A Study of Advanced Smart Packaging Technologies in Plastic Waste Sorting and Recycling

Yu-Ju Wu

Abstract

The World Bank Report predicts that municipal solid waste generation will grow from 2.1 billion tonnes in 2023 to 3.8 billion tonnes by 2050, with plastic waste comprising over 10% of total waste[1]. Packaging is a significant contributor. Flexibles and rigid plastic packaging represent 44% of the total packaging market, yet their recycling rates are significantly lower than paper/cardboard, metal, and glass. A key barrier to effective recycling is consumer uncertainty, as the Ellen MacArthur Foundation reports that 60% of consumers are unsure how to recycle plastics, and it is estimated 86% of plastics are incinerated, leak into the environment, or end up in a landfill[2]. If not collected and managed properly, plastic waste will contaminate and affect waterways and ecosystems. It is important to ensure advanced sorting of mixed plastic waste into high-quality mono-waste fractions for further reuse. However, the large variety of plastics used, the varying lifespan of different products and technical challenges in the identification and separation of plastics create difficulties in tracking plastic flows, making plastic waste recycling a challenging task. Innovative solutions are being developed to tackle the complexities of plastic waste sorting. Advanced technologies such as enhanced near-infrared (NIR) sorting can identify and separate various polymer types, improving recycling efficiency. Digital watermarks, which are small (a postage stamp size), unnoticeable codes printed on packaging, offer another promising solution. Furthermore, AI-driven waste sorting systems integrate computer vision, machine learning, and robotics to optimize the sorting of plastic waste. This paper will explore these innovative sorting technologies - enhanced optical sorting, digital watermarks, and AI-based waste management - highlighting their potential to transform plastic waste management and contribute to a more sustainable future.

Introduction

Plastics have provided significant economic advantages across industries such as packaging, construction, transportation, healthcare, and electronics, thanks to their unique combination of low cost, versatility, strength, and durability. In

Appalachian State University / Graphic Communications Management Program

packaging, plastics are particularly valued for being lightweight, cost-effective, and high-performing. These properties make plastic an ideal choice for packaging materials, offering benefits beyond just convenience. Given plastic packaging's many benefits, the likelihood of a significant reduction in plastic packaging volume remains low. While it is important to pursue strategies that minimize plastic usage, such as reducing single-use plastics, transitioning to alternative materials, and optimizing packaging designs, plastic's versatility and efficiency ensure its continued relevance in the packaging industry[3].

The Challenge of Plastic Waste

Plastic packaging offers significant advantages, including its lightweight, cost-effectiveness, and ability to extend food's shelf life. Due to its lightweight nature, plastic also reduces transportation fuel consumption. These benefits have made plastic a dominant material in packaging across various sectors.

However, despite these advantages, plastic packaging poses a major environmental challenge. The most troubling issue is that 95% of the material value of plastic packaging is lost after just one use. Only about 14% of plastic packaging is collected for recycling, with the remaining 72% being landfilled, incinerated, or lost through leakage. Even worse, the material value of plastic packaging is largely wasted: after the first use, only about 5% of its value is recovered[3, 4]. The inefficiency in recycling, combined with the sheer volume of plastic waste generated, has contributed to a growing global crisis, negatively impacting ecosystems, wildlife, and human health. Plastic waste continues to harm ecosystems, especially marine life. Plastics degrade slowly, staying in the environment for centuries. Mismanaged waste is a major source of pollution, impacting biodiversity and human health. Moreover, plastics in the environment also contribute to climate change, given their fossil-fuel origins and the energy-intensive processes required for their production. The difficulty of recycling plastics only compounds the problem. Due to the wide variety of plastic types, contamination, and inadequate recycling infrastructure, the process of recycling is both costly and inefficient. Plastics often require separate sorting and processing methods, and many cannot be effectively recycled with current technology. Even when plastics are recycled, the quality of the resulting material is often too low for use in high-quality applications, limiting its effectiveness as a sustainable solution[4-5]. Establishing a sustainable after-use plastics economy is essential not only for capturing more material value and boosting resource productivity but also for providing strong economic incentives to prevent plastic waste from leaking into natural ecosystems.

The Circular Economy

The life cycle of plastics, from production to disposal, illustrates a linear economic model - produce, use, and dispose, which is unsustainable given current production and consumption rates. This increasing plastic waste generation requires urgent action to improve recycling rates and implement more sustainable waste management strategies. Moving from linear approach to a more circular approach, where plastics are recycled, reused, and repurposed, is essential to enhance resource efficiency and reduce environmental impacts. As national and local governments embrace the circular economy for recycling and reusing plastics in consumer packaging, smart and sustainable ways to manage plastic waste will help promote efficient economic growth while minimizing environmental impact.

The goal of applying circular economy principles is to minimize waste, reduce pollution, and decrease the need for new plastic production. In a circular economy, as shown in Figure 1, resources are kept in use for as long as possible to extract the maximum value from them. At the end of their life, products and materials are recovered and regenerated, ensuring they stay in the economy and out of landfills or the environment[4, 6-7].

Figure 1. Circular economy model for waste management
Source: Bułkowska K, Zielińska M, Bułkowski M. Blockchain-Based Management of Recyclable Plastic Waste. Energies (19961073). 2024;17(12).

To enable the circular economy, products and packaging need to be designed with recycling in mind. This means using materials that are easier to recycle, avoiding complex multi-material designs, and ensuring that products can be easily disassembled. Collaboration among manufacturers, recyclers, and policymakers is crucial in developing products that can fit into circular systems[4-7].

Advanced recycling technologies are key to overcoming current barriers. For example, innovations in sorting technologies, such as digital labels or QR codes that track materials through the recycling chain, could streamline the identification and separation of different types of plastics. This would improve the efficiency of recycling processes, making it possible to capture more material value[4-7].

One of the central components of the circular economy is traceability - the ability to track the history of materials throughout their lifecycle. By ensuring that recycled plastics maintain high quality and meet standards for reuse, traceability can help improve the overall recycling process. Digital systems, such as QR codes or physical labels, can provide crucial information about the composition, degradation state, and contaminants in recycled plastics[4-7].

Extended Producer Responsibility (EPR) schemes are increasingly seen as a key solution to improve recycling rates. Many new initiatives and legislation have emerged, including the 'EU Green Deal' and PPWR, the 'New Plastics Economy', the Holy Grail initiative, the Circular Plastics Taskforce (CPT), and the EPA's National Recycling Strategy in North America. Many of the largest companies have publicly committed ambitious targets to eliminate single-use plastics and increase the percentage of recycled plastics in their products and packaging[2].

Plastic Waste Recycling

Plastics are classified into various types based on their chemical structure and properties. The most common classification system is the Resin Identification Code (RIC), which uses numbers from 1 to 7 to help sort plastics for recycling (Table 1). Plastics, both structural and functional, are integral to modern life. These polymers are used in large volumes across many industries, combining cost-efficiency with desirable properties like durability, ease of processing, and versatility. In packaging, they protect perishable food. Plastics also play crucial roles in less visible applications, such as in detergents, pharmaceuticals, personal care products, paints, and coatings[4, 8-9].

One of the main challenges in recycling plastics is the need for precise sorting to avoid contamination. Plastics must be sorted by type because different polymers have varying melting points and properties. When mixed, they can result in low-quality recycled products that are less valuable and harder to process. The complexity of plastics recycling is further heightened by the wide variety of materials and compositions in circulation. Multilayer and composite materials, which are often not designed for recycling in standard systems, require additional effort to separate and process. To address these challenges, the plastics industry must adopt a new business model that drives the transition toward a true circular economy. This will require significant changes across the value chain, starting with the feedstock, energy supply, and collection systems. An essential part of this transformation is improving traceability and information sharing among all stakeholders involved in the plastics supply chain. Accurate tracking of materials throughout the recycling process can help overcome current hurdles and improve recycling efficiency.

Code	Resin		Common products:	Recycled products:
1	PET Polyethylene Terephthalate		soda and water bottles, cups, jars, trays, clamshells	clothing, carpets, clamshells, soda and water bottles
2	HDPE High-Density Polyethylene		milk bottles, freezer bags, dip tubs, crinkly shopping bags, ice cream containers, juice bottles, shampoo, chemical and detergent bottles	detergent bottles, flowerpots, crates, pipes, decking
3	PVC Polyvinyl Chloride		cosmetic containers, commercial cling wrap	pipe, wall siding, binders, carpet backing, flooring
4	LDPE Low-Density Polyethylene		squeeze bottles, cling wrap, shrink wrap, rubbish bags	trash bags, plastic lumber, furniture shipping envelopes, compost bins
5	PP Polypropylene		microwave dishes, ice cream tubs, potato chip bags, and dip tubs	paint cans, auto parts, food containers, hangers, plant pots, razor handles
6	PS Polystyrene		cd cases, water station cups, plastic cutlery, imitation 'crystal glassware', video cases	picture frames, crown molding, rulers, flowerpots, hangers, toys
7	Others		polycarbonate, nylon, acrylonitrile butadiene styrene, acrylic, polylactic acid	electronic housings, auto parts

Table 1: Plastic resin identification codes and usage
Source: Bułkowska K, Zielińska M, Bułkowski M. Blockchain-Based Management of Recyclable Plastic Waste. Energies (19961073). 2024;17(12).

Advances in Sorting Technologies

New technologies are emerging to enhance the efficiency of recycling, particularly in the identification and sorting of plastics. Innovations like spectroscopic analysis, optical sorting, and infrared sensors are all part of the cutting-edge technologies being deployed in recycling facilities today. The introduction of digital traceability solutions, such as QR codes or blockchain, could revolutionize how plastic waste is tracked and managed. Automated systems using machine learning and AI can help separate plastics by type, improving material quality and reducing contamination.

Enhanced Optical Sorting

Near-Infrared (NIR) spectroscopy is a widely used technique in plastic sorting systems. It uses near-infrared light to scan plastic materials and identifies them based on how they absorb and reflect different wavelengths of light. The technology is capable of distinguishing between 12 types of plastics, which allows for more accurate sorting and better-quality recycled materials[4, 9-10].

Despite its effectiveness, NIR technology faces some limitations. For example, carbon-black-colored plastics are a major issue. These plastics absorb NIR light and do not reflect it back for analysis, making them virtually invisible to standard NIR systems. To address this issue, several innovative solutions are being explored. Companies like Lanxess have developed new black pigments based on iron oxide, which allow for NIR reflectivity. These pigments enable better detection of black plastics during the sorting process. Other techniques, such as mid-infrared spectroscopy, hyperspectral imaging, and fluorescence imaging, are being developed to complement NIR and improve the sorting of challenging materials like black plastics[11-12].

Another significant issue in plastics recycling is the growing use of multilayer packaging and composite materials, which often contain various layers of different plastics or other substances like paper or aluminum. These materials are difficult to sort with traditional NIR systems, as the technology primarily detects surface characteristics. As a result, multilayer packaging, which is increasingly used in food and beverage packaging, requires additional sorting steps or alternative technologies to achieve efficient recycling[11-12].

NIR sorting has seen substantial improvements over the years. Modern NIR systems can achieve sorting purity levels of up to 96%, which helps reduce contamination and improve the quality of recycled plastics. Several companies and research institutes are working to improve NIR technology to enhance the sorting process. Trinamix, for instance, a subsidiary of BASF, has developed a mobile NIR spectroscopy solution capable of distinguishing between similar polymers, such as nylon 6 and nylon 66, which can often be difficult to separate due to their similar properties. This solution uses robust hardware combined with intelligent data analysis and a mobile app, facilitating more accurate polymer identification during the recycling process. Researchers from Aarhus University in Denmark, in collaboration with Vestforbrænding, Dansk Affaldsminimering Aps, and PLASTIX, have introduced a new NIR camera technology. This advanced camera can identify 12 different polymer types, including PE, PP, PET, PS, PVC, PVDF, POM, PEEK, ABS, PMMA, PC, and nylon 12. This technology, which has been successfully tested on a pilot scale, offers more accurate sorting based on the chemical composition of the polymers, enhancing the quality of recycled materials and improving overall recycling. In the UK, the company Matoha has developed a user-friendly device called PlasTell, which can identify common polymers such as PET, PVC, PE, PP, PS, ABS, and nylons. The device is also capable of detecting specialty plastics on request, though it struggles with identifying thin films (less than 20 microns) and plastics containing carbon black. Additionally, Tomra, a leader in sensor-based sorting systems, has developed add-on laser sensors to complement its NIR technology, enabling the detection of black plastics. Their Autosort system combines multiple technologies—including NIR spectroscopy, laser, electromagnetic, and AI-based camera sensors—to provide more precise sorting and separation, further advancing the recycling.

NIR spectroscopy plays a critical role in the recycling of plastics by enabling more precise sorting of polymer types. However, challenges remain, especially when it comes to black plastics and complex materials like multilayer packaging. Innovations such as new black pigments, alternative sorting technologies, and improved traceability systems are essential for overcoming these obstacles and achieving higher recycling rates.

Digital Watermarks

Traceability plays a crucial role in improving the efficiency and quality of recycling processes, especially in the plastics industry. It refers to the ability to track the journey of materials - from production to disposal - and ensure that they are properly sorted, recycled, and repurposed. This process is vital for creating a circular economy, where materials are continuously reused and recycled, minimizing waste and environmental impact. In the context of plastics recycling, traceability involves gathering and sharing information at every stage of a product's lifecycle. This can include details about the composition of the material, its state of degradation, and the presence of contaminants. These factors are critical for assessing the quality of recycled materials and ensuring they are suitable for reuse in new products.

The industry is moving toward integrating digital traceability systems. These systems can provide detailed, real-time information about the material's history, such as using QR codes or other digital markers that consumers or waste management companies can scan to verify a product’s recyclability at its end-of-life. By enabling better tracking from production to disposal, traceability enhances the transparency and reliability of the recycling process[13-15].

Digital Watermarks are an innovative technology that can significantly enhance the recycling process by improving the sorting of packaging materials. These watermarks are imperceptible barcodes applied to the surface of packaging, either on in-mold or sleeve labels or directly on the product itself (Figure 2). Using a technique called "pixel-scattering," digital watermarks create codes that are invisible to the naked eye but can be easily detected by high-resolution cameras equipped with special software. This design ensures the watermarks can be scanned from any angle, making it easy to detect the code regardless of the package's orientation during the sorting process. Once the packaging enters the waste stream, standard high-resolution cameras in sorting facilities can detect the digital watermarks and decode the information. Based on this decoded data, the sorting system can then categorize the packaging into the correct recycling stream, leading to better sortation and, ultimately, higher quality recyclates. The technology behind digital watermarks is also highly versatile. It does not require special inks, materials, or manufacturing processes. The watermark can be printed using existing encoder software that applies tiles to the graphics on the packaging, or it can be embedded directly into the plastic material through methods such as engraving molds or laser texturing to create topological variations that are detectable by sensors[11, 16, 18-19].

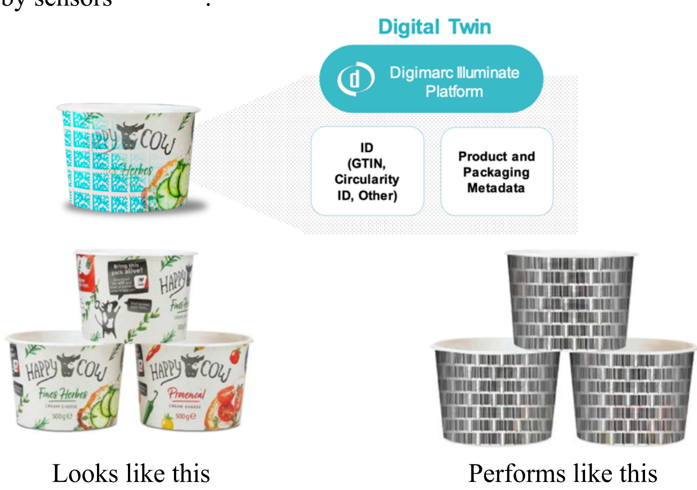

Figure 2: Digital Watermarks
Source: Digimarc Recycle Helping Brands Achieve Circularity, 2024,
https://pmmi.app.box.com/s/xvmxfmtjt38c1x9z3lqvs48wep6wqcfx

One of the primary benefits of digital watermarks is their ability to store detailed information about the packaging material. This information can include key attributes such as the manufacturer, SKU, type of plastics used, the composition of multilayer objects, and whether the packaging is for food or non-food products. This level of detail provides essential data for accurate sorting of materials once the packaging reaches a waste-sorting facility.

In addition to recycling, digital watermarks can also have broader applications. They can be used for consumer engagement, providing additional product information; supply chain visibility, allowing for better tracking of products as they move through the supply chain; and retail operations, aiding in inventory and sales processes.

Digimarc is a leading company in product digitization and is at the forefront of the digital watermarking technology revolution. Its solution, Digimarc Recycle, integrates covert digital watermarks with a cloud-based product attributes database. This enables plastic packaging to be accurately identified at recycling facilities, overcoming the limitations of traditional sorting. It also helps brands meet stringent recycling targets, including Procter & Gamble’s commitment to 100% recyclable or reusable packaging by 2030. Additionally, the technology supports Extended Producer Responsibility (EPR) programs, which aim to reduce the environmental impact of packaging waste[17-18].

HolyGrail 2.0 is a collaborative initiative designed to tackle the growing challenges in plastic recycling, specifically focused on improving sorting processes and the quality of recyclables. Building on the success of its predecessor, HolyGrail 1.0, this project brings together over 160 companies across the entire packaging value chain, including major global brands like Procter & Gamble, Nestlé, PepsiCo, and Danone. The key technology at the heart of the project is digital watermarking, which provides a way to identify and sort different types of packaging more efficiently. The goal of HolyGrail 2.0 is to enhance the ability of waste sorting systems to deal with complex packaging materials, such as multi-materials and flexible packaging, which are difficult to separate and recycle effectively. By using invisible digital watermarks on packaging, waste management systems can more accurately identify and sort these materials, making the recycling process more efficient and effective. A central player in this initiative is Digimarc, which provides the digital watermarking technology that underpins the project. Their technology is designed to improve the performance of recycling infrastructure and sortation systems by allowing automated systems to read the digital watermarks and sort packaging more effectively, leading to higher quality recyclates and reducing contamination in the recycling stream. As the project enters its third and final phase in late 2024, industrial-scale tests will be conducted to validate the technology in real-world sorting environments, simulating the challenges that waste disposal facilities face. These tests will help determine whether the technology can be scaled up for widespread adoption, potentially revolutionizing the way plastic waste is managed and recycled globally[16-23].

AI-based Waste Management

The rapid development of AI and machine learning technologies is transforming the waste management and recycling industries, particularly in plastic waste sorting. AI models used in material recovery facilities (MRFs) typically consist of three components: computer vision technology for recognizing and categorizing materials, AI learning systems for making decisions based on that data, and sorting robots that physically handle the materials. Advances in algorithms have greatly improved the granularity of these systems, allowing them to identify various plastic types, brands, weights, and even distinctions between food and non-food packaging[24-29].

Companies like Glacier, AMP Robotics, EverestLabs, and CleanRobotics are at the forefront of these innovations, leveraging AI to enhance efficiency, increase recovery rates, and provide real-time insights into waste streams. Key Innovations in AI-Based Sorting include[18, 30]:

- Glacier's AI technology provides real-time trend analysis of material streams at MRFs, helping operators identify inefficiencies and optimize operations.
- AMP Robotics: AMP offers Cortex, a high-speed robotic sorting system powered by AI. The system achieves up to 99% accuracy in sorting materials at speeds of 80-120 picks per minute. In addition to the robotic system, AMP provides AMP Clarity, a material-characterization and robot-performance software that monitors real-time performance and material composition. Features like mass estimation, robot assignments, and expanded reporting capabilities help improve efficiency and provide valuable data on the facility's operations. AMP also developed Vortex, a system targeting film and flexible packaging recovery, a persistent challenge in recycling facilities. The addition of Cortex robots for sorting materials like PET, HDPE, and mixed plastics increases material recovery and streamlines sorting processes.
- EverestLabs: RecycleOS, EverestLabs' AI system, uses deep learning and robotics to drastically improve recovery rates at MRFs. It can identify over 100 different materials and guarantee successful picks with accuracy twice that of manual sorters. The system is scalable and can be installed without significant retrofitting. RecycleOS provides real-time analytics on plant operations and offers a granular look at environmental impacts. It tracks materials entering and exiting the facility, helping operators monitor the efficiency of their operations and meet sustainability goals. The system is also instrumental in aiding companies with Extended Producer Responsibility (EPR) compliance, offering data to optimize packaging designs and reduce waste.
- CleanRobotics: TrashBot is a smart recycling bin powered by AI, which uses computer vision and machine learning to sort waste with up to 95% accuracy. Designed for high-traffic locations like airports and stadiums, TrashBot not only sorts waste but also provides data for on-demand waste audits. In pilot

programs, TrashBot has demonstrated significant improvements in accuracy, sorting 90% of waste correctly, compared to 30% accuracy with traditional methods.

The adoption of AI in MRFs is being driven by decreasing computing costs and advances in robotics, but the technology is still evolving. As deep learning and AI models continue to improve, the capabilities of these systems will become even more refined, enabling the sorting of more complex materials and improving the overall performance of recycling systems.

Conclusions

Collaboration between governments, industry representatives, and consumers is crucial in establishing a sustainable circular economy for plastics. Currently, plastics are either designed to be recyclable, compostable, or neither. Optimizing materials for recyclability is crucial to ensure that after-use plastics remain valuable within the economy. The recycling pathway is often preferable over biodegradability, as it allows plastic to be reused and repurposed, reducing waste. On the other hand, biodegradable plastics break down into elements like water and CO2, which do not contribute to long-term material reuse. As plastic consumption and production continue to rise, design innovations that facilitate recycling or reusability - such as materials that are easy to sort and break down into reusable components - are essential.

To ensure plastics do not end up in oceans or other parts of the environment, the improvement of collection systems and recovery infrastructure is key. Governments and industries should work together to incentivize the building of better collection networks, particularly in areas with inadequate waste management systems. Traceability systems, such as digital labeling and advanced sorting technologies, can provide transparency, ensuring plastics are properly collected, sorted, and recycled. Traceability, facilitated by digital and automated systems, will be pivotal in improving recycling rates. Technologies like smart bins, AI-based sorting, and digital watermarks in plastic packaging can help track the lifecycle of materials, ensuring they are recycled properly. This will create a closed-loop system, enabling the continuous reuse of plastics and reducing the demand for virgin materials.

References

1. United Nations Environment Programme (UNEP). (2024). Global Waste Management Outlook 2024: Beyond an age of waste – Turning rubbish into a resource. https://www.unep.org/resources/global-waste-management-outlook-2024
2. Digimarc Recycle Helping Brands Achieve Circularity, 2024, https://pmmi.app.box.com/s/xvmxfmtjt38c1x9z3lqvs48wep6wqcfx

3. The New Plastics Economy: Rethinking the future of plastics Ellen MacArthur Foundation, 2016, https://www.ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics
4. Bułkowska K, Zielińska M, Bułkowski M. Blockchain-Based Management of Recyclable Plastic Waste. Energies (19961073). 2024;17(12).
5. Basf Joins Digital Watermark Initiative for Smart Packaging Recycling. (2021). Food Manufacturing Africa, 10 (2), 7.
6. Rumetshofer, T., & Fischer, J. (2023). Information-Based Plastic Material Tracking for Circular Economy—A Review. Polymers (20734360), 15(7), 1623.
7. Bendix, P., Achenbach, H., Weißhaupt, P., Eckert, D., Oehme, I., & Berg, H. (2022). Circular economy for durable products and materials: the recycling of plastic building products in Germany—status quo, potentials and recommendations. Journal of Material Cycles and Waste Management: Official Journal of the Japan Society of Material Cycles and Waste Management (JSMCWM) and the Korea Society of Waste Management (KSWM), 24(4), 1432–1443.
8. Von Vacano, B., Mangold, H., Vandermeulen, G. W. M., Battagliarin, G., Hofmann, M., Bean, J., & Künkel, A. (2023). Sustainable Design of Structural and Functional Polymers for a Circular Economy. *Angewandte Chemie International Edition*, *62*(12), 1–28.
9. Jakubowicz, I., & Yarahmadi, N. (2024). Review and Assessment of Existing and Future Techniques for Traceability with Particular Focus on Applicability to ABS Plastics. Polymers (20734360), 16(10), 1343.
10. Y. -M. Wang, C. -T. Sun, P. -C. Kuan, C. -S. Lu and H. -C. Wang, "Secured graphic QR code with infrared watermark," *2018 IEEE International Conference on Applied System Invention (ICASI)*, Chiba, Japan, 2018, pp. 690-693, doi: 10.1109/ICASI.2018.8394351.
11. Mangold, H., & von Vacano, B. (2022). The Frontier of Plastics Recycling: Rethinking Waste as a Resource for High-Value Applications. *Macromolecular Chemistry and Physics*, *223*(13).
12. Schmidt, J., Grau, L., Auer, M., Maletz, R., & Woidasky, J. (2022). Multilayer Packaging in a Circular Economy. *Polymers (20734360)*, *14*(9), 1825.
13. Jakubowicz, I., & Yarahmadi, N. (2024). Review and Assessment of Existing and Future Techniques for Traceability with Particular Focus on Applicability to ABS Plastics. *Polymers (20734360)*, *16*(10), 1343. https://doi-org.proxy006.nclive.org/10.3390/polym16101343
14. DeWeerdt, S. (2023). Plastic's Messy End-Game. *Scientific American*, *328*(1), S2–S5. https://doi-org.proxy006.nclive.org/10.1038/scientificamerican0123-s2
15. Rumetshofer, T., & Fischer, J. (2023). Information-Based Plastic Material Tracking for Circular Economy—A Review. *Polymers (20734360)*, *15*(7), 1623. https://doi-org.proxy006.nclive.org/10.3390/polym15071623
16. Mondelez trials digital watermarks for smarter packaging recycling. (2020). *Vending International*, 8.
17. Naitove, M. (2020). New Product ID Technologies For Industry, Retail & Recycling. *Plastics Technology*, *66*(3), 18-20–20.

18. Das, S. (2022). Recycling: What's Ahead in Advanced Sorting Technology. *Plastics Technology*, *68*(9), 56-61–61.
19. PR Newswire. (2020, September 8). Digimarc at Center of Pan-European Development of Digital Watermarking for Improved Plastic Sortation and Recycling. *PR Newswire US*.
20. PR Newswire. (2022, March 30). Digimarc Digital Watermarks Proven to Achieve More Accurate Sorting of Packaging Waste. *PR Newswire US*.
21. Laird, K. (2020). HolyGrail 2.0 to explore potential of digital watermark technology. *Plastics News*, *31*(26), 22.
22. PR Newswire. (2021, September 7). Major Milestone Achieved in the HolyGrail 2.0, the Digital Watermarks Initiative Aimed at Revolutionizing the Recycling of Plastic Packaging. *PR Newswire US*.
23. PR Newswire. (2022, October 17). Results From Canadian Circular Plastics Taskforce Pilot Confirm Digimarc Recycle Improves Sortation of Flexible Packaging. *PR Newswire US*.
24. Lubongo, C., Bin Daej, M. A. A., & Alexandridis, P. (2024). Recent Developments in Technology for Sorting Plastic for Recycling: The Emergence of Artificial Intelligence and the Rise of the Robots. *Recycling (MDPI AG)*, *9*(4), 59.
25. PR Newswire. (2023, May 16). Global Mechanical Recycling of Plastic Packaging Waste Research Report 2022-2030: Partnerships Between Recovery Companies and AI-based Providers to Develop Advanced End-to-End Recycling Capacity. *PR Newswire US*.
26. Lubongo, C., & Alexandridis, P. (2022). Assessment of Performance and Challenges in Use of Commercial Automated Sorting Technology for Plastic Waste. *Recycling (MDPI AG)*, *7*(2), N.PAG.
27. Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., Hamza, E. H., Rooney, D. W., & Yap, P.-S. (2023). Artificial intelligence for waste management in smart cities: a review. *Environmental Chemistry Letters*, *21*(4), 1959–1989.
28. Lu, S., & Serafeim, G. (2023). How AI Will Accelerate the Circular Economy: Digital technology will help companies extend the life of products, use fewer materials in production, and use more recycled materials. *Harvard Business Review Digital Articles*, 1–6.
29. Binder, J., & Wade, M. (2024). digital sustainability for a better future. *Stanford Social Innovation Review*, *22*(1), 52–60.
30. Brzozowski, C. (2023). Welcome to Artificial Intelligence in Recycling. *MSW Management*, *33*(2), 17–23.