AI-enabled automation not only improves waste processing efficacy but also significantly reduces environmental and health-related risks, thereby contributing to the development of more sustainable and intelligent urban environments. Automated sorting technologies leverage sophisticated AI algorithms to classify waste based on material composition. These systems employ sensors such as near-infrared (NIR) spectroscopy, X-ray fluorescence (XRF), and hyperspectral imaging to analyse the physical and chemical attributes of waste (Bobulski & Kubanek, 2019; Yan et al., 2021). Machine learning techniques, including deep learning and neural networks, further enhance the accuracy and scalability of these systems by enabling them to learn from extensive datasets and adapt to a diverse range of materials (Frankowski et al., 2020). This capability facilitates the identification and categorisation of plastics, metals, glass, paper, and organic matter, ensuring higher purity in recyclable outputs (Yan et al., 2021). Figure 3 illustrates an AMP Robotics system using AI-powered computer vision to identify and separate different packaging types on a conveyor. This setup showcases how cloud-based analytics and robotic pickers work together to scale high-speed, precise sorting processes. Such systems reduce contamination in recycling streams but require substantial capital investment and technical expertise to maintain.

Despite these technological advances, several challenges persist. The heterogeneity of waste streams, the presence of contaminants, and the need for reliable deployment across varying operational environments continue to impede performance (Gundupalli et al., 2017). Addressing these challenges necessitates ongoing research to refine AI models and strategic investment in infrastructure and workforce training.

Deep Convolutional Neural Networks (CNNs) have been widely adopted to automate the sorting of recyclable and non-recyclable items. For example, a hybrid model combining CNNs with Multilayer Perceptrons (MLPs) reported an accuracy of 98.2% on benchmark image datasets, though such results are typically achieved under controlled, lab-simulated conditions and may differ when applied to real-world mixed plastic waste streams (Hasan et al., 2024; Liang & Gu, 2021) Other machine learning models, including C-LibSVM, Nu-SVM, and Random Forests (RF), have also demonstrated high accuracy in waste classification tasks, often exceeding 90% in large-scale applications (Kumar et al., 2024. Beyond classification, AI's utility extends to behavioural and demographic pattern analysis. Techniques such as cluster analysis and decision trees have been used to correlate waste output with housing types, seasons, and sociodemographic factors. In one instance, a decision tree classifier yielded results with a minimal margin of error of 3.6%, offering the potential for predictive waste management planning (Meza et al., 2019).

The integration of robotics in AI-powered sorting further enhances performance. AI-guided robotic arms can function as standalone alternatives or supplements to conventional optical sorters, purging inaccurately sorted materials and improving overall efficiency over time through continuous learning (Wilts et al., 2021). These systems typically combine Deep Learning, Visual Imaging Systems (VIS), and NIR technologies, enabling precise plastic sorting by type and colour. Some Material Recovery Facilities (MRFs) have already implemented AI-based solutions, significantly improving throughput and reducing operational costs. Innovations such as smart bins, developed using Raspberry Pi and CNN algorithms, exemplify the potential of AI in localised, real-time sorting (Gunaseelan et al., 2023). These intelligent units can recognise and segregate waste at the point of disposal and operate at significantly higher speeds, up to 170 sorting cycles per minute, compared to manual labour, which averages 40–50 cycles per minute.

The integration of AI and IoT is transforming the operations of Material Recovery Facilities (MRFs). Real-time sensor data and machine learning enable dynamic adjustment of sorting processes based on material flow and demand. AI-powered computer vision systems scan conveyor belts to identify materials by shape, colour, and texture, improving the separation of complex packaging and boosting the purity of recycling streams while lowering energy use (Lakhouit, 2025). This synergy between AI, robotics, and IoT enhances material recovery and supports the goals of a circular economy. As a result, manual sorting and outdated machinery are being replaced by intelligent robotic systems guided by deep learning models. Convolutional Neural Networks (CNNs), for example, can classify and sort waste in real-time, reducing both labour needs and errors (Figure 4).

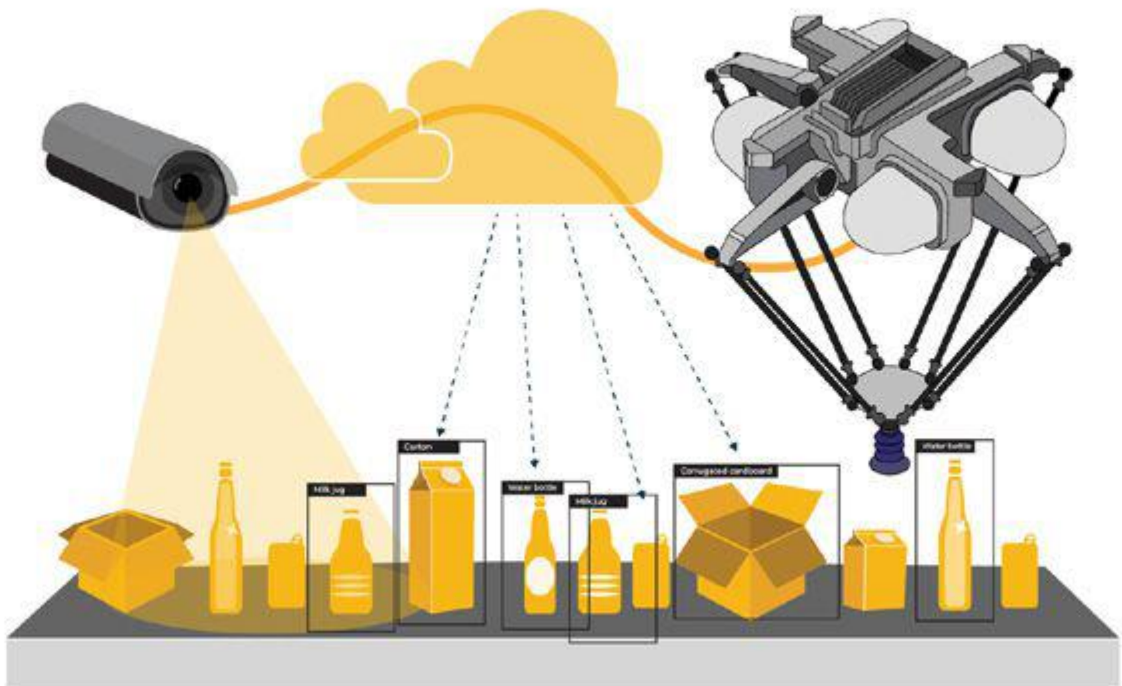

Figure 3: AMP's Vortex solution will be used to help identify and recover film and flexible packaging in MRFs. (PTC, n.d.)

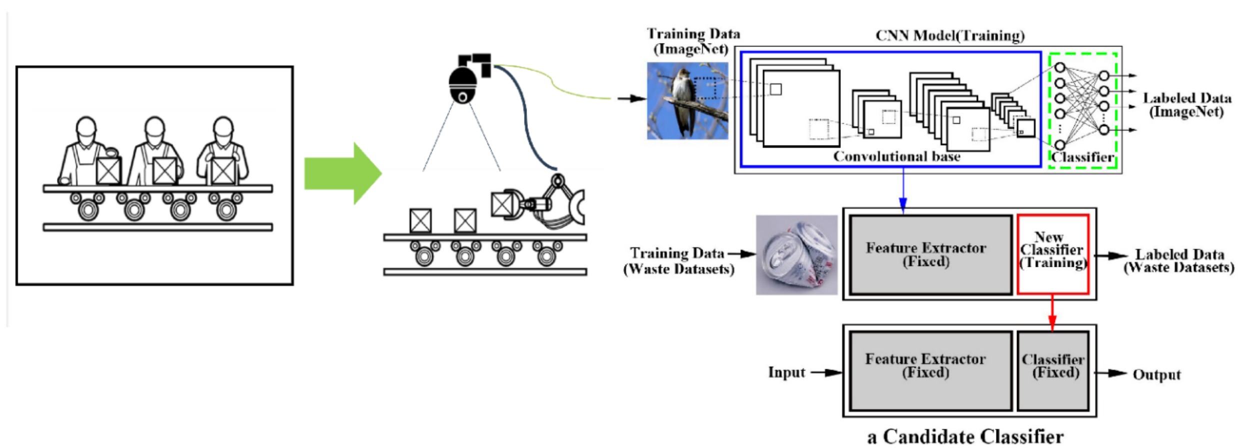

Figure 4: Replacing traditional manual or outdated mechanical waste sorting methods with AI-powered robotic systems utilising a Convolutional Neural Network (CNN) model (Huang et al., 2020)

Robotics in Recycling Facilities

The integration of robotics into recycling facilities marks a transformative shift in the efficiency, precision, and safety of waste management systems. Traditionally reliant on labour-intensive methods, the recycling industry has faced increasing pressure to enhance throughput and material purity while minimising occupational hazards. In response, modern facilities are turning to robotic automation powered by artificial intelligence (AI), computer vision, and machine learning, technologies that have matured significantly in recent years and now offer promising applications for complex sorting and separation tasks (Chen et al., 2019; Bogue, 2019). Robots in recycling facilities are primarily deployed to sort and segregate materials with a level of consistency and speed that surpasses human capabilities. Notably, systems such as ZenRobotics' Fast Picker and Heavy Picker demonstrate the use of suction and two-finger grippers, respectively, to manage a diverse array of materials ranging from lightweight plastics to industrial construction debris (ZenRobotics, 2023). These robotic arms operate within defined working envelopes, up to 80 picks per minute for lightweight objects and a handling capacity of up to 30 kg for heavier materials, exemplifying both speed and strength (Bogue, 2019). Figure 5 shows AMP Robotics equipment deployed at Single Stream Recyclers in Florida, demonstrating a real-world application in a large-scale materials recovery facility. This case underlines the scalability of AI robotics in commercial settings, while raising questions about adaptability in lower-resource contexts typical of many municipalities in the Global South. Other systems, such as AMP Robotics' Cortex Dual-Robot System and the Max-AI® AQC, leverage high-speed actuation and deep learning algorithms to enable real-time decision-making. These systems can perform up to 160 picks per minute and adapt dynamically to material variability (AMP Robotics, 2019; Max-AI®, 2023). Equipped with advanced sensors, including RGB cameras, near-infrared, and 3D imaging, such robots classify objects by composition, colour, and shape, achieving material purity rates exceeding 99% (Raptopoulos et al., 2020; Bollegraaf, 2023).

A significant advantage of robotic sorting lies in its scalability and adaptability. While vacuum grippers are optimised for flat and lightweight items, two-finger grippers offer more flexibility in handling irregular or heavier objects, though typically at a slower pace (Daniels et al., 2023). These design choices underscore a central challenge in robotic recycling: the need for universally applicable end-effectors that can grasp a wide range of object shapes, weights, and surface conditions.

Beyond mechanical hardware, the true intelligence of modern robotic systems lies in their computational backbone. Deep learning and computer vision enable not only recognition but contextual understanding of waste streams. This capability is particularly critical for distinguishing between visually similar materials, such as clear plastic and glass, or identifying contamination, tasks that have traditionally confounded automated systems (Kazmi et al., 2023). As the sector advances, the incorporation of cyber-physical systems, IoT frameworks, and blockchain infrastructures is further enhancing traceability and optimisation in material recovery processes (Bernat, 2023).

Robotics also offers flexible deployment configurations. While fixed robots are commonly found in materials recovery facilities (MRFs), mobile robotic platforms are increasingly used in decentralised or hazardous environments. These units, often equipped with conveyor belts, robotic arms, and multi-spectral imaging systems, extend the operational reach of automation into previously inaccessible domains (Bobulski & Kubanek, 2021; Leveziel et al., 2022). One emerging paradigm is human-robot collaboration, where robotic systems handle repetitive, high-risk tasks, and human operators oversee complex decision-making or delicate manipulations (Ramos et al., 2024). This model has seen promising applications, such as battery dismantling stations, where robots unscrew and remove components while humans manage safety-critical operations (Bogue, 2019). Such synergy not only improves overall system resilience but also fosters a safer and more ergonomic working environment. Despite these advancements, limitations persist. Robotic perception systems still struggle with heavily soiled or composite materials, and gripping mechanisms must evolve to accommodate deformable or entangled items. Addressing these challenges will require continuous innovation in sensor technology, actuator design, and adaptive control algorithms (Rianmora et al., 2023; Sundaralingam & Ramanathan, 2023). Robotics is reshaping the operational landscape of recycling facilities, offering unprecedented gains in efficiency, precision, and scalability. By combining mechanical dexterity with AI-driven intelligence, these systems are not only improving the economics of recycling but are also contributing to broader sustainability goals.

Figure: 5 AMP Robotics, whose systems are deployed at Single Stream Recyclers in Florida (Robotics 24/7, 2023)

Mobile Apps and Citizen Engagement Platforms in Waste Management

The rapid proliferation of smartphone technology and mobile applications has significantly transformed urban waste management systems by bridging the gap between citizens and municipal services. Mobile apps now serve not only as informational tools but also as interactive platforms that enable real-time communication, education, behavioural incentivisation, and operational optimisation across waste management systems.

One of the most profound impacts of these applications lies in their ability to engage the public in recycling and waste reduction efforts directly. Mobile apps have been developed to streamline everyday waste interactions, such as scheduling curbside pickups, reporting overflowing bins, and accessing real-time recycling guidelines. In many urban centres, these apps function as intermediaries that connect households with waste collection services, facilitating a more transparent and responsive ecosystem (Lakhouit, 2025). A notable example is the Ghanaian mobile system, which allows users to schedule pickups, monitor collector schedules, and receive rewards for recycling. This model transforms passive residents into active stakeholders in urban sanitation (Rachmawati et al., 2021).

Gamification features such as digital points, leaderboards, and reward-based systems further increase user participation. These incentives foster sustained engagement and behavioural change by making recycling activities not only practical but also rewarding. In cities like those in Iran and the Philippines, innovative models have emerged where mobile applications enable users to register, categorise, and even photograph their waste. After collection, agents weigh the waste and upload data to the user's profile. Based on this record, users receive monetary rewards in digital wallets, which can be withdrawn or spent within the app ecosystem. This approach reflects a broader global trend of aligning financial incentives with environmental behaviour, thereby fostering systemic participation (Rahman & Dura, 2022)

Beyond incentivisation, mobile apps enhance operational efficiency through integration with Internet of Things (IoT) sensors. Sensors embedded in waste bins monitor fill levels and transmit real-time data to centralised platforms, enabling authorities to optimise collection routes and schedules. Such dynamic routing minimises fuel consumption, reduces traffic congestion, and lowers greenhouse gas emissions (Djavadian et al., 2020; Puscasiu et al., 2019). When integrated with fleet management systems, mobile apps help ensure the timely dispatch of collection vehicles, supporting both environmental sustainability and cost efficiency. These apps allow users to report issues like missed pickups or illegal dumping, enabling swift municipal responses and strengthening civic accountability. This two-way communication fosters community ownership and reinforces the social norms necessary for sustainable urban living (Ivanyi & Biro-Szigeti, 2019; Simonofski et al., 2023). Many apps also include educational features that guide users on proper waste segregation and disposal, reducing recycling contamination and improving material recovery efficiency.

User experience is further enhanced through features like electronic billing, multilingual support, and push notifications. Residents can pay for services, view billing history, and receive reminders about pickups or recycling events, increasing participation and reducing missed collections. Built-in data analytics add strategic value, as aggregated user data reveals waste generation trends, peak disposal times, and operational inefficiencies. These insights help city planners optimise routes, allocate resources efficiently, and refine policies to meet environmental goals (Xiao et al., 2024). Mobile applications and citizen engagement platforms are not merely technological add-ons but foundational components of modern smart-city infrastructure. Their multifaceted role, spanning service optimisation, user education, behavioural motivation, and policy feedback, positions them as indispensable tools in achieving sustainable urban waste management.

As illustrated in Figure 6, mobile apps support plastic waste management by enabling service scheduling, locating recycling points, and delivering sustainability education. Figure 7 (adapted from Nelms et al., 2022) outlines six key challenges in collecting robust data on plastic pollution. Overall, this tech-enabled approach empowers individuals and communities to participate in circular plastic economies actively.

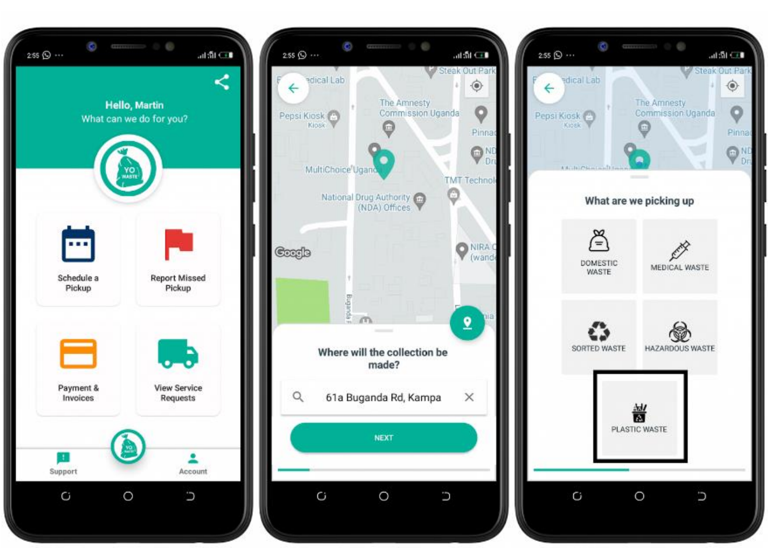

Figure 6: Mobile app interface for plastic waste management (Adapted from YoWaste, n. d.)

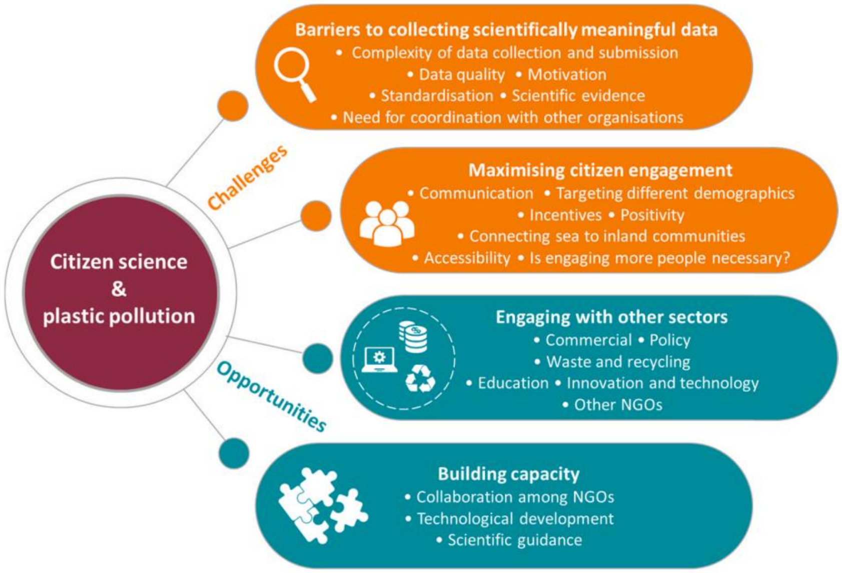

Figure 7: Six challenges for collecting scientifically meaningful data on plastic pollution. (Nelms et al., 2022)

Mobile Apps and Citizen Engagement Platforms in Waste Management

Blockchain technology, initially introduced in 2008 for cryptocurrencies like Bitcoin (Nakamoto, 2008), has since evolved into a powerful tool for ensuring transparency, data integrity, and security (Gietzmann & Grossetti, 2021). While rooted originally in finance, its applications now span various sectors, including food supply chains, where it enhances end-to-end traceability (BASF, 2022a). Recognising its broad utility, the European Commission has identified blockchain as a cornerstone of Europe's digital transformation (European Commission, 2022).

Blockchain technologies offer flexible data management models ranging from open public systems to restricted group-based and private networks (Jiang et al., 2019; Pilkington, 2016; Gramoli, 2020), allowing a balance between transparency and secure data handling (Feng et al., 2019). In plastic waste management, blockchain is increasingly explored for its ability to track and verify recycling processes. Research since 2019 reflects this growing interest (Phung, 2019). Projects like PlasticChain and PlasticCoin use blockchain models to facilitate circular economies through traceable waste flows and reusable materials (Bułkowska et al., 2024). Similarly, PlasticBank applies blockchain to incentivise plastic collection in coastal communities (Bhubalan et al., 2022).

These applications often incorporate smart contracts to streamline transactions and enhance accountability. For example, Mondal and Kulkarni (2022) proposed a blockchain-based supply chain system powered by smart contracts, while Chidepatil et al. (2020) integrated sensor data to improve confidence in recycled plastics. Initiatives like Oceanworks and those reported by Gong et al. (2022) monetise recovered marine plastic, blending economic and environmental goals (BASF, 2022b). Blockchain's ability to reduce information asymmetry is also emphasised in marine debris recycling (Tsao et al., 2022).

Several platforms are now operationalising blockchain's promise. SAP's GreenToken® supports private life cycle tracking of plastics (SAP, 2022), while Circularise and CIRbase focus on transparency and overcoming data silos (Circularise, n.d.; Bolier et al., 2019). ReciChain by BASF uses blockchain and physical tracers to assign material ownership and incentivise recycling (BASF, 2020). Municipal projects have adopted blockchain for practical use, such as Arep's sensor-equipped bins that log waste data (Taylor et al., 2020) and Parry & Evans' shipment tracking (Recycling Today, 2017). In India, CITAG uses blockchain to document citizen complaints, reinforcing local governance.

These examples show the flexibility of blockchain for different waste management contexts. However, when considering implementation in many African cities, private blockchains are generally more feasible than public ones because they offer controlled participation, faster transactions, and better privacy for municipal and industry use. Examples include Hyperledger Fabric for modular, permissioned networks (Androulaki et al., 2018), Corda for secure asset tracking and compliance (R3, 2023), and Quorum for private Ethereum-compatible deployments (Baliga et al., 2018). However, challenges such as technical complexity, security risks, limited user-friendly interfaces, and digital literacy gaps must be addressed through intuitive app design, targeted training, streamlined KYC processes, and clear regulatory guidance to support adoption (World Economic Forum, 2021).

Beyond urban waste systems, blockchain has the potential to enhance environmental enforcement. When plastics are tagged and recorded on blockchain, illegal dumping can be traced back to the source (Steenmans & Taylor, 2018). Similar ideas have emerged in the construction sector through material passports supporting circular building practices (Honic et al., 2019; Kovacic et al., 2018). Despite its advantages, challenges remain, including difficulties with data integrity during material degradation and regulatory uncertainties over data custody (Taylor et al., 2020).

Integrating blockchain with the Internet of Things (IoT) further amplifies its capabilities. IoT sensors collect real-time data from devices and machinery, and when this data is stored on a blockchain, it becomes immutable and traceable (Rathore et al., 2018; Almalki et al., 2021). This combination enhances supply chain transparency, asset tracking, and product certification, with platforms like IoTeX and VeChain leading these integrations (Pieroni et al., 2020; Song et al., 2022).

In smart cities, where waste includes diverse streams such as electronic, industrial, and medical waste, blockchain supports accurate, tamper-proof tracking of waste types, volumes, and processing stages (Angelidou, 2014; Sarangi et al., 2023). This improves data credibility and enables efficient service delivery (Bao et al., 2020). Unlike centralised systems susceptible to manipulation, blockchain offers resilient data governance throughout the waste lifecycle.

Digital tokens assigned to waste assets allow granular tracking and reduce public-sector costs while aligning operations with regulatory requirements (Esposito et al., 2021; Gopalakrishnan et al., 2021). When integrated with smart contracts and monitoring tools, blockchain promotes transparency, minimises environmental leakage, and automates key processes like payments and compliance (Centobelli et al., 2022; Bashir, 2020). The verifiable transaction history fosters trust across stakeholders, reinforcing blockchain's role in advancing a circular plastic economy. Figure 8 illustrates a conceptual framework of blockchain's contributions to traceability, accountability, and efficiency in plastic value chains.

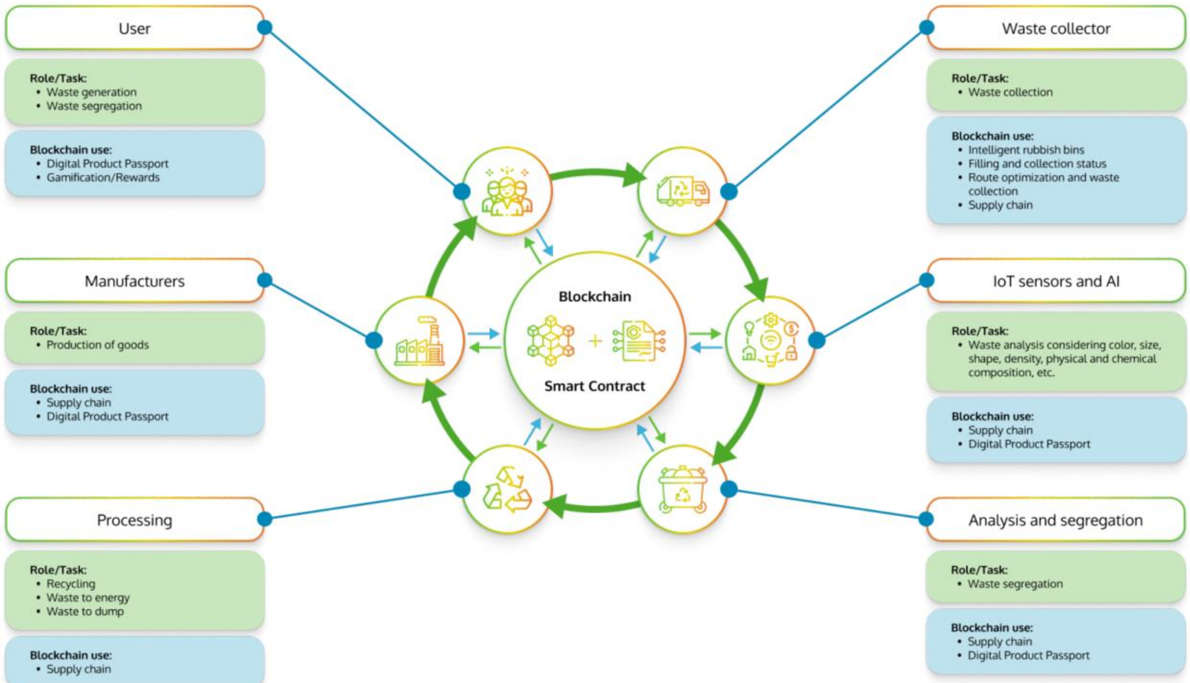

Figure 8: Implementation of blockchain and smart contracts in plastic waste management (Bułkowska et al., 2024)

Incentive mechanisms such as tokenisation and digital rewards are additional strategies supported by blockchain to motivate responsible waste behaviour (Tian et al., 2020; Pramanik et al., 2020). These incentives encourage participation in sustainable practices and contribute to the realisation of circular economy goals (França et al., 2020). When integrated with AI and IoT, blockchain's capacity to reshape waste management becomes even more powerful. Smart systems can track waste metrics, optimise routes, and analyse recycling efficiency in real-time, while blockchain secures this data and supports informed decision-making (Atlam et al., 2020; Damadi & Namjoo, 2021). This confluence of technologies positions blockchain as a cornerstone for a more intelligent, transparent, and sustainable approach to managing plastic waste.

APPLICATIONS OF SMART TECHNOLOGY FOR PLASTIC WASTE REDUCTION

The growing plastic waste crisis demands innovative, technology-driven solutions. Building on the technical foundations discussed in Section 2, this section explores how smart technologies, including sensor-enabled bins (IoT), artificial intelligence (AI), robotics, mobile applications, and blockchain, are being applied in real-world systems to improve waste collection, sorting, and engagement. These tools support optimised routing, automated classification, transparent material tracking, and citizen participation. The following subsections highlight their practical applications and impacts across various urban contexts, demonstrating their contribution to a cleaner, more sustainable future

Optimised Collection and Route Planning

Effective plastic waste management relies heavily on efficient waste collection systems, and route optimisation has become a potent technique for increasing operational effectiveness while lowering environmental impact. Route optimisation is a crucial tactic for contemporary waste collection organisations, which are under growing pressure to reduce their carbon impact while preserving cost-effectiveness (NextBillion.ai, 2024). Artificial intelligence (AI), real-time data analytics, and sustainability objectives are being integrated into sophisticated route planning software to transform waste collection procedures. To determine the most effective routes for collecting vehicles, these systems consider various factors, including traffic patterns, road conditions, garbage loads, and vehicle capacities (NextBillion.ai, 2024). Advanced route optimisation technologies created by businesses like Associations Management

Companies (AMCS, 2025) Group and NextBillion.ai can increase collection efficiency by 10–20% (Recycling Today, 2025). The following are important technological elements that allow for optimal collection:

a) Telematics and GPS -Tracking: Fleet managers may significantly reduce downtime and fuel waste by using real-time vehicle tracking to monitor routes, reroute cars to avoid traffic, and ensure adherence to timetables (NextBillion.ai, 2024).
b) IoT-enabled Smart Bins: As explained in Section 2.1, smart bins equipped with ultrasonic, weight, and gas sensors provide real-time fill-level data. This enables demand-based collection rather than fixed schedules, helping maximise fleet efficiency and reduce unnecessary trips (Fang et al., 2023).
c) Dynamic Route Adjustment: Systems can automatically modify routes in response to changing conditions by integrating with real-time traffic and weather data, which avoids delays and lowers fuel usage (NextBillion.ai, 2024).
d) Using "super-fast algorithms to schedule up to 300,000 orders on different routes at once" and allowing planners to optimise routes with a single button click, the Associations Management Companies (AMCS, 2025) Route Planner exemplifies the potential of these technologies (Recycling Today, 2025). In addition to increasing efficiency, this degree of automation enables ongoing optimisation as circumstances evolve, resulting in a trash collection system that is responsive to external factors.

Improved Plastic Sorting Accuracy

The challenge of accurately separating different types of plastic has long hindered recycling efficiency, contributing to contamination and lower-quality recycled materials. As discussed in Section 2.2, AI-powered sorting systems have addressed this limitation by integrating machine vision and deep learning to automate and refine material classification. In practice, these technologies are now widely deployed in Material Recovery Facilities (MRFs), where they dramatically enhance throughput and accuracy. For instance, AMP Robotics' systems can recognise and sort plastics—such as PET, HDPE, and LDPE — by colour and resin type at speeds exceeding 80 items per minute, compared to 35 items per minute by human workers (World Economic Forum, 2025). Such systems also reduce contamination by up to 85%, continually improving their performance through adaptive learning models. This operational efficiency not only increases the volume of recoverable plastic but also raises the quality and market value of recycled output. Their deployment in industrial settings supports scalable, high-precision plastic recovery, which is central to achieving circular economy goals. Key advancements in sorting technology include:

a) Hyperspectral Imaging: Modern sensors can identify even the smallest impurities in plastic streams, resulting in recycled output that is 95% pure (World Economic Forum, 2025).
b) Robotic Sorting Arms: Robots powered by AI put in endless hours to pick and sort plastic objects with a level of accuracy that is significantly higher than that of humans (World Economic Forum, 2025).
c) Point-of-Disposal Sorting: AI-powered interactive bins like MyMatR guide users to correctly sort waste at the source, reducing contamination before it reaches recycling facilities (see Figure 9).

Tomra, a pioneer in sensor-based sorting solutions, has installed artificial intelligence (AI) systems at recycling facilities around Europe that employ near-infrared sensors to accurately identify various plastic polymers (World Economic Forum, 2025). For the production of high-quality recycled plastics that may rival virgin materials in manufacturing applications, this degree of sorting accuracy is essential. These technologies have an impact that goes beyond operational effectiveness. They enhance the economic viability of recycling programs by improving the quality and consistency of recycled plastics, thereby increasing the value of plastic waste as a resource in the circular economy. Moreover, their deployment can stimulate investment and policy support, particularly by creating new opportunities for collaboration between public authorities and private sector actors (World Economic Forum, 2025).

Enhanced Data for Decision-Making

Data-driven strategies are transforming the management of plastic waste by providing businesses, waste management operators, and policymakers with valuable insights. A useful knowledge foundation for strategic decision-making is created by the growth of disclosure platforms, such as CDP's global system, which enables businesses to report their plastic-related activities, impacts, risks, and opportunities (Routeware, 2025a).

In order to create a critical baseline for tracking advancements in corporate plastic pollution mitigation, CDP gathered plastic disclosure data from about 3,000 businesses in 2023, representing $25 trillion in market capitalisation (Routeware, 2025a). While showcasing industry best practices, this kind of thorough data collection aids in identifying awareness and action gaps. Data analytics has several important uses in reducing plastic waste, including;

a) Predictive Analytics: Proactive resource allocation is made possible by AI algorithms that use past data to forecast recycling trends, seasonal fluctuations, and trash generation patterns (NextBillion.ai, 2024).
b) Performance Tracking: Continuous improvement is made possible by sophisticated reporting tools that track important variables, including fuel usage, collection effectiveness, and recycling rates (NextBillion.ai, 2024).
c) Supply Chain Transparency: Accountability and circularity are made easier by blockchain-enabled tracking systems that offer insight into material flows throughout the plastic value chain (NextBillion.ai, 2024).

Although these solutions continue to be chronically underfunded, receiving only 2.3% of the $190 billion invested in circular plastic initiatives between 2018 and 2023, the World Economic Forum highlights that digital tools, such as track-and-trace systems, have the potential to transform material flows and optimise circularity (MyMatR, 2025). Through data-optimised collection techniques, Coca-Cola increased their plastic collection rates by 20% in critical regions, demonstrating the promise of these approaches through its relationship with an AI firm (World Economic Forum, 2025). Figure 9 illustrates MyMatR™ interactive bins that use AI to identify and sort trash or recyclables on deposit, thereby improving waste stream separation and enabling better data collection to support circularity. Platforms like Routeware give governments and waste management companies access to extensive data analytics tools that allow them to get insights into their operations, spot inefficiencies, and monitor progress over time (Routeware, 2025). In addition to supporting sustainability reporting, these systems analyse carbon emissions and recommend ways to reduce them, bringing waste management practices into line with more general environmental objectives.

Figure 9: AI-powered interactive trash or recycling bins. (MyMATR, 2023)

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Public Awareness and Behaviour Change through Technology

One of the biggest obstacles and opportunities to reducing plastic waste is altering consumer behaviour. At both the individual and community levels, technology plays a crucial role in public education and promoting sustainable habits (Liu et al., 2023).

The information gap that frequently results in recycling contamination and ineffective trash disposal is being filled by digital tools. Routeware's education resources best demonstrate this strategy and Notify & Inform platform, which helps local governments educate citizens about proper recycling practices while promptly informing them of collection dates and policies (Routeware, 2025b). It has been demonstrated that these measures greatly improve recycling efficiency and lower contamination. Among the creative methods for engaging the audience are:

a) AI-Powered Educational Apps: Applications such as Recycle Coach employ artificial intelligence (AI) to respond to user inquiries regarding local recycling regulations, improving users' recycling practices by 10% (World Economic Forum, 2025).
b) Interactive Waste Bins: As discussed in Section 2.1, smart bins enhanced with IoT and AI go beyond convenience to actively reinforce recycling behaviour. MyMatR units, for instance, deliver real-time visual feedback to users, correcting sorting mistakes on the spot. Deployed in cities, universities, and workplaces, these bins consistently achieve sorting accuracy rates near 90%, significantly reducing contamination.
c) Gamification: In order to increase the engagement and social visibility of sustainable practices, digital platforms integrate game components such as challenges and rewards (MyMatR, 2025).

The interactive trash cans from MyMatR serve as an example of how technology can establish real-time, palpable links between human behaviour and environmental results. In addition to guiding appropriate sorting, their systems gather information that enables communities to recognise and resolve particular issues in their recycling streams (MyMatR, 2025). A feedback loop that continuously enhances systems and behaviours is produced by the dual purposes of education and data collection. These technological advancements, as previously described in Section 2.1, play a crucial role in addressing contamination caused by incorrect sorting—one of the most significant barriers to the efficient recycling of plastics. By making recycling rules more accessible, intuitive, and even rewarding, these tools are shifting public engagement from a challenge to a key enabler of plastic waste reduction (deSousa, 2023; MyMatR, 2025).

REAL-WORLD IMPLEMENTATIONS AND CASE STUDIES

As the world continues its search for effective waste management, smart technologies have been incorporated to ensure that waste, including plastic waste, is managed efficiently. Across the world, numerous real-world implementations of smart technology to transform the plastic waste management system.

Table 1: Comparative Summary of Smart Technology Implementations in Plastic Waste Management

Case Study / Project	Geography	Key Features	Outcomes	Scalability / Challenges	References
Plastic Free Rivers in Asia	Mekong & Ganges Rivers (Asia)	GIS-based geospatial modelling, hydrological mapping, material flow analysis	Identified plastic leakage hotspots; informed policy and interventions	Expanded to Southeast Asia; limited by data quality and local engagement	Tran-Thanh et al. (2022); CounterMEASURE (2021)
Trashmap (Dar es Salaam)	Tanzania	Drone mapping, spatial analysis, QGIS, ODK apps	Mapped informal dumpsites and waste hotspots; supported flood resilience and recycling efforts	High potential; depends on drone access, open data, and local technical training	OpenMap Development Tanzania Ramani Huria (2016).
Coliba & Regenize Apps	Côte d'Ivoire; South Africa	Mobile apps, rewards systems, route optimisation algorithms	Improved collection efficiency; incentivized recycling; door-to-door pickups	Easily scalable with proper adaptation; dependent on smartphone and infrastructure access	Wilson et al. (2021); White & Omondi (2022)
Bigbelly Smart Bins	Global (NYC, London, Berlin)	Solar-powered, fill sensors, WiFi, compaction, AI route prediction	Reduced collection trips; improved public hygiene and operational efficiency	Widely deployed; initial costs and maintenance may limit adoption in developing cities	Xue (2023); YTL Community (2016)
TrashFill Sense	No record of deployment	Ultrasonic + weight sensors, fill alerts, route optimisation, predictive analytics.	Prevented overfills; improved route planning; tracked user disposal patterns	Scalable; integration with municipal dashboards needed	Faststream Technologies (2021); Xue (2023)
Plastic Bank (Blockchain)	Haiti, Philippines, Indonesia	Blockchain-based incentives, digital tokens, waste tracking, deposit-return scheme	Encouged plastic recycling; ensured transparency and traceability	Scalable where blockchain and mobile infrastructure are feasible	Xue (2023); Plastic Bank Initiative

The Plastic Free Rivers in Asia

Smart technologies have helped in the identification of sources and pathways of plastic pollution in the Asian river system, particularly the Mekong and the Ganges Rivers. Xue (2023) reported on a GIS-based geospatial model used to identify plastic leakage pathways across six Asian countries, combining material flow analysis and hydrological mapping to simulate the movement of plastics from urban hotspots into river systems. This smart technology helps to identify plastic waste hotspots and reduce leakage into the rivers. This process has been successfully adapted beyond the Mekong and Ganges to other regions in Southeast Asia (Tran-Thanh et al., 2022) through partnerships between UNEP and Google. However, expansion faces challenges such as variable data quality, limited technical capacity, and the need for local stakeholder engagement (CounterMEASURE, 2021).

Trashmap Plastic Waste Visualisation

In Dar es Salaam, Tanzania, a community mapping for trashmap plastic waste visualisation was created by OpenMap Development Tanzania in 2019 (GSMA, 2021). The project focused on mapping informal dumpsites and waste hotspots along polluted rivers in Dar es Salaam, including informal settlements, using over 35 drones equipped for spatial analysis. The spatial data also informed flood resilience efforts by pinpointing clogged drains and waste-prone waterways in flood-vulnerable wards, guiding targeted drainage upgrades and municipal disaster preparedness (Ramani Huria Flood Resilience Atlas, 2016). Additionally, other open-source applications, such as ODK and QGIS, were also used. These dumpsites cause clogging of the river, resulting in an increased flood risk in the area. The data was used to develop a more efficient plastic recycling and recovery system in the region (Xue, 2023).

Asia Mobile App for Plastic Waste Collection and Recycling

A mobile app was developed and implemented for waste collection and recycling in Coliba, Côte d'Ivoire. This is in connection with the Coliba local factory for converting plastic waste into pellets. The app facilitates smart plastic waste management by connecting waste pickers to homes and businesses while also offering plastic collection and recycling services. The program was launched in 2017 to help waste pickers collect plastic bottles in exchange for points, enabling door-to-door collection (Wilson et al., 2021). Similarly, in South Africa, the Regenize app supports residential plastic recycling through a rewards-based model. It uses backend optimisation algorithms to schedule efficient pickups, predict collection volumes, and track participation rates—improving both operational planning and user engagement (White & Omondi, 2022). With the app, customers can drop their plastic waste at the collection points free of charge. It also provides a door-to-door collection service for certain payments. Furthermore, customers are rewarded with virtual money to encourage such environmentally sustainable practices (Xue, 2023).

Smart Bins with Free WiFi

As explained in Section 2.1, smart bins integrate fill-level sensors, compaction systems, and IoT connectivity to improve the efficiency of urban waste collection. A prominent example is the Bigbelly smart bin, a solar-powered, WiFi-enabled compacting bin deployed across Southeast Asia in 2016–2017. These bins monitor fullness and send automated alerts to waste collectors, significantly reducing the frequency of collection. Bigbelly bins compact waste to increase internal capacity—holding over eight times more than standard bins, which reduces overflow and cuts down the number of collection trips. WiFi functionality not only increases public visibility and engagement but also assists in route optimisation by displaying updated bin status and location on smartphones or navigation devices.

Advanced AI features predict waste generation patterns and estimate optimal vehicle size and route selection, factoring in variables such as traffic congestion and weather conditions. With over 40,000 units deployed globally in cities such as New York, London, and Berlin, Bigbelly illustrates how smart bins, when paired with predictive logistics, enhance productivity, reduce operational costs, and support low-carbon urban waste management (Xue, 2023; YTL Community, 2016).

TrashFill Sense

The TrashFill Sense is a regular trash bin that is turned into a smart technology. It combines ultrasonic sensors and a weight sensor on top and bottom of the trash, respectively, allowing for live notification of filled bins and their location. Through route optimisation, it determines the best route for collection. Also, the technology notifies the driver and operator when the maximum load capacity of the waste truck is reached. Additionally, it learns the residents' waste disposal trends and habits to predict filling trends, minimise overfill and maintain a healthy environment around the bins. Furthermore, it provides information on the waste management dashboard for easy coordination and management. Such information includes the number of empty and full bins, locations, weight, and fill level (Faststream Technologies, 2021; Xue, 2023).

Blockchain for Plastic Waste Management

Blockchain technology has also been integrated into the management of plastic waste. This application of blockchain contributes to plastic waste management by facilitating incentive payments that promote plastic recycling and by monitoring and tracking plastic waste streams for improved management. The approach involves rewarding plastic waste depositors with a blockchain-secured digital token, which can be exchanged for goods or other currencies. This has been implemented in the Plastic Bank Project. In this, blockchain rewards were used to incentivise individual plastic waste collectors. This is facilitated through a blockchain-based banking application with high immutability and transparency, thereby preventing fraudulent and corrupt practices. This application has been tried in Haiti, the Philippines and Indonesia. Beyond incentivisation, blockchain has also been used to revolutionise tracking through a Deposit Return Scheme for plastic bottles. Also, the type of waste collected and waste transfer can be recorded on a blockchain. This can involve streamlining and automating waste transportation, as well as providing real-time verification of the steps in the plastic waste management process (Xue, 2023). To summarise these case studies, Table 1 presents key features, locations, outcomes, and scalability of the smart technology implementations discussed above.

CHALLENGES AND BARRIERS

Despite the fact that the integration of smart technology into plastic waste management provides a new dimension in enhancing collection and efficiency in the waste management processes, it is faced with various challenges as below:

Conflict of Interest

The use of smart technology in waste management requires some digital skills for efficiency. This includes skilled workers with knowledge of digital technology to manage it effectively. Smart technologies risk displacing informal workers such as waste pickers and sorters, who remain vital to local waste systems. In response, cities like New Delhi have piloted inclusive models, such as solar-powered micro recovery centres staffed by trained pickers, that preserve livelihoods while modernising operations. However, such transitions can trigger institutional friction between regulators and market actors (Xue, 2023), and fragmented implementation may result from misaligned goals among tech developers, municipal authorities, and policymakers (Prabawati et al., 2023).

Costs

Smart and AI-driven technologies in waste management demand significant upfront investment and depend on secure, high-performance software and hardware for effective operation. Costs arise from installation, ongoing maintenance, and cybersecurity requirements. Despite these initial expenses, a recent municipal case study showed that integrating life cycle cost analysis with route optimisation led to a 45.7% reduction in global warming potential and a 52% decrease in vehicle travel distance over ten years—demonstrating both environmental and long-term economic advantages (Nematollahi et al., 2024). Such findings underscore the value of comprehensive evaluation in helping public-sector decision-makers assess long-term returns against initial investment. Additionally, the cost of deploying sensor networks and automated waste sorting systems can vary widely, from basic prevention and collection tools to more advanced treatment technologies. These higher costs, along with the availability of cheaper traditional methods, may lead to resistance from stakeholders accustomed to conventional waste management approaches (Kannan et al., 2024; Xue, 2023).

Security

Smart technologies are generally at risk of data breach, system malfunction, unauthorised access and data manipulation. And since effective and integrated waste management requires data collection, surveillance, IoT, and cloud computing, it is susceptible to these risks. It can pose risks, such as complete monitoring of citizens, not only by the state but also by marketers and criminals through illegal data breaches or hacking. Additionally, digital data are high-priority targets for foreign offensive IT Warfare Operations, digital attacks, and hackers. This makes it prone to more attacks if not well-designed and thoroughly managed (Olawade et al., 2024; Xue, 2023).

Weather Challenges
Some smart technologies, such as unmanned aerial vehicles, have high requirements for the weather conditions. Such weather conditions include calm waters, low winds, and minimal sun glint, allowing for efficient operation. Furthermore, extreme weather can affect the functionality of these technologies. They present limitations on further application in plastic debris observation, especially in offshore areas. The effects of weather conditions reduce the clarity of sensors in the monitoring of coastal and marine shores (Olawade et al., 2024; Xue, 2023).

Skilled Personnel
The use of smart technologies in plastic waste management requires intensive operations and maintenance. They are highly technical and not readily available in many regions. Hence, technical expertise is required. However, there is a persistent lack of skilled labour, which further complicates the operations, management and maintenance of smart technologies (Kannan et al., 2024; Olawade et al., 2024).

Technological Challenges
The availability of proper sensors, insufficient spectral resolution, and a lack of standardisation are some of the technological challenges facing smart technologies for plastic waste. There are also difficulties in integrating smart technologies in the recycling of collected plastic waste. This is due to contamination from various chemical and biological pollutants, as well as weathering by processes such as wave fragmentation, UV radiation, and biochemical oxidation, which damage the original structure of the plastics. These present technological constraints to the use of smart technologies for plastic waste management (Kannan et al., 2024; Xue, 2023).

Potential Environmental Impact
Smart technologies for plastic waste management face some potential environmental impacts, such as the distortion of the ecosystem. For example, marine wildlife entanglement may occur due to the installation of plastic clean-up devices. Such concerns have been raised regarding several types of technologies that employ a suction mechanism and potentially entangle small organisms in their surroundings. Other possible environmental impacts are the energy consumption of active technologies, such as wheels and watercraft. There is also a concern that these technologies will become e-waste, which is a dent to sustainability (Kannan et al., 2024; Xue, 2023).

Microplastic Prevention and Collection Technologies
Microplastics continuously fragment in the environment and eventually break down into smaller particles, ultimately becoming microplastics. Currently, available prevention and collection technologies primarily target large particulates of plastic waste. The design of technology for microplastics is still in its infancy; hence, limited options are available to accomplish such objectives due to significant uncertainties and inconsistencies for future large-scale applications (Kang et al., 2019; Schmaltz et al., 2020).

CONCLUSION
The integration of smart technologies into plastic waste management has delivered clear benefits over the past decade, especially in urban areas across countries like Spain, South Korea, and the United States. Cities such as Barcelona and Seoul have reduced collection costs and contamination rates using sensor-enabled systems and real-time data tools. Technologies such as ultrasonic fill-level sensors, gas sensors like the MQ-135, RFID tracking, and machine-vision sorting have enhanced route planning, reduced overflow, and increased recycling efficiency.

Distributed-ledger technologies further enhance system transparency by creating immutable audit trails from collection to processing. This provides recyclers, waste management operators, and regulators with greater assurance that plastics are reintroduced into the circular economy, supporting performance-based procurement of recycled content. These stakeholders also benefit from lower operational costs through predictive maintenance and route optimisation, while consumers gain improved transparency and confidence in the recycling process.

For these systems to deliver low-carbon, circular plastic economies, broad collaboration is essential. Governments should offer incentives and enforce open-data standards; industries can pilot open-source solutions; technology providers must ensure the availability of accessible tools; NGOs can support local adoption; and individuals can use digital tools to enhance recovery. Urban planners, municipal waste authorities, and policy developers should consider funding mechanisms, pilot programs, and technology transfer models to enable adoption and scaling. Integration with global policy frameworks, such as the United Nations Sustainable Development Goals 11 and 12, will also be important to ensure these innovations contribute meaningfully to sustainable cities and responsible consumption. With a coordinated effort, we can advance toward the goal of achieving at least 50% circular plastics by 2030, as outlined in EU and national roadmap initiatives (TNO, 2022).

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CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

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