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AI-Driven Innovations in Waste Management: Catalyzing the Circular Economy †

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Abstract: An effective CE approach will require new waste management practices that provide more value and have improved resource use and ecological consequences. The innovations offered by artificial intelligence (AI) are revolutionary: automation, predictive analytics, and generative AI enhance sorting and recycling of waste and recovery of materials. This paper analyzes AI applications at the micro, meso, and macro levels, detailing practical examples of improved efficiency AI solutions offer, as well as the sustainability and circularity benefits. By adopting AI within CE frameworks, businesses and policymakers confront existing barriers to change, instigate deep shifts, and catalyze from new waste designable surfaces, designable surface engineering, and sustainable industrial symbiosis opportunities.

Keywords: circular economy; artificial intelligence; waste management; sustainability; smart waste systems

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1. Introduction

The pioneering idea of a circular economy differs greatly from the classical linear economy system, as it intends to dissociate economic growth from the consumption of limited resources. Its priority is to take advantage of resources on a continuous basis while trying to mitigate waste and its negative environmental impacts by preserving products, parts, and material for as long as possible. Turning towards circular economy practices, however, does come with some very complicated challenges that need novel solutions.

Revolutionary technology issues like the ones listed above, along with those associated with a circular economy model, can now be solved with the emergence of artificial intelligence. Artificial intelligence uses a range of methods designed to solve sophisticated issues through cognitive-based techniques such as machine learning, deep learning, and natural language processing. With the role of modern technologies that enable the independent or semi-independent performance of tasks such as decision making, problem solving, learning, and actual speech, resource and waste management can greatly be improved, as well as sustainable corporate practices.

This paper investigates the importance of AI in enabling circular economy approaches at the micro, meso, and macro levels. We analyze the roles of AI in waste management, providing particular examples to demonstrate the benefits AI brings. Moreover, we discuss the implications of AI integration within the circular economy on ethics and social

dimensions while identifying relevant gaps concerning data availability, integration, and implementation that pose challenges to wider acceptance.

By providing a detailed assessment of the application of AI in the circular economy, this paper aims to draw the attention of policymakers, businesses, and academics towards the realities and complexities of the application of AI towards sustainable development. Addressing the application of AI's potential is essential to advancing towards an ideal future for us—a future where economic development is delinked from resource consumption and the negative impact on the environment is significantly reduced.

This paper is a systematic literature review analyzing AI use cases in circular economy waste management, and focuses on the following tasks and goals:

- Search Strategy: Literature was collected from databases including Scopus, Web of Science, and IEEE Xplore;
- Time Period: The review encompasses research published between 2015 and 2025;
- Inclusion Criteria: We included papers discussing AI-driven innovations in waste management with empirical evidence or theoretical contributions;
- Exclusion Criteria: Articles lacking substantial discussion on AI integration or non-peer-reviewed sources were omitted;
- Classification System: The literature was categorized based on AI applications at the micro, meso, and macro levels, further grouped into decision-making, generative, and optimization AI.

2. Circular Economy: Definition and Framework

2.1. The Circular Economy

The circular economy (CE) is an economic model where activities like resourcing, purchasing, production, and reprocessing are designed to improve environmental performance and human well-being. CE is based on principles from industrial ecology, industrial ecosystems, and industrial symbiosis, with reverse logistics playing a significant role in its implementation. The main goal of CE is to use resources more efficiently, reduce waste, and limit the environmental impact of economic activities [1].

Furthermore, the principles of a circular economy focus on sustaining economic progress while reducing reliance on non-renewable resources, ensuring that materials and products remain in circulation through distinct technical and biological pathways [2]. It enhances sustainability through resource efficiency and waste reduction and is a core part of the EU's industrial strategy, though adoption varies across member states [3,4]. CE also drives systemic changes in material and energy flows, minimizing non-circular inputs and promoting decarbonization [5]. In developing countries, particularly in construction, CE improves material efficiency and ecosystem recovery through innovative waste management [6]. Despite lacking a universal definition, CE focuses on closing resource loops and improving information exchange between lifecycle stages [7].

Implementing principles of the circular economy requires handling different operational levels of complexity. Achieving this goal can be facilitated by developing a comprehensive framework that integrates micro, meso, and macro dimensions. It tailors strategies at different levels, unlocking new synergies and coordination among actors, and xthereby, optimizing resource use and sustainable development within various sectors and regions.

2.2. Multilevel CE Framework

A multilevel framework for the circular economy (CE) integrates various dimensions and scales to address the complexity of transitioning from a linear to a circular model. This framework, as shown in Figure 1, typically encompasses micro (company), meso (industrial

park), and macro (national) levels, each with distinct but interconnected roles. These three levels are detailed as follows:

- **Micro Level:** At the micro level, CE practices are implemented within a single enterprise, focusing on cleaner production, eco-design, green purchasing, and product recycling or reuse [1]. It includes detailed analysis on specific material categories or emissions, covering activities like resource consumption, production of goods, services, value added jobs, corporate research and development, waste disposal, and air emissions [8].
- **Meso Level:** Most CE practices occur at the meso level, where efforts are concentrated on developing eco-industrial parks. These parks are communities of businesses that work together to achieve joint economic and environmental benefits by efficiently using resources [1]. Indicators at this level detect activities of a specific consumption domain or sector, such as waste materials, efficiency of production processes, and pollution caused by a specific sector, often assessing the performance of industrial parks [8].
- **Macro Level:** At the macro level, CE deals with the circulation of materials and energy in a given region or country. This includes Industrial Metabolism—the input–output processes, with regard to energy and materials, in a given area [1]. It considers the enclave or closed system of circulation of resources and products within a country—the international trade system including recycling, repairing, reuse, remanufacturing, refurbishment. It covers all economic activities within a country that are part of the circular economy, embodying both primary and secondary resources, i.e., manufactured goods, used goods, waste, and scraps. The total performance of these resources is evaluated at a national level [8].

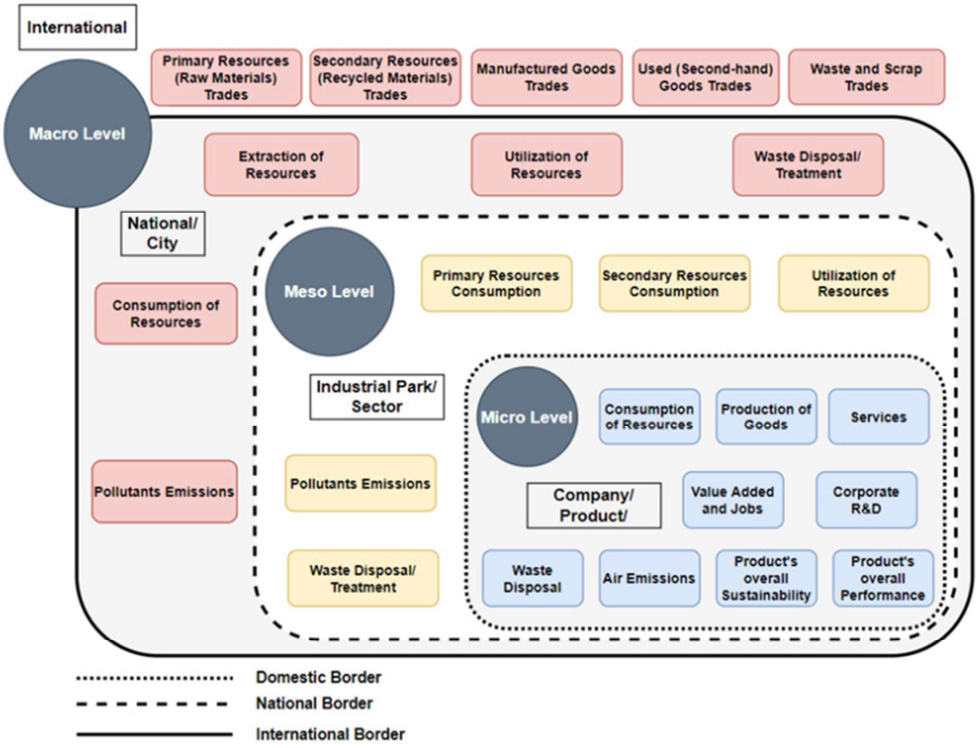


Figure 1. Multilevel framework of circular economy [8].

Building on the multilevel framework for CE, the integration of advanced technologies can significantly amplify the impact of these practices. Artificial intelligence (AI), with its ability to analyze vast datasets, optimize processes, and forecast outcomes, offers powerful tools to enhance CE efforts. By embedding AI within the CE framework, it is possible to

tackle specific challenges and discover new opportunities at the micro, meso, and macro levels, thus driving a more efficient and effective circular economy.

3. AI-Powered Approaches to Boost the Circular Economy: A Focus on Generative AI

3.1. AI: Categorization and Capabilities

AI refers to a broad field that includes various techniques and methods designed to mimic human intelligence and solve complex problems efficiently [9]. These techniques can range from simple algorithms to advanced machine learning models [9].

Additionally, AI is a field that blends multiple disciplines to develop systems with the ability to make decisions independently, problem-solve, and process languages [10]. Through machine learning, AI transforms big datasets, detects patterns, and executes tasks with minimal human intervention [11]. Its applications span across various industries, from cybersecurity and autonomous transport to health and real-time analytics [12]. Coupled with IoT and robotics, AI continues to transform technology for the better, driving efficiency and innovation across many fields.

AI tools can be categorized from multiple perspectives, reflecting their diverse applications and technologies. One approach classifies them by development lifecycle stages—data collection, model training, and deployment—helping identify development niches. Sharma classified AI in urban design based on algorithms and methods, emphasizing its purpose-driven nature [13]. Mosqueira-Rey et al. categorized AI tools in machine learning (ML) by lifecycle trends, including human involvement and engineering shifts [14]. Chang et al. focused on AI algorithms for smart manufacturing, highlighting learning-based applications and fault diagnosis [15]. This broad categorization underscores AI's evolving role across domains.

Existing classifications of AI tools, either according to development lifecycle, algorithms, or uses, are informative. However, application-based classification—decision-making, generative, and optimization AI—carries strong merits. Illustrated in Figure 2, application-based classification aligns better with real-world applications, making AI tools easier to use for technical as well as non-technical stakeholders. By identifying primary functions, it simplifies selection, enhances business integration, and maintains a keen focus on objectives.

Generative AI is among the fastest-growing fields with huge potential, particularly for application in the circular economy. Generative AI models possess the phenomenal ability to generate new content, whether images or text or even design [16]. This ability comes from strong techniques like Generative Adversarial Networks (GANs), where deep learning is achievable with minimal training data and where cross-transformation among various datasets becomes simple, as seen in application examples like artwork style comparison [17]. This ability can be extended to fields like radiology, where software like DALL-E 2 can potentially generate and modify pictures [16]. The implication for the circular economy is deep, in that generative AI can potentially achieve the following:

- Material Design and Innovation: Creating novel materials with desired properties for improved recyclability and biodegradability;
- Waste Reduction: Improving resource use efficiency in design and production to minimize waste generation;
- Product Life Extension: Redesigning new products or redesigning existing products for extended use and reduced consumption;
- Recycling and Up-cycling: Developing efficient processes and systems for effective recycling and up-cycling of materials.

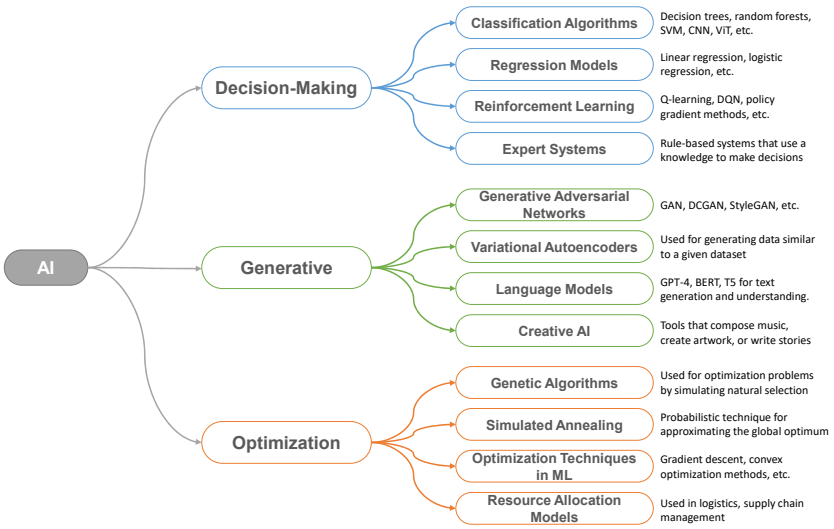


Figure 2. Application-oriented AI categorization.

3.2. AI for Waste Management

While AI encompasses a wide range of tools and techniques, generative AI stands out with unique potential to accelerate the transition towards a circular economy. This section explores how AI, with a particular emphasis on generative AI, can enhance the circular economy across the domain of waste management. Real-world examples will illustrate how AI-driven systems can optimize processes and achieve significant improvements at the micro, meso, and macro levels. For example, studies have shown that implementing AI-based route optimization in waste collection can lead to substantial benefits. For instance, AI-driven systems have achieved up to a 36.8% reduction in transportation distances, 13.35% cost savings, and 28.22% time savings [18].

Generative AI is transforming the circular economy by streamlining waste management and recycling. AI-driven chatbots supports individuals in segregating waste and simplifying sustainability efforts. AI also helps in developing products that are reusable and repairable, with closed material loops. Machine learning and big data further optimize the utilization of materials, reducing waste to a large degree. Generative AI has immense potential to change waste management in every sector, moving from traditional mechanisms to a smarter and resource-based mechanism.

At the micro level:

- Personalized Waste Sorting Guidance: AI-driven mobile apps, powered by generative models, could scan photos of domestic trash and offer customized sorting and disposal guidelines. Such apps could even create 3D simulations of ideal container stuffing for recycling containers, optimizing space and reducing contamination. For example, the MWaste application utilizes computer vision and deep learning techniques to classify waste materials into various classes such as trash, plastic, paper, metal, glass, or cardboard with an impressive average accuracy of 92% when evaluated on actual images [19]. Similarly, the 'Pilahin' prototype app encourages household waste sorting by allowing users to scan and detect trash, providing categories for identification and sorting, and locating nearby trash banks [20]. These advancements demonstrate the potential of AI-powered applications to revolutionize waste management by providing personalized, efficient, and sustainable solutions for household waste sorting and disposal.
- Smart Bins: Generative AI can power smart bins that not only identify and sort waste but also learn from collected data to optimize waste collection routes and schedules. These bins could even generate alerts for contamination or overflow, improving effi-

ciency and reducing operational costs. By employing IoT components such as RFIDs and sensors, smart bins can monitor trash levels, indoor humidity, temperature, and detect harmful gases, thereby preventing overflow and environmental pollution [21]. IoT use in smart bins optimizes their performance by enabling real-time data collection through sensors, fill-level tracking, and composition detection of waste. The sensors inform waste collection systems, enabling optimized collection time routing and dynamic route planning to conserve time and fuel. IoT-enabled smart bins also help in environment enhancement by preventing overflow, illegal dumping, and optimizing recycling efficiency through source-level waste segmentation by type. Furthermore, the incorporation of artificial intelligence algorithms like convolutional neural networks (CNNs) and hybrid genetic algorithm-fuzzy inference systems enables these waste bins to actively track waste collection activities and optimize the route of trash collection vehicles (TCVs) [22]. Generally, the incorporation of intelligent bins with generative AI and Internet of Things (IoT) technologies not only optimizes waste collection routes and schedules but also greatly enhances the efficiency and economic viability of urban waste management systems.

At the meso level:

- Enhanced Recycling in Smart Cities: Generative AI can enhance existing AI-powered waste sorting systems in smart cities. For example, AI models can analyze the composition of mixed waste streams and generate optimized designs for sorting facilities or even new recycling processes tailored to the specific material composition. AI models, such as those utilizing deep learning and computer vision, can accurately identify and classify waste materials, achieving high accuracy rates, as demonstrated by models like GECM-EfficientNet and AIEWO-WMC, which have reached accuracies of 94.54% and 99.15%, respectively [23,24]. These models can be further improved by the addition of generative AI to analyze mixed waste streams and propose optimized facility designs that achieve highest sorting efficiency at lower operational costs. For instance, the hybrid genetic algorithm-fuzzy inference engine model can control waste collection adaptively, with fewer errors and higher robustness [22]. The integration of state-of-the-art artificial intelligence methods with generative AI enables smart cities to design more effective, economical, and sustainable waste management systems that enhance sustainability and public health gains.
- Revamping Electronic Waste Management: Generative AI can aid in the design of robotic systems that can disassemble electronic waste more accurately and efficiently. Such systems can be trained on large datasets of electronic designs to learn how to extract valuable components and materials in the best possible way, with the goal of maximizing resource recovery while minimizing environmental hazards. The integration of AI in waste management systems, including smart bins and robots for waste sorting, has the potential to enhance resource recovery, reduce transportation distances, and lower operational expenses [25]. For instance, Fractional Horse Herd Gas Optimization-based Shepherd Convolutional Neural Network (FrHHGO-based ShCNN) has shown excellent performance in e-waste classification with high accuracy, sensitivity, and specificity that are critical for effective resource recovery and mitigating environmental hazards [26]. In conclusion, the combination of generative artificial intelligence with robotic platforms for electronic waste management can enhance resource recovery, reduce environmental effects, and facilitate achieving sustainable waste management systems.

At the macro level:

- Designing for Circularity: Generative AI can be a powerful tool for designing products with end-of-life in mind. By inputting desired properties and materials, designers can use generative AI to explore a vast design space and generate optimized product designs that prioritize disassembly, recyclability, and material reuse. Ghoreishi [27] and Shennib [28] both highlighted the potential of AI in designing products for circularity and improving waste management. Ghoreishi explicitly referred to applying artificial intelligence to circular product design, referencing the applicability in analyzing real-time information, optimization procedures, and minimizing waste during design [27]. Shennib continued describing the application of data-driven technologies, or AI, in waste management, stating that open data opportunities would be of high value in this field [28]. Collectively, these studies illustrate the important function of artificial intelligence in making products and waste management more circular.
- Industrial Symbiosis Optimization: Generative artificial intelligence can be used to augment industrial symbiosis through the discovery of new interlinks and synergies between different industries. Artificial intelligence algorithms can sift through waste streams, energy usage patterns, and material flows to architect effective symbiotic interactions, thereby maximizing resource exchange and reducing the overall environmental footprint. Based on statistical datasets merged with industrial symbiosis databases, generative AI can enable the prolonged investigation of prospective symbiotic relationships without requiring costly surveys [29]. This method not only streamlines the identification of IS partnerships but also promotes circular economy development by connecting previously unrelated industry sectors, as demonstrated in Sweden [29]. Moreover, AI can play a crucial role in managing waste quality within industrial symbiosis, ensuring the efficiency of integrating waste suppliers into operational processes [30].

By embracing generative AI, waste management can evolve from a linear system of disposal to a closed-loop system of resource optimization and value creation. This transformation, coupled with effective communication and collaboration between stakeholders, can significantly advance the circular economy and contribute to a more sustainable future.

4. Discussion

In conclusion, AI plays a critical role in streamlining waste management within the circular economy through increased efficiency of processes, reduction in contamination, and optimization of resource recovery. AI-driven waste management also facilitates resource efficiency and environmental sustainability. Furthermore, AI-optimized route planning within waste collection ensures logistics efficiency is maximized while fuel consumption and emissions are reduced. These advancements facilitate a more circular and resilient economy through the minimization of waste generation and optimization of material reuse.

However, despite these benefits, the successful integration of AI into waste management systems requires overcoming barriers such as data accessibility, system compatibility, and ethical concerns regarding decision-making processes. The lack of standardized and accessible data hinders the seamless integration of AI-driven waste management systems across the value chain, as highlighted in an exploratory study in the Norwegian AEC industry [31]. Similarly, interoperability issues prevent AI systems from effectively communicating across different waste management platforms, limiting their full potential, as discussed in a systematic literature review focusing on AI applications in circular economy practices [32]. Furthermore, the ethical implications of AI-driven waste management decisions, such as algorithmic biases in sorting processes and potential impacts on employment, must be carefully considered to ensure responsible AI deployment [33].

While AI offers numerous benefits in waste management, challenges persist. Data limitations hinder AI model accuracy due to fragmented datasets and inconsistent waste categorization standards. Interoperability barriers between different AI systems and IoT platforms create many integration points leading to various efficiencies. Ethical considerations arise in decisions made based on AI, for example, waste sorting algorithms could have biases which lead to negative socio-economic impacts for entrants into the waste management job sector as a result of automation. These limitations need to be surmounted to create sustainability in the application of AI in the waste management sector.

Follow-up research need to consider ways to put in place solutions to overcome barriers to implementation and unleash AI's capabilities and potentials in waste management for a circular economy. Adding constraints with the development of as much data that is available and then developing standardized AI platforms could help AI solutions become more scalable and sophisticated. There is a lot to explore with respect to AI capabilities, including machine learning, big data analytics, and the potential of IoT integration. Each of these can offer new capabilities to maximize the efficiency of waste collection, material recovery, and recycle systems. Ultimately, surrounding oneself with collaborators (policymakers, waste management companies, researchers, and technology experts) will promote innovative collaboration. This can assist in knowledge sharing and best practices that will drive sustainable waste management within the circular economy.

5. Conclusions

AI implementation in waste management is central to the further development of circular economy models, which maximize the utilization of resources and promote a sustainable future. The manuscript has outlined how AI optimizes waste sorting, recycling, and collection logistics to reduce landfill, waste treatment, and environmental load. AI-based technologies like machine learning and computer vision allow for efficient waste characterization and collection efficiencies. Prior to the complete integration of artificial intelligence in waste management, various challenges concerning the availability of data, exchangeability of data, and ethical concerns have to be resolved to achieve significant breakthroughs.

Future research should focus on overcoming these barriers and scaling AI applications in waste management. Finally, collaboration among policymakers, industry, and researchers is essential to drive innovation and accelerate the transition to a more sustainable circular economy.

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